

## Part II:

### Effects of Recreation and the Built Environment on Water Quality



*Canoeists at Ozark Landing, Buffalo National Wild and Scenic River,  
Buffalo National River, Arkansas. Photo by Bill Lea*

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## Chapter 5

# Hydromodifications—Dams, Diversions, Return Flows, and Other Alterations of Natural Water Flows

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### Introduction

The term hydromodification is commonly used to describe all activities, which alter the natural flow of water. This chapter addresses the effects of structures, such as dams, headgates, reservoirs, canals, water wells, diversion ditches, and flumes upon the quality of raw drinking water before it arrives at the water treatment plant. It also includes a discussion of the effects of land application of treated sewage sludge, return flows, wetland modifications, and reclaiming wastewater upon drinking water quality.

### Issues and Risks

The U.S. Environmental Protection Agency (EPA) ranked hydromodification as the third leading cause of water-quality impairment to rivers. Only agriculture and municipal sewage treatment plants ranked higher (U.S. EPA 1995). Nationwide, there are over 68,000 medium and large dams built for hydropower, water supply, flood control, and other purposes. The U.S. Geological Survey estimates the cumulative storage capacity of these dams is almost 450 million acre-feet [550 billion meters (m<sup>3</sup>)].<sup>2</sup> The Bureau of Reclamation manages about 600 dams and 53,000 miles [85,000 kilometers (km)] of canals in 17 Western States; the Army Corps of Engineers has about 700 dams and accounts for about one-third of all water in storage in the Nation (Reetz and others 1998). There are about 2,350 dams with a total storage capacity of about 55 million acre-feet (68 billion m<sup>3</sup>) on land administered by the U.S. Department of Agriculture, Forest Service. Half are owned and operated by the Agency mostly for recreation, fire protection, and fish or wildlife needs. The others are owned and operated by other Federal agencies, States, and private parties under special-use authorizations, mostly for irrigation, recreation, and water supply.<sup>3</sup>

There are also thousands of small dams in the United States that were designed and built to store drinking water during periods when inflows to the reservoir are greater than the water removed from the reservoir. Some of these reservoirs were built and are still operated solely to provide a reliable water supply. Since the 1940's, however, some of the existing ones and almost all new reservoirs became multi-purpose; that is, they serve recreation, irrigation, flood control, and sometimes hydropower needs, while supplying drinking water. Often these other purposes create water-quality problems for human health by altering water temperature, sediment transport, biological oxygen demand, chemical oxygen demand, total dissolved solids, and streamflow. Related information on these problems can be found in chapters 2 and 3.

The diversion and transport of water from one watershed to another can result in physical, chemical, and microbiological contamination of the receiving waterbody and cause channel erosion, sediment transport, and deposition in reservoirs and channels. Subsequent dredging in large rivers and reservoirs often accelerates downcutting of headwater streams and destabilizes streambanks, even where stream gradients are quite flat, such as in Mississippi.

Drainage of wetlands with ditches is a form of hydromodification that can change water chemistry by adding organic compounds, thereby affecting water treatment processes and costs. Application of treated sewage sludge to forested land has been evaluated for its risk of contaminating water supplies with pathogens and found to be a low risk in most situations. Reclaiming sewage effluent water for drinking water is done in other countries, but is not yet commonplace in the United States.

Nearly all these hydromodifications are influenced by water rights laws which vary considerably from State to State. In most Western States, laws require water users to divert water out of streams or rivers to obtain a State water right. This removal often results in higher water temperatures, lower oxygen levels, reduced sediment transport capacity, and other water-quality problems in the remaining water

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(Getches and others 1991). The riparian water rights doctrine used in most States east of the 100<sup>th</sup> meridian generates water-quality problems because most of the water is returned to the channel.

### Findings

Hydromodifications can impact water quality via algae blooms, trihalomethane production, sediment transport and deposition, and changes in chemical, physical, and microbiological properties.

## Effects of Dams and Impoundments on Water Quality

The size and depth of impoundments and the residence time of water within them can affect water quality chemically, physically, and biologically. As water flows into a reservoir, its velocity slows, reducing the diffusion of oxygen from the air into the surface water. In turn, biological and chemical oxygen demands may deplete oxygen, especially near the bottom. This phenomenon has been well studied, and detailed models that quantify this effect have been developed. Anoxic conditions generally cause secondary problems in drinking water, usually taste, smell, color, and increased concentrations of iron, manganese, and sulfide. These problems usually do not pose health risks, but may increase water treatment costs. Under some conditions, impoundments can cause toxic algae blooms which can pose health risks.

### Case Study: Toxic Algae Bloom at Hebgen Lake, MT

The operation of dams can affect the likelihood of blue-green algae blooms, which sometimes produce toxins that have been reported to be fatal to livestock, wildlife, and pets, and pose risk to human health. For example, Hebgen Lake, Gallatin National Forest, MT, experienced a toxic algae bloom in June 1977 (Juday and others 1981). A family camping at the Forest Service campground on the Grayling Arm of Hebgen Lake (actually a medium-size reservoir) was hysterical after their pet dog went into convulsions after drinking some of the lake water. Their dog died a few minutes later. When Forest Service personnel and a Gallatin County sanitarian arrived at the campground, they were besiged by people frightened by what they had witnessed that day. Several more pet dogs had died, and everyone could see the bodies of dead cattle lying near the lakeshore beyond the campground fence. A green scum was on the surface of the water that was different from the algae seen in previous years. This coating resembled thick, green pea soup, was odorless, and went at least 50 feet (15 m)

offshore. Water samples were taken, including the green algae, and packed in ice. The sanitarian posted his Area Closed signs at the campground and it was closed down that day.

The next day the samples were taken to the State Water Quality Bureau scientists in Helena. After they heard what had been found, they agreed to go to Hebgen Lake with Forest Service personnel. They phoned some toxic algae experts and reported this episode. These experts arrived a few days later and began intensive studies of the algal bloom. They identified the culprit as *Anabaena flos-aquae*, a blue-green alga that sometimes produces a very potent toxin (anatoxin-a), which is released into the water. No human deaths have been attributed to anatoxin-a poisoning, but over the past 100 years, the number of domestic and wild animal deaths from *A. flos-aquae* poisoning has sometimes numbered in the thousands. With the Fourth of July holiday approaching, a meeting was held to decide what protective measures should be implemented to prevent any more loss of pets, or cattle, or risks to people. The decision was to close the lake to recreational boating, and to keep the shoreline and campground on the Grayling Arm of the lake closed until the toxicity of the water had ended. Daily sampling of the Grayling Arm algae and water continued. The bloom gradually declined during July and was nontoxic by July 30<sup>th</sup>.

Possible explanations for the bloom include starting to fill the reservoir in February instead of the normal late April because of low winter snowfall and expected low snowmelt runoff that year, with subsequent early warming of the water. The 21-foot (6.4-m) drawdown of this reservoir may have allowed for bottom sediments of the Grayling Arm to be extracted for nutrients. The upper watershed lies inside Yellowstone National Park where it drains highly mineralized volcanic materials and geysers that produce a naturally high concentration of nutrients. As a result, phosphate content is relatively high. The reservoir is nitrogen limited. Juday and others (1981) classified the main part of Hebgen Lake reservoir as mesotrophic and the Grayling Arm as eutrophic. They also found the *A. flos-aquae* algae disappeared about 1 km out in the main part of the lake. Apparently the water chemistry outside Grayling Arm was inhospitable to the *Anabaena*.

If dam owners begin to fill their reservoirs earlier than normal in the spring to capture snowmelt runoff in drought years, the water has extra time to warm up. With enough nitrogen and phosphorus in the warm water from natural and manmade sources, conditions favor algae blooms. In many States, including Montana, both Dakotas, Indiana, Iowa, Minnesota, Missouri, and Wisconsin, toxic blooms of blue-green algae have been reported, even in forested and largely

pristine watersheds (Carmichael 1981, Fawks and others 1994, Horpestad and others 1978). Whether a given bloom will turn toxic is still unknown. Accidental ingestion by people engaging in water sports is a risk to human health. Although no deaths have been reported, prudence calls for prohibiting all water contact sports and closure of public drinking water intakes when toxic blue-green algae blooms are suspected. Improved methods of detection of toxic blue-green algae blooms have resulted in more reports on their occurrence.

### **Trihalomethane**

Trihalomethanes are compounds that form when chlorine or bromine, added to drinking water for disinfection, reacts with certain naturally occurring organic molecules (trihalomethanes precursors). Trihalomethanes may cause cancer and genetic mutations in humans. Researchers (Arruda and Fromm 1989, Martin and others 1993) report that reservoir and lake organic sediments can contain and release trihalomethane precursors. In one study in Ohio, all sediment samples had significantly more trihalomethane precursor releases than controls. Anaerobic conditions and deep water sediments had much fewer trihalomethane precursors than aerobic sediments from shallower zones. Karimi and Singer (1991) and Wardlaw and others (1991) reviewed the role of algae as trihalomethane precursors. They found that a variety of natural organic compounds, especially humic and fulvic acids derived from soils and decomposition of plant material, are the trihalomethane precursors. No discernible trends in the ability of particular algae species to generate trihalomethanes can be drawn from published data. Trihalomethane concentrations arising from a natural algal bloom, however, could theoretically exceed maximum allowable concentrations for drinking water. Understanding trihalomethane precursor sources is important because limiting them may lower risks to human health and lower water treatment costs. Management of a reservoir to limit algal growth may reduce water treatment costs and improve water quality in the reservoir (Kortmann 1989).

### **Sediments Deposited in Reservoirs**

Sediment deposited in reservoirs can also pose public health problems if it contains heavy metals, radioactive elements, or pesticides and other synthetic organic compounds. Many of these chemically bond to the sediment particles under the right chemical conditions. The risk to human health often remains low as long as the sediment remains undisturbed at the bottom of a lake or reservoir. The accidental failure or deliberate removal of a dam may pose a human health problem by destabilizing accumulated sediment, but literature is lacking on this topic. Modifying streamflows

has the potential to mobilize and later deposit sediment that may then reduce the quality of drinking water. See chapter 2 for more information on this topic. Further research needs to be conducted on remobilization of toxic sediments.

Splash dams and log flumes were constructed on many rivers in New England, the Lake States, and the West. The dams were earthen structures <20 feet (7 m) high with the main spillway constructed of wooden boards. They typically held from a few hundred to 1,000 acre-feet (up to 1.25 million m<sup>3</sup>) of water. When the boards were removed, an artificial flood was created downstream, sweeping logs down the channel. Such dams are no longer constructed, and their residual effects upon drinking water quality today are likely to be minor.

Controlled removal of sediment by dredging from channels, lakes, or reservoirs can degrade domestic water supplies. These sediments pose special problems if they contain toxic substances or if they are massively released.

### **Water Diversion Structures and Water Import/Export Between Watersheds**

Water is frequently removed from a river by means of a diversionary dam or headgate along one side of the channel. The water then enters a ditch, aqueduct, or pipeline to be carried to the place of use, often miles away. The removal of this water results in changes in the remaining river water. Concentrations of pollutants increase, water temperatures rise, and biological activity of aquatic organisms increases. The acidity of the water often rises as well, changing the solubility of metals and rates of chemical reactions in the water column. Suspended sediment transport declines as flow declines, causing increased deposition of fines on the beds of rivers (Heede 1980).

The effects of removing water from rivers upon drinking water quality at intakes located below points of diversion can usually be overcome at the water treatment plant—as long as there is enough water left to be treated. There is no scientific literature on this subject. The same is true for water added to stream channels by diversions from other watersheds or aquifers. Differences in chemical, physical, or microbiological quality of such waters may create complications when they are mixed together.

## Water Well Effects on Drinking Water Quality

High pumping rates from water wells can decrease flows of nearby streams used for drinking water, sometimes for months or longer. Decreases in streamflow usually degrade drinking water quality by changing acidity, dissolved oxygen, and water temperature. Rates of pumping that exceed the recharge rate of the aquifer draw down the water table, altering the yield and water quality at other wells tapping the same aquifer.

Wells in floodplains can become contaminated during high streamflows if they are not properly protected ahead of time. Singer and others (1982) found that bacterial counts, nitrate nitrogen, turbidity, conductivity, sulfate, chloride, phosphate, total organic carbon, and several ratios of these variables were the best indicators of surface water contamination of aquifers in a karst area of southeastern Minnesota. Improper sealing or grouting of the annular space of the well itself can result in cross contamination, aquifer damage, loss of well performance, and damage to the well (Ashley 1987). The most commonly used sealing materials in wells, cement and bentonite clay, have properties that can cause them to fail if unsuitable drilling and well construction methods are employed in some hydrogeologic environments. There is a large body of literature on well construction and maintenance. The reader should obtain expert assistance if it appears that local water wells could be responsible for pollutants in forest or grassland watersheds. An Internet site to go to for information on wellhead protection is EPA's Office of Ground Water and Drinking Water, located at <http://www.epa.gov/OGWDW/whpnp.html>.

## Sewage Effluent and Sludge/Biosolids Applications to Forest and Rangeland

Return flows of sewage effluent or sludge and biosolids or both are sometimes applied to the land surface rather than returned to water bodies. Research on effluent and sludge or biosolids applications was conducted in the Pacific Northwest by Machno (1989), in New England by Koterba and others (1979), and in the Lake States and Southeastern United States by other researchers. Materials were applied under hardwood forests. Koterba and others (1979) found little change in soil water and stream chemistry after light application [11 tons per acre or 25 metric tonnes (Mg) per hectare] of limed and dewatered sludge on sandy loam soils in a northern hardwood forest in central New England. They measured short-lived and relatively small increases in calcium, magnesium, sodium, chloride, and sulfate after

56 tons per acre (125 Mg per hectare) were applied. There were no changes in infiltration capacity of the soil and no visual evidence of overland transport of the sludge.

Brockway (1988), Brockway and Urie (1983), and Sorber and Moore (1986) studied effects of applying municipal or papermill sludge and wastewater to forests by monitoring the movement of nitrogen and other constituents in the leachate and ground water. Results showed nitrate nitrogen concentrations exceeded 10 parts per million in ground water under aspen (*Alnus* spp.) plots treated once with 7 or more tons per acre (16 Mg per hectare) of undigested papermill sludge, and under pine (*Pinus* spp.) plantations receiving 8.5 tons per acre (19 Mg per hectare) per year of anaerobically digested municipal sludge in a single application. Brockway and Urie (1983) estimated that anaerobically digested municipal sludge could be safely applied to a red pine (*P. resinosa* Ait.) and white pine (*P. albicaulis* Engelm.) plantation at 7.25 dry tons per acre {880 pounds total nitrogen per acre [986 kilograms (kg) per hectare]} per year or less, and to aspen stands at rates up to 8.4 dry tons per acre [1,015 pounds total nitrogen per acre (1138 kg per hectare)] per year. Although long-term additions of nitrogen to soil could lead to nitrogen saturation (see chapter 3), this effect has not been studied for sewage sludge applications.

Spray applications of treated municipal wastewater on forests in Michigan have been studied by Urie and others (1990) and Brockway (1988). Overall, it appears that nitrate contamination of ground water can be avoided at appropriate application rates on most acidic forest soils.

Edmonds (1976) studied the survival rate over 3 years of coliform bacteria in sewage sludge applied to a forest clearcut on gravelly glacial outwash soils. Results indicated that few viable fecal coliforms penetrated deeper than 2 inches (15 centimeters) into the soil and that practically none moved into the ground water. The soil was effective as a biological filter for hazardous pathogens, but coliforms can remain viable for years in the surface soil. He concluded there was little danger of ground water contamination from vertical bacterial movement.

Harris-Pierce and others (1995) applied sewage sludge on a semiarid grassland in Colorado. They found that increasing rates of single applications from 0 to 9.7 to 18 tons per acre (22 to 40 Mg per hectare) increased concentrations of sediment, organic nitrogen, ammonia nitrogen, potassium, boron, phosphorous, copper, nickel, and molybdenum in surface runoff from a single sprinkler rainfall event on the plots. All constituents remained below EPA's drinking water standards. However, Burkhardt and others (1993) argued for a careful approach to sludge applications on rangeland

without irrigation because of the limited opportunity for nutrient uptake and sludge assimilation by the native vegetation. They saw risks of the nutrients and metals moving off-site when rainfall events do occur.

Sagik and others (1979) evaluated microbial survival and movement in soils subjected to sludge applications and concluded that both bacteria and viruses can survive and move through the soil profile for up to 2 years; prudence says that nondisinfected sludge should not be applied to soils used to grow crops or feed for dairy cows or livestock for human consumption. See EPA's Web site at <http://www.epa.gov/owm/bio.htm> for additional information about biosolids recycling.

### Wetland Drainage

Effects of wetland drainage on drinking water quality have been studied. Results show some small increases in nitrogen leaching and coliform movement with the leachate, but that the drainage water is easily handled by the water treatment plant.<sup>4</sup>

### Reclaimed Water and Return Flows

After use, water withdrawn from rivers or aquifers is often returned to these sources. Quantity and quality of the returned water may be changed, depending upon the type of use and type of treatment it receives prior to return. There is a large body of literature and regulations about sewage treatment because it is a point source of pollution under the Clean Water Act. Reuse of water effluent from sewage treatment plants is growing in the United States and has passed the 1-billion-gallon-per-day (4-billion-liter-per-day) mark for both nonpotable (water not intended for human consumption) and potable (drinkable) uses. Water reuse for nonpotable applications, such as irrigation, lawn watering, car washing, and toilet flushing is widely accepted where water supplies are scarce, as in Arizona, California, Florida, and Texas. The EPA and the National Academy of Sciences have recommended limits for many physical parameters and chemical constituents of nonpotable water. The health risks from disease-causing microorganisms are not as well known; hence, there is no direct potable reuse in the United States (Crook 1997).

Of course, indirect potable reuse occurs when effluents are treated and returned to rivers that are water sources downstream. Required treatments may include: (1) chemical clarification and two-stage recarbonation with intermediate settling, multimedia filtration; (2) activated carbon adsorption; (3) ion exchange for nitrogen removal; and (4) breakpoint chlorination. Indirect potable reuse can also occur when effluent is used for ground water recharge by means of injection wells. Some States prohibit that practice if potable aquifers would be contaminated. Other States have set stringent water-quality standards and require high levels of effluent treatment before it is returned to the aquifer (Crook 1997). Crook also lists a number of references on water reuse that would be very helpful to managers of land influenced by water reuse or officials responsible for completing source water assessments.

While irrigation return flows are exempt from the National Pollutant Discharge Elimination System permitting process, they can carry potentially harmful concentrations of pesticides, heavy metals, or other toxic substances acquired from atmospheric deposition, soils, and plants. Crop irrigation is beyond the scope of this report; there is a large amount of literature on this subject by EPA and various universities.

### Reliability and Limitations of Findings

Scientific literature on the direct effects of dams, water diversion and conveyance structures, water wells, and other related engineered structures upon drinking water quality is very limited. Far more is known about their effects on physical habitats of aquatic life forms. Most of the studies mentioned did not describe how the water facility was operated or whether the manner of operation could have, or did, influence the results. Facility operational details should be better evaluated in future research studies.

The indirect effects of dams, water diversions and conveyance structures, water wells, and applications of sewage sludge should apply in all forest and rangeland watersheds in the United States. The magnitude and timing of the indirect effects will vary by region and perhaps by elevation because of variations in temperature and precipitation. None of the studies reported were national or even regional in scope, and only a few were carried out for a decade or more, so long-term trends have been ignored or are not known.

<sup>4</sup> Personal communication. 1999. James D. Gregory, Professor of Watershed Hydrology, Department of Forestry, North Carolina State University, Raleigh, NC 27695.

## Research Needs

1. The direct effects of dams and their operation, mobilization of sediments when dams are removed, water diversion and conveyance structures, and water wells upon human drinking water quality need to be studied.
2. Research is needed to determine why some blue-green algae blooms turn toxic and how to predict the toxicity levels.

## Key Points

1. Managers who experience blue-green algae blooms in their reservoirs need to recognize that such blooms sometimes become toxic without prior warning or previous history. These toxins are invisible when released by the algae into the water, and are extremely deadly to all mammals if ingested. Most of the other risks to human health from water storage and control structures are known and can be assessed in local watersheds by professionals in hydrology and health sciences.
2. Risks from applying sewage sludge on forest and rangelands are manageable as long as disease-causing organisms have been killed at the sewage treatment plant before the sludge is applied to the soil.
3. Improper construction or inadequate well head protection of water wells can be a cause of ground water contamination. People doing source water assessments in forest and rangeland watersheds should carefully examine wells in the vulnerability assessment.

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## Chapter 6

### Urbanization

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#### Introduction

This chapter specifically examines drinking water issues related to urbanization. The discussion is limited principally to land that is developed or being developed within and adjacent to public land. Urbanization issues include current and past land uses and Forest Service facilities. Forest Service buildings and administrative sites are included because they are similar to other developed sites.

The effects of urbanization on drinking water quality encompass many topics with extensive published literature. Because of limited space, selected topics of current and past land use are examined including wastewater treatment, urban storm runoff, underground storage tanks, abandoned wells, and landfills. However, land managers need to realize that these selected topics do not include all effects caused by urbanization, land fills, and abandoned mines on drinking water and serve only to illustrate potential effects.

Vitousek (1994) has identified land cover changes as a primary effect of humans on natural systems. With the projected global increase in urbanization, land cover conversions for urban use will only increase. In this chapter, we examine the potential impacts on drinking water of current and past use of land in and adjacent to public land. Nationally, development and growth rates are not available for such land. To estimate these rates, we have used in-holding data from the Forest Service.

Inside the boundaries of publicly owned land are parcels not administered by the Agency. They are called in-holdings. In-holdings are managed or owned by other Federal, State, local, and tribal government agencies, and by private landowners. Of particular interest is the private land because of its propensity for development. The occurrence of in-holdings varies by Forest Service region (table 6.1). The States that comprise each region are listed in table 6.1.

Region 4 has the least area of in-holdings; only 6.9 percent of the land inside national forest boundaries. By comparison, Regions 8 and 9 had 48.6- and 45.6-percent in-holdings within national forest boundaries, respectively.

Unfortunately, no data are available on how rapidly these in-holdings are being developed. To estimate this rate, we used the growth rates of counties that intersect with or are adjacent to a national forest. Population growth was calculated for 1980–90 and 1990–96 using census data (U.S. Census Bureau 1997). Between 1980 and 1990, the population of these counties grew by 18.5 percent, while the Nation's population grew by 9.8 percent (table 6.1). For 1990 to 1996, the population in these counties grew by 10.1 percent, while the Nation's population grew by 6.4 percent. In 1996, these counties contained 22.4 percent of the Nation's population (U.S. Census Bureau 1997).

Population change in these counties varied by region and time period. Between 1980 and 1990, Region 5 experienced the greatest percent increase (28.9 percent), while Region 1 experienced a decrease of 3.5 percent. Between 1990 and 1996, Region 4 and 6 showed the largest increases of 14.9 and 14.3 percent, respectively, and Region 9 showed the least growth of 5.2 percent. Overall, Regions 2, 3, 4, 5, and 6 had growth rates greater than the national average for the period between 1990 and 1996. The effects of this development on drinking water quality depend on the location within the watershed, the concentration of development, and existing conditions. Unfortunately, data are unavailable to examine those variables.

#### Issues and Risks

During the past 20 years, private tracts in and adjacent to public land have been developed rapidly for residential, commercial, and recreational use. This development poses a significant threat to drinking water quality through surface and ground water contamination. Development occurs near the headwaters of streams where water quality is generally the highest and is easily degraded because of stream size. For ground water, about 95 percent of rural communities use

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**Table 6.1—Reported acres inside national forest boundaries and percent population changes in counties containing or adjacent to national forests by administrative Forest Service Region in the conterminous United States**

Region <sup>a</sup>	Area <sup>b</sup>				Population change 1980–90	Population change 1990–96
	Gross	NF	In-holding	Other		
	-----Acres-----				-----Percent-----	
1	28,180,534	25,375,333	2,805,201	10.0	-3.5	5.7
2	24,477,648	22,098,044	2,379,604	9.7	3.6	10.6
3	22,381,905	20,702,312	1,679,593	7.5	17.2	10.9
4	34,257,094	31,903,934	2,353,160	6.9	14.8	14.9
5	23,739,894	20,022,650	3,717,244	15.7	28.9	10.3
6	27,357,569	24,629,048	2,728,521	10.0	6.8	14.3
8	25,034,868	12,874,851	12,160,017	48.6	6.1	6.8
9	21,934,418	11,942,218	9,992,200	45.6	1.8	5.2
Total	207,363,930	169,548,390	37,815,540	18.2 <sup>c</sup>	9.8 <sup>d</sup>	6.4 <sup>d</sup>

<sup>a</sup> Region 1: Montana, northern Idaho, North Dakota, and northwestern South Dakota; Region 2: Colorado, Kansas, Nebraska, and southeastern South Dakota; Region 3: Arizona and New Mexico; Region 4: southern Idaho, Nevada, Utah, and western Wyoming; Region 5: California, Hawaii, Guam, and Trust Territories of the Pacific Islands; Region 6: Oregon and Washington; Region 8: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, Puerto Rico, South Carolina, Tennessee, Texas, and Virginia; and Region 9: Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, Virgin Islands, and Wisconsin.

<sup>b</sup> In-holding = parcels of land within the boundaries of publicly owned lands that are not administered by the public agency; NF = national forest; Other = percent of in-holdings within the gross acreage inside national forest boundaries.

<sup>c</sup> Percent of in-holdings within national forest boundaries for the conterminous United States (calculated as in-holdings/gross).

<sup>d</sup> Percent population change in counties containing or adjacent to national forests for the conterminous United States.

ground water as the principal source of drinking water. Sources of pollution result from wastewater treatment, nonpoint-source pollution, underground storage tanks, solid waste storage, and hazardous material storage. The extent of ground water contamination depends on depth of ground water. Shallow ground water sources < 100 feet [30 meters (m)] below land surface may be more readily and significantly contaminated than deeper ground water sources (U.S. Geological Survey 1999).

In 1995, the U.S. Environmental Protection Agency (EPA) (U.S. EPA 1998d) summarized water-quality information submitted by States, tribes, and other jurisdictions. For rivers, streams, lakes, ponds, and reservoirs, municipal point and nonpoint sources from residential and commercial sources were identified as significant contributors of pollution to rivers, streams, lakes, ponds, and reservoirs. For ground water, principal sources included leachate from leaking underground storage tanks, septic tanks, and

landfills. Of specific importance is the effect of urbanization on the quality of surface water and ground water in rural areas (table 6.2).

The report identified urbanization as a major factor in contaminating surface and ground water, and modifying hydrologic processes. Urbanization replaces natural vegetation cover with impervious surfaces, decreasing natural infiltration of water, increasing peak flows, and decreasing ground water recharge (Weiss 1995). Increased peak flows can negatively affect drinking water quality by causing bank destabilization and streambed scouring, which increase turbidity and sedimentation (Phillips and Lewis 1995). Reduced ground water recharge decreases baseflow in streams and increases pollutant concentrations. Decreased baseflow impairs aquatic habitat and riparian wetlands and increases the stream's sensitivity to pollution and sedimentation (Weiss 1995).

**Table 6.2—Estimated use from freshwater surface and ground water sources in the United States, 1980–95**

Source	1980	1985	1990	1995
----- Cubic kilometers -----				
Ground	120	101	110	105
Surface	400	366	358	364
Total	520	467	468	469

Source: Adapted from Gleick 1999.

## Wastewater Treatment

Residential and commercial wastewater is treated by decentralized and centralized systems. Decentralized systems treat water onsite. They include individual and large septic systems, and cluster wastewater systems. Generally, septic systems treat and dispose of relatively small volumes of wastewater. They are for individual dwellings or groups of dwellings and businesses located close together. A centralized system is a collection and treatment system containing collection sewers and a central treatment facility (U.S. EPA 1997a). Centralized systems are used to collect and treat large volumes of water. Decentralized systems affect both surface and ground water, while centralized systems generally affect surface waters.

The 1990 census indicates that 25 million households use onsite disposal systems for wastewater. Data on the failure rates associated with these systems are limited and no national estimates are available. Each State has its own definition of failure, but estimates of failure rates range from 18 to over 70 percent (U.S. EPA 1997a). Twenty-seven States have cited onsite disposal systems as a potential source of ground water contamination (U.S. EPA 1998d). Contaminants from onsite disposal can be classed as inorganic (sodium, chlorides, potassium, calcium, magnesium, sulfates, and ammonium), microorganisms (bacteria and viruses), and chemical organics originating in household products (Phillips and Lewis 1995, U.S. EPA 1997a). Effluent from septic systems usually contains high concentrations of ammonium and organic nitrogen.

Water supplies are vulnerable to pathogenic bacteria and viruses from onsite disposal systems. Reported outbreaks of waterborne disease in the United States are uncommon (table 6.3), but 404,000 people fell ill to a *Cryptosporidium*

spp. outbreak in Milwaukee, WI, in 1993. To some extent, low occurrence may be attributed to individuals being unaware that their illness was a waterborne disease or to the number of illnesses being so small that they go unreported by local health departments. Ground water sources have a higher incidence of waterborne outbreaks than surface water because ground water often is not filtered or disinfected before it is used for drinking (table 6.4). Disease-causing microorganisms isolated from domestic sewage include *Salmonella*, *Shigella*, pseudomonas, fecal coliform, and protozoa (*Giardia lamblia*) (U.S. EPA 1997a). Other microorganisms found in contaminated drinking water include *Cryptosporidium*, *Microsporidium*, *Cyclosporidium*, *Helicobacter pylori*, hepatitis E, and the enteric viruses hepatitis A and Norwalk virus (U.S. EPA 1997b). See chapter 2 for a more thorough discussion of waterborne pathogens.

**Table 6.3—Waterborne disease outbreaks in the United States by water supply system, 1990–94**

Source	1990	1991	1992	1993	1994
Municipal	5	2	9	9	5
Semi-public	7	13	14	4	5
Individual	2	0	4	5	2
Total outbreaks	14	15	27	18	12
Total cases	1,758	12,960	4,724	404,190 <sup>a</sup>	1,176

<sup>a</sup> Includes Milwaukee, WI.

Source: Adapted from Gleick 1999.

**Table 6.4—Comparison of outbreak percentages by drinking water source from pathogenic contamination for the period 1971–96<sup>a</sup>**

Water source	Total outbreaks		Cases of illnesses	
	No.	%	No.	%
Ground	371	58	84,408	52
Surface	215	33	66,721	41
Other	56	9	10,625	7

<sup>a</sup> Excludes outbreak in Milwaukee, WI, 1993.

Source: Adapted from Craun and Calderon 1996, U.S. EPA 1999.

The fate and transport of parasites, bacteria and viruses from sewage effluent depend on the characteristics of the subsurface environment (U.S. EPA 1997a). Pore size and chemical charges of the soil matrix are important in removing bacteria and viruses. Bacteria have been reported to travel distances of up to 300 feet (100 m) in sand aquifers, 2,500 feet (800 m) in gravel aquifers, and over 3,000 feet (1000 m) in limestone rock (Kaplan 1991). Certain viruses, because of their size and long survival times, can travel distances up to 1 mile [1.6 kilometers (km)] in areas with karst geology (Yates and Yates 1989).

Organic chemicals in onsite disposal systems are a less commonly reported problem because they often are below levels considered hazardous to human health (U.S. EPA 1997a). These chemicals can significantly affect aquatic systems, however. Organic chemicals commonly found in septic systems originate from household products, paints and varnishes, shampoos, cosmetics, and polishes.

Septic systems fail for two reasons: poor design or poor maintenance (Kelley and Phillips 1995). Design includes construction, soils and hydrological characteristics of the site, and drainfield layout (Kelley and Phillips 1995). If drainage is too slow, there will be upward seepage and ponding, which are likely to contaminate surface water. If drainage is too fast, downward percolation occurs without sufficient biological treatment; contamination of ground water is likely to result.

Even with properly installed systems, maintenance is absolutely necessary. Unfortunately, the typical owner of an onsite disposal system is unaware of the need for proper maintenance (Kelley and Phillips 1995). Maintenance includes periodic testing of drainfields and emptying of septic tanks. Frequency of maintenance depends on soil conditions, type of septic system, and weather patterns.

Class V injection wells is another type of onsite disposal unit. An injection well can include any manmade hole in the ground for injection of wastewater (U.S. EPA 1998a). They are used by dry cleaners, laundromats, paint dealers, hardware stores, funeral homes, and other industrial and commercial facilities for materials other than domestic and sanitary wastes. Motor vehicle waste disposal wells, industrial waste disposal wells, and large-capacity cesspools have high risk for ground water contamination. Field studies have shown that ground water sources can be degraded significantly by organic and inorganic contaminants from dry wells in automotive shops (Ogden and others 1991). See the section on abandoned wells in this chapter.

Approximately 10 percent of the wastewater produced in the United States originates from communities of

< 10,000 people. With the passage of the Clean Water Act in 1972, many such communities elected to use Federal funds to install centralized systems for wastewater treatment. In small communities, contractors frequently installed the most economical and not necessarily the most effective systems. Currently, many of these systems are obsolete and need replacing because they have operated beyond their 20-year life span. Small communities also face an economic factor of scale. Costs of maintenance and staffing must be divided among fewer people, resulting in higher costs per person. Consequently, small communities have nearly twice the number of violations than larger communities (> 10,000 individuals). Violations include leaking sewage systems (cracked and broken sewer lines), illegal connections of sewer and storm drainage lines, and inadequate treatment. Violations often affect local water quality and potentially affect drinking water quality for downstream communities. Since 1970, new technologies have been developed to treat water more effectively and cheaply. However, many small communities have not adopted these systems because of a lack of knowledge, public distrust of new technologies, and legislative and regulatory constraints (U.S. EPA 1994). Additional discussion of centralized wastewater treatment can be found in chapter 5.

## Urban Runoff

### Findings

Urban land generates nonpoint-source pollution. People apply various chemicals around their homes, businesses, and adjacent land. These chemicals are carried by surface runoff to receiving waters. As land is developed and impervious surface area increases, the amount of urban runoff increases. Consequently, land development increases the amount of nonpoint-source pollutants discharged into surface water (Phillips and Lewis 1995). The Nationwide Urban Runoff Program (U.S. EPA 1983) reported that 10 times as much suspended solid material was being discharged from storm sewers serving residential and commercial areas as was discharged from sewage treatment plants providing secondary treatment (Weiss 1995). Major pollutants associated with residential and commercial runoff include floatables, sediments, suspended solids, oxygen-demanding materials, nutrients, organics, biocides (herbicides, fungicides, pesticides), polycyclic aromatic hydrocarbons, and petroleum hydrocarbons (U.S. EPA 1997a, Weiss 1995).

Because residential and commercial construction creates site disturbances, it is highlighted here. Sediment loading from site preparation, and construction and maintenance of buildings and roads can exceed the capacity of streams to

transport it (Yoder 1995). Sediment loads from inadequately controlled construction sites typically are 10 to 20 times per unit of land area those from agricultural land and 1,000 to 2,000 times those from forest (Weiss 1995). In a relatively short period, urban site construction can contribute more sediment to a stream than was deposited over the previous several decades (Weiss 1995).

Urban runoff is highly intermittent. Short-term loading, associated with individual storms, is high and may have a shock effect on the receiving water (Weiss 1995). When predicting the effect of urban runoff on water quality, it is important to determine the duration of the effect. Effects may be acute (short term) or chronic (long term) (Phillips and Lewis 1995). Oxygen-demanding substances and bacteria create acute effects; whereas nutrients, sediments, toxic metals, and organics create chronic effects. For an acute effect, estimates are based on the probability that pollution concentrations will exceed acceptable drinking water standards (Phillips and Lewis 1995). For a chronic effect, a simple method has been developed to predict the increase in pollution loading above current conditions (U.S. EPA 1983). This simple method is employed by EPA and uses information readily available to the resource manager. Input variables include pollutant type and concentration, precipitation, and percent impervious cover. The method, however, is limited to areas < 1 square mile (2.6 km<sup>2</sup>).

Findings from engineering research show that pollution and sediment loading from runoff can be reduced. Practices for mitigating storm runoff include attenuation, conveyance, pretreatment, and treatment of runoff (U.S. EPA 1997a). When selecting mitigation practices, it is important to consider

- How will practices meet watershed and site objectives?
- What are the limitations of a practice to meet objectives?
- What are the drainage field, soil types, and topography?
- Are practices compatible with a region's rainfall pattern and annual runoff?
- Are they derived from scientific research?
- How will practices function as a system (Phillips and Lewis 1995)?

A number of manuals and practical guides have been written to select, design, and maintain mitigation practices to meet local, State, and Federal mandates (Birch 1995, Phillips and Lewis 1995). As with plans and guides for wastewater treatment, managers need to check with State and local agencies for specific performance ratings and regulations.

Like wastewater treatment facilities, new mitigation practices must be maintained and existing ones upgraded to meet expected performance standards. Adequate funds often are lacking to maintain or enhance these facilities (U.S. EPA 1997a). Without proper maintenance, water quality degrades as systems fail.

### **Reliability and Limitation of Findings**

Although development of private land in or adjacent to public land has occurred for decades, scientific studies of the effects on water quality and drinking water sources are lacking. Extensive research has been conducted on urban effects on natural systems, however. These studies provide the basis for identifying the potential impacts of development on drinking water.

When applying findings across a watershed, scale becomes an important issue. Evaluating cumulative effects requires examination of more than just local impacts of individual pollution sources, such as urban runoff, wastewater treatment, and landfills. The timing and location of all activities that contribute contaminants within the watershed and their hydrologic connection to source water intakes must be considered to estimate cumulative effects. Consequently, these developments must be evaluated both independently and collectively within the watershed. Ages of wastewater treatment facilities and urban storm runoff structures must be considered. For various reasons, existing infrastructures may not meet sanitation and water-quality regulations. Success of management plans to mitigate the effects of wastewater treatment and urban runoff is predicated on sound infrastructure.

The ability to address the effects of development on drinking water quality depends on ownership. On publicly owned land, resource managers directly determine whether facilities comply with Federal and State regulations. On privately owned land, resource managers can only indirectly influence development effects on drinking water quality through the planning process.

Planning and development of private land in and adjacent to public land involve complex issues including the interplay of the physical, biological, and social components of a watershed. A number of factors need to be considered. First, planning must include all stakeholders, including public land managers. Second, private tracts are owned by a diversity of individuals for various reasons. Third, new regulations often cause resentment among landowners. Any changes in drinking water regulations and statutes create the need for communication and education. Fourth, a comprehensive approach is needed to account for the

cumulative effects of individual developments in a watershed and to address the needs of individual stakeholders.

Because of the interplay, technology and management practices are not the only solutions to drinking water issues. A number of communities have adopted a whole watershed approach to manage water and land planning issues (Birch 1995, Kelley and Phillips 1995, Phillips and Lewis 1995). This approach provides a framework not only to design the optimal mix of water-quality management strategies but also to design land management strategies by integrating and coordinating management priorities across stakeholders, governments, and agencies. Livingston (1993) identifies the big “C’s” of watershed management that must be considered:

- Comprehensive management.
- Continuity of management over a long period.
- Cooperation among Federal, State, local, and tribal governments; cities and counties; public and private sectors; and all citizens.
- Communication to educate elected officials and ourselves.
- Creativity in best-management-practice technology.
- Coordination of stormwater retrofitting to reduce pollution loading.
- Consistency in implementing laws, rules, and programs.
- Commitment to solving current problems and preventing future ones.
- Cash in funding programs and maintenance over a long period.

### Research Needs

Development of private tracts in and adjacent to public land represents an opportunity to examine how development alters ecosystem processes and what are the long-term implications of these changes.

1. Long-term monitoring stations are needed not only to monitor changes in water quality and habitat modification but also atmospheric deposition.
2. In addition, studies are needed to determine the limitation of management practices, wastewater treatment, and urban runoff in extreme environments such as at high elevations [ $>8,000$  feet ( $>2,400$  m)]. Research also is needed to determine threshold levels of the corresponding changes in processes that affect source water quality as land use shifts to urban.

### Key Points

1. Levels of drinking water protection need to increase with increasing amounts of urban development.
2. Because of their depth, shallow ground water sources are especially prone to contamination from septic systems.
3. Septic systems fail for two reasons: poor design and poor maintenance.
4. Septic system designs need to consider site conditions, such as soil characteristics (permeability, depth to bedrock, depth to ground water table), topography (floodplain, hillslope, ridge top), and climatic patterns (rainfall and snowfall amounts and patterns, winter temperatures).
5. A comprehensive approach towards development planning must be taken. The approach needs to consider issues ranging from the local to watershed scale.
6. Urban runoff is reduced by maintaining and enhancing existing vegetation and by minimizing the amount of impervious surfaces.

## Underground Storage Tanks

### Issues and Risks

Underground storage tanks pose a risk of ground water contamination because nearly all tanks contain petroleum products. The tanks are associated with service stations, convenience stores, and organizations that have fleets of vehicles (U.S. EPA 1998b). Current estimates indicate that 25 to 35 percent of these tanks do not comply with existing regulations. In 1986, EPA published regulations with the goals of preventing and cleaning up releases from underground storage tanks. These regulations (40 CFR 280) require that underground storage tanks, which contain hazardous substances, including fuels, be removed by December 1998 or have spill, overfill, and corrosion protection. The regulations also require that installation and closure of underground storage tanks must be registered with the State or EPA. These regulations have had a significant impact on land management agencies, which, due to the remote locations of administrative offices, recreation sites, and workshops, have installed underground storage tanks for easy access to fuel. For example, in order to comply with these regulations, the Forest Service has removed over 1,600 underground storage tanks and has initiated several projects to cleanup contaminated soil caused by leaking tanks.

The primary concern about underground storage tanks is leakage, which can seep into the soil and contaminate ground water. Since 1988, over 330,000 confirmed releases have occurred from regulated underground storage tanks. Gasoline is the most common contaminate of ground water. Although not all of those releases contaminated ground water, drinking water wells have been shut down because of petroleum contamination (U.S. EPA 1996). In 1988, EPA regulations established minimum standards for new tanks and required owners to upgrade existing tanks, to replace them, or close them by December 1998 (U.S. EPA 1996).

### Findings

Recent studies have identified methyl tertiary butyl ester (MTBE) as a potential major health hazard in drinking water. Methyl tertiary butyl ester is added to gasoline to increase its oxygen content and to reduce airborne emissions. Effects on drinking water include widespread impacts from low concentrations and local impacts from high concentrations (U.S. EPA 1998c) (see chapter 7 for more detailed information on the effect of vehicular emissions).

Local impacts primarily result from leaking underground storage tanks. A survey of ground water plume data from over 700 service stations showed that 43 percent of the sites had MTBE concentrations  $> 1,000$  micrograms ( $\mu\text{g}$ ) per liter. However, a survey of drinking water wells from 20 National Water Quality Assessment study units showed that 2 percent of 949 rural wells had a median concentration of approximately  $0.5 \mu\text{g}$  per liter (well below the EPA drinking water advisory of 20 to  $24 \mu\text{g}$  per liter) (U.S. EPA 1998c, Zogorski and others 1998). A study of private wells in Maine showed 1.1 percent of 951 wells with MTBE levels exceeding  $35 \mu\text{g}$  per liter. Maine officials estimated that 1,400 to 5,200 private wells across the State could be contaminated at levels exceeding  $35 \mu\text{g}$  per liter (U.S. EPA 1998c). The potential threat of underground storage tanks contaminating ground water should diminish as older tanks are upgraded and sites are cleared of contaminates.

### Reliability and Limitation of Findings

Records should be available through the State or EPA identifying where underground storage tanks are located, where cleanup operations are ongoing, and where tanks have been removed. The possibility also exists that underground storage tanks may be present and not registered with the appropriate agency. During field visits, resource managers need to look for indications of former structures or operations on the property, and they need to note the presence of partially exposed, capped, or uncapped pipes. These pipes may be vent pipes or fill pipes for underground

storage tanks. On properties where motor vehicles were operated regularly, be skeptical where there is no apparent refueling source. An underground storage tank is likely to be present (U.S. Department of Agriculture, Forest Service 1999).

### Research Needs

1. More data are needed to determine the extent of contamination of drinking water sources by MTBE and the potential health hazard.
2. Research also is needed to develop more effective and cost efficient cleanup methods. Cleanup of ground water and soil contaminated by leaking underground storage tanks can be expensive and take long periods of time.

### Key Points

Underground storage tanks are a potential threat to drinking water supplies through contamination of surface and ground water by storage tanks that have leaked or have been overfilled.

## Abandoned Wells

### Issues and Risks

Abandoned wells and wells that are no longer used may or may not have been properly closed or plugged after their use ceased. Abandoned wells are of concern because they can serve as conduits for migration of contaminants into aquifers and between aquifers.

Numerous types of abandoned wells exist on public land. Some were drilled for mineral exploration, others for oil and gas production, and still others for stock watering. Those associated with administrative and recreational developments include water wells for irrigation and drinking water and disposal wells for stormwater runoff or waste products from vehicle shops. Septic systems may be considered disposal wells when industrial or commercial wastes are treated along with sanitary wastes.

Although Federal, State, and local regulations address proper closure of abandoned wells, not all abandoned wells have been closed or plugged properly. Many of the improperly closed wells were abandoned before regulations existed. Other wells have been abandoned temporarily to allow for further use if the need should arise. Certain wells, such as automotive dry wells in vehicle shops, may still be in use but would be banned or subject to permit under proposed

regulations for Underground Injection Control (U.S. EPA 1998e). Certain States already have banned such dry wells and have required cleanup, per the Resource Conservation and Recovery Act of 1976, due to contamination at such sites.

The number of abandoned wells on public land is unknown. For example, the Forest Service has inventories of some categories of in-use wells but not of abandoned wells. Knowledge of number and location of such wells is limited, and in most instances, might be gained only by a field survey.

### Findings

Abandoned wells are commonly cited as avenues of contamination in Federal, State, and local programs dealing with ground water protection (Nye 1987). The EPA's Adopt Your Watershed campaign supports properly closing abandoned wells. Many States, such as Iowa, Kansas, and Nebraska, provide financial incentives for proper well abandonment because it is considered so important for ground water protection.

Proper abandonment of water wells is regulated at the State or local level. Oil and gas well closure is specified in 43 CFR 3160. Motor vehicle waste disposal wells (dry wells) are regulated in the underground injection control program as class V wells (40 CFR 146).

Field studies have shown that ground water sources can be degraded significantly by organic and inorganic contaminants from stormwater runoff and dry wells in automotive shops (Ogden and others 1991). In certain geologic formations, abandoned water wells are prone to collapse, and, when wells are drilled through multiple aquifers, contamination problems may occur (Blomquist 1984). Gass (1988) reported that abandoned water supply wells became conduits for cross contamination between aquifers. Abandoned oil and gas wells allowed leakage of contaminated or highly mineralized water, leading to ground water pollution including salinization (Gass 1988). Even plugged boreholes may have defects in structural integrity, allowing pollutant transport between confined aquifers (Avci 1992).

### Reliability and Limitation of Findings

The issue of abandoned well closure is well defined in Federal, State, and local regulations. The extent of the problem on public land is unknown because wells have not been inventoried. Proper well closure is heavily regulated at present, but not heavily enforced. Existence of improperly

closed wells does not mean ground water contamination will occur; only that it has the potential to occur.

Wells on public land possess the same general characteristics as other abandoned wells. Drilling and development methods for all types of wells have usually followed industry standards. For all types of wells, the newer the well the more likely that it was drilled and closed properly. On public land, dry wells in vehicle shops may not have as much waste or as much variety of waste in them as a commercial facility would, but the pollution potential still exists. Some could have greater potential for contamination than others because of hydrogeologic formations and duration of well use. For example, in the Allegheny and Appalachian Mountains, where abandoned oil and gas wells are more numerous and older, problems may be greater than in other regions of the country.

### Research Needs

1. Methods need to be developed to inventory abandoned wells on both public and private land. Inventorying methods need to incorporate the capabilities of remote sensing technology and Geographical Information Systems.
2. The inventorying process also needs to be linked to a monitoring program.
3. Further, an abandoned-well typology needs to be developed that integrates type of well, geological formation, soil, topography, climate, and potential for ground water contamination.

### Key Points

1. Abandoned wells may serve as conduits for the transport of pollutants.
2. Where there may be no records of abandoned wells on a property, the property must be surveyed to locate wells.
3. The type of abandoned well influences the types of pollution that may enter ground water sources.
4. Improperly sealed abandoned wells may be a source of contamination.

## Solid Waste Landfills and Other Past Land Uses

In 1990, citizens in the United States generated over 195 million tons [215 million metric tonnes (Mg)] of municipal solid waste. Currently, over 6,000 regulated municipal landfills exist (U.S. EPA 1993). However, an estimated 30,000 to 50,000 unregulated waste disposal sites are thought to exist in the United States (Woldt and others 1998). Both regulated and unregulated sites may have impacts on water quality and the environment. In 1976, the Resource Conservation and Recovery Act (RCRA) addressed waste management and separated hazardous waste management from solid waste management. Prior to RCRA, municipal and industrial wastes were deposited at the same landfills. The practice was to spread hazardous waste sludge and liquids over municipal waste, using the municipal waste to soak up the sludge (Brown and Donnelly 1988). Consequently, landfills existing prior to RCRA may contain hazardous waste and may be the origin of organic compounds found in municipal landfill leachate. Other sources of hazardous materials in landfills include household and agricultural materials, incinerator ash, and sewage sludge.

The U.S. EPA (1993) defines a municipal solid waste landfill as:

A discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile, as those terms are defined in the law. (Household waste includes any solid waste including garbage, trash, and septic waste derived from houses, apartments, hotels, motels, campgrounds, and picnic grounds.) A municipal solid waste landfill unit also may receive other types of waste such as commercial solid waste, non-hazardous sludge, small quantities of generator waste, and industrial solid waste.

In many rural areas, small communities are served by small landfills that may be exempt from some regulatory requirements. The U.S. EPA (1993) defines a small landfill as one that receives less than an average of 20 tons (22 Mg) of waste per day, receives <25 inches (62.5 centimeters) of rain per year, and shows no evidence of ground water contamination. About half of the regulated landfills serve communities with <10,000 people and are considered small landfills. Many of these small landfills may be on or adjacent to public land.

### Issues and Risks

Municipal solid waste landfills that contaminated ground water often were poorly designed, located in geologically

unsound areas, or accepted toxic materials without proper safeguards (U.S. EPA 1993). Decomposing municipal solid waste in landfills form leachates, liquids containing extremely high concentrations of organic and inorganic pollutants. Ground water contamination is common near landfills, but the effect may decrease with distance (Borden and Yanoschak 1990). A study of 71 North Carolina sanitary landfills found that 53 percent had ground water violations for organic and inorganic pollution based on North Carolina ground water-quality standards (Borden and Yanoschak 1990). Only a few landfills had organic contamination. When predicting the performance of a landfill, it is important to know its age, history of material disposal, design, and capability of handling toxic waste.

Another threat of landfills to ground water is volatile organic compounds (VOC). Volatile organic compounds come from biological and chemical degradation of materials in the landfill. Recently, VOC's have been detected in ground water (Baker 1998) and management procedures have been developed to minimize this threat (Rickabaugh and Kinman 1993). Ground water contamination was linked to methane diffusion as VOC concentrations increased. Mitigation involves improving gas removal systems at the landfill (Baker 1998). The extent of ground water contamination by VOC's and subsequent health effects need to be evaluated further.

Illegal dumping may occur on or adjacent to public lands. This practice is usually done to avoid disposal fees or the time and effort required for proper disposal. Dumped materials may include nonhazardous material such as scrap tires, yard waste, and construction waste. It also may include hazardous waste such as asbestos, household chemicals and paints, automotive fluids, and commercial or industrial waste. The potential for contaminated runoff and ground water depend on such factors as the proximity of the dump to surface water, elevation of the ground water table, and permeability of the soil.

Other sources of contamination on public land include shooting ranges, formerly used defense sites, and wood treatment sites. Shooting ranges pose the potential for lead contaminates entering surface water and ground water. Acidic rainfall or acidic soil can dissolve the weathered lead compounds. In a dissolved state, lead can move through the soil and enter surface water and ground water. Shooting ranges in areas with acidic soils or acidic rainfall have an increased potential for transporting contaminates offsite and into drinking water. Bare ground on ranges may further increase the risk of migration of lead compounds offsite.

Sites once used by the Department of Defense (DOD) for military training and industrial facilities are on both public

and private land. The DOD estimates that over 9,000 such sites exist. They pose a wide range of environmental hazards, including unexploded ordnances from the training sites and soil contamination from solvents, fuels, and other petroleum compounds used at industrial facilities. Sites are being cleaned up to minimize environmental effects. The Forest Service, for example, has identified over 100 formerly used defense sites on national forests.

Field treatment of wood posts is another past land-use activity that may have led to surface and ground water contamination. The common practice was to dip wooden posts into tanks that contained creosote, pentachlorophenol, or a chromium, copper, and arsenic compound and move them to an area for dripping and drying. The practice has been discontinued on public land such as national forests. However, a potential exists for surface and ground water contamination from past wood treatment operations.

### Reliability and Limitation of Findings

Most available information on types of hazardous material activities and the contaminants associated with these activities is reliable because it is based on extensive site-specific data from Federal agency hazardous waste site cleanup programs. A limitation is that inventories identifying all hazardous waste sites on or adjacent to public land are incomplete. During field visits, areas of stressed vegetation, discolored or stained soil and water, indications of former structures or operations, and land disturbances may indicate the presence of old, abandoned, or illegal waste disposal sites. Due to the potentially hazardous nature of these disposal sites, discovery of such conditions should be reported to the appropriate agency official for further action (U.S. Department of Agriculture, Forest Service 1999). Other potential sources of ground water and surface water contamination, which should be considered in conducting source water assessments, are cemeteries and small airports and airstrips, especially those used for aerial application of chemicals.

Because the need for landfills exists, the design and management of safe landfills are paramount. To meet this need, Federal, State, tribal, and local governments have adapted an integrative approach that involves three waste management techniques: (1) decreasing the amount of waste through source reduction, (2) recycling of materials, and (3) improving design and management of landfills (U.S. EPA 1993). A number of regulations exist for the management of a municipal solid waste landfill, and many regulations have flexibility to meet local conditions; managers are advised to contact a local EPA or State agency office for information on siting, designing, and managing for their landfill.

### Research Needs

Cleanup of ground water and soil contaminated by solid and hazardous wastes can be expensive and take long periods of time. Research is needed to develop more effective and cheaper cleanup methods.

### Key Points

Several factors need to be considered when resource managers address the effects of landfills on drinking water quality:

1. Identification of landfill sites—proximity to wells, aquifers, geological and hydrological features, and surface waters.
2. Knowledge of the landfill age (a) old landfills—landfills existing before RCRA may contain hazardous material and may be improperly designed for hazardous material storage and municipal waste; (b) existing landfills—landfills existing after RCRA may still pose a problem for ground water contamination because the site may contain older units where hazardous waste was deposited improperly (these sites may have been improperly designed or may have punctured liners or clay layers); and (c) new landfills—landfills being managed under current Federal and State regulation should pose fewer problems, but small landfills may be exempted from certain regulations.
3. Knowledge of landfill history—What was deposited on the site and when? How was the landfill constructed? Does it have a clay layer, a liner, or a combination of the two?
4. Monitoring data—Is the site being monitored for VOC's and ground water contamination? Is monitoring sufficient to safeguard ground water sources?
5. Extent of contamination plume—If ground water is contaminated, what is the vertical and horizontal extent of the contamination? What is the effect of the plume on drinking water sources?
6. Compliance with current Federal and State regulations—What mitigation actions have been taken to comply with Federal and State laws if contamination occurred?

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## Chapter 7

### Concentrated Recreation

Myriam Ibarra and Wayne C. Zipperer<sup>1</sup>

#### Introduction

This chapter specifically examines drinking water issues related to concentrated recreation. The effects of concentrated recreation on drinking water quality encompass many topics with limited published literature. Because of limited space, selected components—campgrounds, ski resorts, water recreation, and traffic—are discussed in this report. However, land managers need to realize that these selected topics do not include all effects caused by concentrated recreation on drinking water and serve only to illustrate potential effects.

One of the most important attractions for public recreation is public land with natural cover. Increased demands for outdoor recreation result in greater needs for drinking water and in increased amounts of wastewater. Expanding recreation resorts invites larger numbers of visitors, and private tracts adjacent to public land are magnets for real estate development. This development may negatively affect drinking water and alter hydrologic processes. To illustrate the effects of concentrated recreation on drinking water supplies, we use data from the Forest Service, but our findings and recommendations are applicable to managers of other public and private land.

The National Forest System is the single largest supplier of public outdoor recreation in the United States. The national forests offer visitors 4,385 miles of national wild and scenic rivers; one-third of the National Wilderness Area System; about 8,000 miles of scenic byways; 133,000 miles of trails; more than 18,000 campgrounds, picnic areas, and visitor facilities; and 2.3 million acres of fishing lakes, ponds, and reservoirs. The Forest Service manages over 23,000 developed facilities, including campgrounds, trailheads, boat ramps, picnic areas, and visitor centers, in addition to permitted, privately owned facilities. These facilities can accommodate approximately 2.1 million people at one time. In 1997, the Forest Service hosted more than 800 million

recreational visits that included skiing, hiking, camping, boating, fishing, hunting, and pleasure driving. The number is expected to grow to 1.2 billion by 2050.

The Forest Service manages over 3,000 drinking water systems. These systems range in complexity from hand pump wells to full water treatment plants at major installations. Primarily, these systems use ground water to provide drinking water at recreation sites and facilities. The Forest Service manages all public water systems in accordance with EPA and respective State regulations. In many cases, this approach exceeds minimum requirements for system operation.

The principal sources of pollutants produced by concentrated recreation are: (1) fuel residues from automobiles, watercraft, snowmobiles, and snow making machines; (2) wastewater from service facilities such as toilets, showers, restaurants, laundries, etc; and (3) soil and construction materials carried to surface waters with runoff at the time of construction. Detrimental effects of concentrated recreation are likely to be episodic or seasonal. The negative impacts of increased vehicular traffic and concentrated water recreation may be more apparent on surface water supplies, while the greater impact of concentrated winter recreation may be in ground water. This chapter deals with the effects of increased vehicular traffic, water recreation, and winter recreation.

#### Campgrounds

##### Issues and Risks

The effects of concentrated camping on drinking water quality are similar to those reported in chapter 8 for dispersed recreation. However, the magnitude, severity, and frequency of disturbance are greater with concentrated camping and the associated showers and toilets than with dispersed camping because of the greater density of humans using the site. Like other developments, the effects of a campground on drinking water quality depend on soil conditions, the presence of vegetation, and existing infrastructure.

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## Findings

With the intense use of a site for camping, soil conditions become extremely important. Soils may lose their organic layer, become compacted, and become more erodible. Consequently, more surface erosion may occur as runoff increases. Without treatment to mitigate effects, the increase in erosion may result in increased stream turbidity and sedimentation. Techniques used to minimize soil compaction in urban parks (Craul 1992) may be applicable to campgrounds. Concentrated camping also could lead to streambank destabilization and further erosion and sedimentation. The proximity of campgrounds and picnic areas to water increases the chance of streambank erosion and destabilization as people use the water for swimming, bathing, and cleaning cooking and eating utensils.

Vegetation plays a key role in minimizing site degradation. Vegetation reduces erosion by slowing the movement of water across the ground surface and increases infiltration of water by decreasing soil compaction. However, with increased recreational use, vegetation presence decreases if active management does not occur to promote vegetation growth and reduce soil compaction (Craul 1992).

Unlike dispersed camping, concentrated campgrounds require infrastructure, including parking areas, restrooms, and shower facilities. This infrastructure may contribute to the contamination of surface water and ground water. Proper planning, design, and maintenance of facilities can minimize contamination of drinking water sources.

Contaminants associated with campers include fecal material, household cleansers and detergents, garbage and other floatables, cooking grease and oil, and antifreeze and motor oil. Because of their remote locations, campgrounds may serve as sites for illegal dumping of hazardous materials. Enforcement of clean water policies and educational programs may reduce the levels of these contaminants.

## Water Recreation

### Issues and Risks

Concentrated recreation on surface water produces chemical and microbial contamination. Individual boats, marinas, and swimmers usually release only small amounts of pollutants that can go undetected. When the number of participants is large, however, these sources can cause tangible water-quality problems in lakes, reservoirs, and rivers. Boating and marinas are associated with increased chemical pollutant concentrations and high levels of pathogens in the water

(Gelt 1995, 1998). The effects of swimmers on drinking water supplies are an emerging problem that has prompted some utilities to limit or ban recreation on reservoirs used as drinking water sources. People with weak immune systems are particularly at risk because current methods for drinking water treatment do not detect or eliminate all pathogens, and some residues of chlorination are toxic.

### Findings

The use of gasoline with methyl tertiary butyl ester (MTBE) in motorboats, particularly those using older two-cycle engines, contaminates surface water (U.S. EPA 1998a). An estimated 345 million motor boating trips and 29 million jet skiing trips occurred in the United States during 1994–95 (Cordell and others 1997). Nearly all personal watercraft and outboard motors use two-cycle engines. The fuel-inefficient design of two-cycle outboard motors is essentially unchanged since the 1930's. Up to 30 percent of the gas used in the motor goes into the water unburned. Similarly, 10 percent of the fuel used by a personal watercraft, such as a Jet Ski, leaks into the water.

To assess the impact of two-cycle motorboat engines on water quality and aquatic life, scientists measured fuel residues in water in the Lake Tahoe Basin. They found MTBE; benzene, toluene, ethylbenzene, and xylene (BTEX); and polycyclic aromatic hydrocarbons (PAH's) near shore in lakes that allow motorized watercraft. In open water, the concentrations of MTBE and BTEX were at or under the analytical detection limit. On sites with 50 to 100 watercraft engines, MTBE and benzene exceeded drinking water standards, but concentrations did not approach the criteria for protection of aquatic life. Concentrations decreased by the end of the boating season (Allen and others 1998).

Inefficient two-stroke carburetor engines used in personal watercraft and as outboard motors are the main source of fuel pollutants. These engines emitted more than 90 percent of the MTBE, 70 percent of benzene, and 80 percent of toluene into Lake Tahoe. In contrast, four-stroke inboard fuel-injected engines emitted an estimated 8 percent of MTBE, 28 percent of benzene, and 17 percent of toluene. Estimated volume of constituent load for Lake Tahoe during the 1998 boating season from two-stroke engines was in the order of thousands of gallons of MTBE, hundreds of gallons of benzene, and tens of hundreds of gallons of toluene. There was no evidence that MTBE or BTEX were transported to the bottom of the lake or accumulated there (Allen and others 1998). Laboratory testing of newer engine technology suggested that emissions from marine outboard engines could be virtually eliminated by using more efficient Ficht injected engines (Allen and others 1998).

Proposed legislation in California moves the implementation date for stricter EPA emissions controls on personal watercraft engines up 5 years to 2001 from 2006.

Because marinas are located at the water's edge, pollutants can go directly to waterways. Water pollution from boating and marinas is linked to several sources. They include leaks from underground storage tanks, watercraft engines, and boat maintenance garages; discharge of sewage from boats; and stormwater runoff from parking lots (U.S. EPA 1993). Moreover, physical alteration of shorelines, wetlands, and aquatic habitat during the construction and operation of marinas may change flow patterns and result in poorly flushed waterways.

During boat maintenance, significant amounts of solvent, paint, oil, and other pollutants potentially can seep into ground water or be washed directly into surface water. Paints used to protect boats generally contain toxins that limit aquatic organism growth. Many boat cleaners contain chlorine, ammonia, and phosphates that harm plankton and fish. Small oil spills released from motors and refueling activities contain petroleum hydrocarbons that may attach to sediments. Hydrocarbons persist in aquatic ecosystems and harm bottom-dwelling organisms that are at the base of the aquatic food web. The EPA recommends that boaters use nontoxic cleaning products to reduce pollution. Boat owners can prevent pollution from paint and other chemicals by vacuuming up loose paint chips and paint dust and by using a drop cloth when cleaning and maintaining boats away from the water. Carefully fueling boat engines, recycling used oil, and discarding worn motor parts into proper receptacles can prevent needless petroleum spills. Most importantly, good engine maintenance prevents fuel and lubricant leaks and improves fuel efficiency (U.S. EPA 1993). Pollution from boating can potentially impair drinking water reservoirs or seep into ground water wells that provide drinking water along the shoreline.

Discharge of sewage and waste from boats can degrade water quality, especially in marinas with high boat use. Improper disposal of human and pet waste may introduce pathogenic bacteria, protozoans, and viruses into water (Gelt 1995, U.S. EPA 1993). Sewage from boats can make water unsuitable for recreation, destroy shell fishing areas, and cause severe human health problems. Sewage discharged from boats also stimulates algal growth, which can reduce the available oxygen needed by fish and other organisms. Although fish parts are biodegradable, large amounts of fish-cleaning remains can reduce water quality. Marinas should have adequate wastewater-disposal hook-ups and disposal sites for solid waste from boats. Well kept toilet

facilities, designated pet areas, and health education postings also promote public health.

The locating and design of marinas are two of the most significant factors impacting water quality. Mastran and others (1994) found that inlets had higher concentrations of pollutants than the main channel, suggesting that hydrology plays a role in the distribution of the pollutants. Poorly placed marinas disrupt natural water flushing and cause shoreline soil erosion, habitat destruction, and consequently, degradation of water quality. Marinas should be located and designed to be regularly flushed by natural currents. Good design of a marina can provide an optimum combination of capacity, services, and access, while minimizing environmental impacts and onsite development costs (U.S. EPA 1993).

Concentrated swimming may cause microbial contamination of drinking water sources. A study conducted for the metropolitan water district of southern California determined that a swimmer or bather releases 0.1 gram of feces when entering the water; infants can add significantly more. Human feces may harbor viruses, bacteria, protozoa, and worm pathogens, some of which have been found in water treated by standard water purification methods. Bacteria are generally removed by present water treatments. Some viruses, like hepatitis A and Norwalk, are hardier and can be controlled only with additional amounts of disinfectant. See chapter 2 for further discussion on waterborne pathogens.

Water that is accidentally drunk while wading or swimming poses serious risks. Even small numbers of microbes may cause disease. It is estimated that in one outing a swimmer or wader ingests from 0.3 to 1.7 ounces of water that may be contaminated with feces (Gelt 1998). Outbreaks of Cryptosporidiosis have been documented from lakes, community and hotel pools, a large recreational water park, a wave pool, and a water slide. From January 1995 to December 1996, 37 outbreaks in 17 States were attributed to recreational water exposure. Diseases caused by *Escherichia coli* O157:H7, a specific strain of *E. coli* that is known to cause death if ingested, were associated primarily with recreational lake water. *Cryptosporidium* spp. and *Giardia* spp. were associated with a few outbreaks in swimming pools. Outbreaks of *Cryptosporidium* affected almost 10,000 people, and occurred in swimming pools that were chlorinated (Levy and others 1998).

It is difficult to estimate how many people become sick after contact with fecal contaminated water. For most people the symptoms are not acute. A person experiencing diarrhea, fever, vomiting, and nausea for 2 or 3 days may assume that he or she has the flu or ate some unsuitable food. In fact, a

person may have a gastrointestinal infection acquired from drinking water (Gelt 1998). Epidemic outbreaks of waterborne disease have been recognized only after thousands of acute cases were reported (Levy and others 1998). Isolated and chronic waterborne diseases probably go undetected or unrecognized (also see chapter 6 on wastewater treatment).

Methods used to detect enteric pathogens are not always sensitive to low concentrations but very small numbers of microbes can cause illness (Gelt 1998). Routine microbiological testing may miss transient contamination by swimmers. Measures that can be taken to minimize fecal contamination include: (1) providing changing tables for infants in locker rooms, (2) providing adequate toilet and hand washing facilities, (3) posting signs against drinking water or defecating in the water, and (4) recommending against swimming for children with gastrointestinal illness. Unfortunately, other mammals defecating in a waterbody may introduce enteric pathogens (see chapters 14, 15). Hence, fecal contamination cannot be completely eliminated.

## Winter Recreation

### Issues and Risks

The increasing public demand for winter sporting opportunities has led to creation and rapid expansion of skiing resorts in forested watersheds (Brooke 1999). These facilities may alter the water quality of pristine environments. The National Ski Area Association estimates that 60 percent of all downhill skiing in the United States occurs on national forests. In cooperation with the 135 ski area operators, through the National Winter Sports Program, the national forests provided downhill skiing opportunities to approximately 31 million people in fiscal year 1997. The ski industry hopes to extend the ski season or even have the ski resorts open year-round (Hoffman 1998). Some ski resorts are proposing to develop facilities for summer outdoor recreation activities such as golf, swimming, and tennis. With ski resort expansion, real estate development also expands. To maintain predictable revenues in spite of unpredictable weather, ski resorts increasingly rely on artificial snow to cover the slopes. While there is not an apparent direct effect of skiing on drinking water, environmentalists warn that large ski resorts alter natural hydrological cycles, increase traffic congestion, and are magnets for urban sprawl, all of which may impair water quality.

### Findings

To satisfy public demand, the Forest Service is authorizing the development or expansion of ski resorts. For example,

between January 1997 and January 1999, the EPA Office of Federal Activities filed environmental impact statements for work on 12 ski resorts inside of national forests. Development of ski resorts includes new construction or expansion of parking lots and service roads, downhill ski runs, cross-country ski trails, snowmobile trails, chair lifts, lodges, restrooms, ski patrol facilities, ski schools, ski repair shops, stores, hotels, and restaurants (U.S. Department of Agriculture, Forest Service 1992, 1998, 1999). The construction and operation of ski facilities affect drinking water sources in various degrees. Clearing of vegetation for ski runs increases the chances of soil erosion and hence higher turbidity and sedimentation in streams (Hoffman 1998). Pollutants from car emissions are deposited on the soil with precipitation. Runoff from roads, parking lots, or lawns may be contaminated with salt, heavy metals, petroleum residues, or landscaping chemicals. Expansion of impervious surfaces leads to increased peak runoff and shorter resident time of water in the watershed.

Newly developed ski resorts may cause shortages or dramatic fluctuations in drinking water supplies. Some resorts are projecting to host 5,000 to 10,000 visitors a day. The typical average consumption rate of water at ski areas is 10 gallons per day per skier capacity; if water conservation measures are in place, the intake could be reduced to 7 gallons per day. Thus, a ski resort with 13,000 skiers may need between 94,500 and 135,000 gallons per day (U.S. Department of Agriculture, Forest Service 1998). At the same time, a small but irretrievable loss of ground water may occur due to evaporation and sublimation from snow making (Hoffman 1998). To prevent artificially drastic pulses in downstream flow and to maintain channel stability, ski resorts may need to stop making snow when natural water levels are too low, or use water stored in ponds or lakes (U.S. Department of Agriculture, Forest Service 1997).

Ski resorts are often located on environmentally sensitive sites. In mountainous regions, the slopes are steep, the soils are thin, the subsurface is predominantly gravel and cobble, and the aquifers are fractured bedrock. This type of aquifer is very sensitive to pollution because the rapid ground water flow can carry microbes and other pollutants for long distances (U.S. EPA 1999). Ski resorts have a special problem with wastewater treatment. The peak need is in the winter, when conventional sewage treatment methods function at slower rates and microbial pathogens survive longer in water and soil. One solution is to build storage ponds and apply wastewater treatment in warmer weather. Such storage, however, is not always economically or logistically feasible. Another method being tested makes artificial snow from wastewater and stores the snow on

slopes where skiing is not permitted (Gibson 1996). In ideal conditions, the wastewater stored would melt and percolate very slowly, producing a clean effluent. However, sudden snowmelt could contaminate surface water and ground water with effluent.

Ski resorts rely more and more on snow making and grooming to attract skiers. Some snow making operations require massive amounts of stream water. To get enough water, resorts have relocated stream channels, excavated wells, constructed ponds or pumped water from neighboring surface water sources. Each activity may alter the natural flow of water and ultimately influence drinking water quality. Not only is water being redistributed to another location, the generators that power the snow machines and pumps may contribute to air pollution. For instance, the diesel generators in one resort in Vermont are the eighth largest air polluters in the State (Hoffman 1998). This pollution may contribute to atmospheric deposition of contaminants.

## **Increased Traffic**

### **Issues and Risks**

Vehicular traffic in forests and grasslands creates fuel emissions that are deposited on the ground through wet and dry deposition. Pollution from fuel emissions may migrate to surface water and ground water through rain or snowfall. The most significant sources of fuel pollutants are cars, but in some places all-terrain vehicles and snowmobiles also are important contributors. In the last decade, the number of recreational visits to national forests increased by 40 percent, and the number of visits was highly correlated with the number of vehicles (Cordell and others 1997). Additionally, tourism to recreational resorts promotes urbanization, which in turn adds traffic. For example, in the Eisenhower Tunnel connecting Denver with the busiest ski areas in Colorado, the traffic has quadrupled in the last 25 years. Improvement and expansion of parking lots and roads increase peak runoff and nonpoint-source pollution from impervious surfaces. Runoff may be contaminated with salt, heavy metals, petroleum residues, or landscaping chemicals that can degrade surface water and ground water quality (U.S. EPA 1983). Oxygenates and PAH's are gasoline residues that have been found in drinking water supplies and are potential threats to human health. Deposition of MTBE, an oxygenate, may be especially significant during the winter because concentrations of MTBE in precipitation are higher at colder than warmer temperatures (Delzer and others 1996). Widespread impacts may result from vehicular emissions that dissolve in rain or snowfall and subsequently

infiltrate to shallow ground water. Additional research needs to be conducted to determine the significance of increased auto emissions on drinking water quality in rural areas.

Auto emissions also contribute to the amount of nitrogen in the atmosphere. Nitrogen deposition from the atmosphere varies across the country with the greatest concentrations occurring in a broad band from the Upper Midwest through the Northeast (U.S. Geological Survey 1999). Recent studies have shown that atmospheric deposition of nitrogen can be quite significant. For example, approximately 25 percent of the nitrogen entering the Chesapeake Bay Estuary comes from the atmosphere (Fisher and Oppenheimer 1991). The effect of nitrogen deposition on drinking water is an area that needs further research (see chapter 3). See chapter 6 for further discussion of urban runoff and MTBE.

### **Reliability and Limitation of Findings**

The potential negative impacts of concentrated recreation on drinking water supplies have been recognized and addressed in a qualitative way, but quantitative assessments are very rare. The material presented here comes almost exclusively from government reports and newspaper articles rather than from the primary scientific literature. This fact suggests that the issue has not been subjected to adequate scientific investigation.

A simplistic first approximation is to consider the expansion of concentrated recreation in forests as small-scale urbanization. However, it is important to keep in mind that the toxicities of some pollutants produced by recreational activities have been measured only in the laboratory. Furthermore, survey data on impacts on water quality by recreation are mostly from water that is not used for drinking (Cox 1986, Gelt 1995). The extremely varied ecology of each forest together with the diverse nature of recreation activities suggests specific analysis for each situation. Drinking water sources seldomly appear to be susceptible to long-term degradation because of recreation, but some lakes and well water probably are susceptible to episodes of local pollution (Peavy and Matney 1977). Environmental impact statements are prepared when designing recreation resorts, and they often present plans to monitor surface water and ground water. In the absence of specific studies, analysis of these data could be the first step in describing regional or national patterns.

The EPA and Centers for Disease Control and Prevention (CDC) recognized that waterborne diseases are common in the United States (Levy and others 1998), but data on their occurrence are very sparse. The United States has recorded incidences of waterborne diseases only since 1985. The EPA

and CDC are conducting a series of pilot studies to produce the first national estimate of waterborne disease occurrence (U.S. EPA 1998b). Of particular importance are the levels of disease associated with drinking water that otherwise meet Federal and State standards. This research would also serve as a springboard for more localized assessments of drinking water quality.

General principles of urban water pollution are applicable in expanding recreation resorts in all regions. However, data to quantify impacts on specific sites are not readily available. The Forest Service and others have monitoring programs that document some aspects of water resources, but we are not aware of any efforts to collect data specifically to evaluate the impact of concentrated recreation on drinking water supplies.

### Research Needs

The field of recreation ecology is relatively new. Only recently have scientists begun to study the relationships among use-related, environmental, and managerial factors (Marion 1998). Evaluation of the effect of recreation on drinking water could be approached through monitoring the effects of the visitor population and the impacts of population growth in communities adjacent to recreation sites.

1. One basic task is to document the kinds of data that have been collected as part of routine water-quality monitoring and sanitary engineering operations.
2. The next step is to design a sampling program for evaluating impacts of recreation on drinking water supplies.
3. Impacts also need to be assessed across the range of scale from local to major watershed.

### Key Points

1. Concentrated recreation, like urbanization, affects water quality through wastewater treatment and urban runoff.
2. Ski resorts alter hydrologic processes by changing the availability of water during the year.
3. Decreased streamflows may increase the concentration of contaminants from wastewater and runoff.
4. Wastewater treatment is especially precarious for ski resorts because peak treatment is during the winter.
5. Water recreation, both swimming and boating, may have direct effects on drinking water quality at the local scale.
6. Increased traffic may affect drinking water quality through deposition of MTBE and nitrogen.

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## Chapter 8

### Dispersed Recreation

David Cole<sup>1</sup>

#### Introduction

Dispersed recreation is a common and growing use of forests and grasslands that has the potential for significant impacts on the quality of public drinking water sources.

#### Issues and Risks

Trails are constructed to provide access. Visitors walk, ride, and bicycle along trails. Runoff from trails can add sediment to streams, particularly at trail fords. Visitors picnic, camp, and walk or ride off-trail; in some places, they use off-road vehicles to travel cross country. The resultant loss of vegetation and compaction of soil can lead to increased runoff, erosion, and sedimentation. Visitors who pull off roads to view scenery, picnic, camp, or access the immediate surroundings can cause increased erosion and sedimentation of streams. Where people pull off roads to picnic or camp adjacent to streams, foot traffic and vegetation loss on streambanks can result in streambank erosion and channel instability.

Visitors and their animals can contaminate water supplies by carrying and depositing feces containing microorganisms that cause human diseases. Contamination comes from fecal deposition and from direct contact with water during activities, such as swimming and washing. Recreational behaviors are commonly unrestricted, visitor education is typically inadequate, and where activities are dispersed, few facilities are provided to ensure proper disposal of human waste. Consequently, drinking water quality problems associated with recreation use may be expected. In a recent survey of Forest Service watershed managers, recreation was the most commonly reported cause of water-quality concerns. However, this high frequency of concern does not necessarily mean that recreation is the most common or serious source of water contamination in national forest watersheds.

#### Findings from Studies

The impacts of dispersed recreation on sediment have not been systematically quantified. Recreation facilities (particularly trails) and recreation use elevate sediment levels (see chapter 9). Nonmotorized recreation simply does not disturb much of the watershed. Cole (1981) found, for example, that <0.5 percent of a heavily used portion of the Eagle Cap Wilderness in Oregon was directly affected by trails and camping. Most of the disturbed area was located far enough from streams so that the effect was negligible. Recent research indicates that sediment yield from trails is much higher when trails are used by horses than by hikers or llamas (DeLuca and others 1998).

Impacts of dispersed motorized recreation activities on sediment, while not well quantified, are more likely to be significant. Impacts will vary greatly with such factors as type of vehicle, driving behavior, topography, vegetation type, soil erodibility, and climate. Both the extensiveness and the intensiveness of impact are much greater with motorized recreation than with nonmotorized recreation. In the extreme case of an off-road vehicle area in California, erosion rates were estimated to be 52 tons per acre per year (116.5 metric tonnes per hectare per year) (Wilshire and others 1978).

Pathogenic organisms can be introduced by recreationists into watersheds in which dispersed recreation is the primary land use. In a broad survey of surface municipal drinking water sources, LeChevallier and others (1991) found oocysts of *Cryptosporidium* spp. and cysts of *Giardia* spp. species even in protected watersheds. Suk and others (1987) found cysts of *Giardia* in 27 of 78 samples from back-country streams in several large wilderness areas in the Sierra Nevada in California. Taylor and others (1983) found *Campylobacter jejuni* in the stools of 23 percent of people reporting diarrhea and *G. lamblia* in the stools of 8 percent of such people. They also found these organisms in streams in the Grand Teton National Park, WY.

It is generally accepted, although still controversial, that mammals other than humans can spread these pathogenic organisms to humans. Since horses, mules, and dogs are

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more likely than humans to defecate directly in or near water, they may be a major concern if they are important disease carriers. Taylor and others (1983) found *Campylobacteria* in a sample of packstock stool in Grand Teton National Park, as well as in samples from humans. More than 40 mammals, both wild and domestic, have been found to harbor *Cryptosporidium parvum* (Current 1987). This evidence, along with the finding that *C. parvum* readily crosses host species barriers, has convinced most experts that human infections are often the result of transmission from wild and domestic animals, including horses and dogs (Current and Garcia 1991, Rose 1990). As for *Giardia*, Hibler and Hancock (1990) state, "some investigators considered the parasite found in humans (*Giardia lamblia*) to be host-specific, but the majority of the research performed to date questions this assumption." *Cryptosporidium* and *Giardia* have been found in humans and a wide variety of birds, mammals, fish, and reptiles (see appendix D). It has been cross transmitted between humans and a number of these animals (Hibler and Hancock 1990).

The issue of transmission by wild animals (chapter 14) is also relevant to the question of whether or not water quality can be adequately protected by eliminating or severely restricting recreation use. Questions remain about which pathogens are transmitted and the relative importance of humans and other animals as agents of transmission. Consequently, management actions such as the improvement of human waste disposal behavior and facilities, and even outright elimination of recreation use, while likely to reduce the transmission of disease organisms, are unlikely to eliminate the problem.

Studies that have attempted to relate intensity of recreation use to degree of water contamination have produced mixed results. Some studies report positive correlations (e.g., Suk and others 1987), others report no correlation (e.g., Silverman and Erman 1979), and at least one series of studies reports a negative correlation (Stuart and others 1971, Walter and Bottman 1967). One potential explanation for these divergent findings is that wild animal contamination may dwarf the effects of low levels of recreation. Indeed, some authors have noted that as levels of contamination increase, the strength of positive correlations between recreational use and contamination and between fecal coliform and the occurrence of *Giardia* and *Cryptosporidium* also increase (LeChevallier and others 1991).

The study finding a negative correlation between recreation use and bacterial contamination of water supplies initially compared a watershed closed to recreation use with a

watershed open to use. Fecal coliform and fecal streptococci counts were higher in the closed watershed (Walter and Bottman 1967). After the watershed was opened to recreation and limited logging, bacterial contamination decreased. They concluded, "...these human activities drove from the watershed a large wild animal population which had contributed substantially to the previous bacterial population" (Stuart and others 1971: 1048).

From these findings, several implications can be drawn. First, surface water is not likely to be safe for drinking without purifying treatment, even where recreation use is excluded. In fact, Suk and others (1987) found in wilderness watersheds that 45 percent of high-use samples contained *Giardia* cysts, and 17 percent of the low-use samples contained cysts. Back-country visitors are advised to purify drinking water obtained from all surface water sources, regardless of the level of recreation use in the vicinity (Cilimburg and Monz, in press). Adequate purifying treatment for public drinking water may be expensive.

Second, it is more critical to improve management of recreation use and of human waste disposal in heavily used than in lightly used watersheds. Management options for areas with heavy dispersed recreation use include reducing recreation use, prohibiting pack animals and pets, providing adequate toilet facilities, and educating visitors in appropriate waste disposal techniques (see, e.g., Hampton and Cole 1995, Meyer 1994).

The relationship between the amount of dispersed recreation and water contamination depends on other variables including the type of recreation use, soils, slope, and climate. None of these relationships has been systematically evaluated. It is difficult to determine if recreation use is heavy or light, or to confidently prescribe management in field situations.

The importance of educating visitors in the proper disposal of human waste is suggested by studies of the survival of bacteria in feces buried in soil in Montana. Samples of feces were inoculated with two bacteria, *Escherichia coli* and *Salmonella typhimurium*, and both survived in large numbers for 8 weeks after burial in early summer (Temple and others 1980). Moreover, substantial numbers of *Salmonella* survived over winter. Depth of burial had no effect on persistence, and differences among burial sites were minor (Temple and others 1982). Clearly, the idea that shallow burial (in catholes) renders feces harmless in a short time is inaccurate. Removal of feces is the best means of disposal if toilets are not provided. The second best option is careful and complete burial far from water sources, campsites, and other heavily visited locations.

## Reliability and Limitation of Findings

There is strong evidence to support the general findings that (1) dispersed recreation use can adversely affect the quality of surface drinking water supplies and (2) surface drinking water supplies will contain pathogenic microorganisms even in the absence of recreation use. Our ability to quantify the effect of dispersed recreation is very limited, as is our understanding of the importance of recreation as a source of contamination. Consequently, there is a weak foundation in science for decisions about where recreation use should be prohibited or restricted and where sanitary facilities should be provided or improved.

These general findings should be broadly applicable throughout the United States. Specifics of quantitative relationships between recreation use and water quality will vary with many environmental parameters. Logic suggests that one important regional distinction can be made between arid and mesic regions. In arid lands, visitors and animals are particularly drawn to water sources, increasing the likelihood of contamination and the effects may persist longer because these systems are not flushed rapidly or frequently.

## Research Needs

1. We need to know if some pathogens, such as human enteric viruses, pose a significant threat to human health. As Gerba and Rose (1990) note, even though there are few cases where virus isolations in source water have been linked to human disease, there are many reasons to suppose that there is much more illness due to viral contamination than is recognized. We need a better understanding about the mechanisms of transmission for different pathogenic microorganisms, especially their presence in recreation pack animals, pets, and wild animals. Further research on *C. parvum* and *G. lamblia* is particularly important.
2. Additional research is needed to provide a more solid foundation for decisions about where and how to restrict dispersed recreation and where to invest in more and better sanitary facilities. We need better quantification of the relationship between drinking water microbiology and amount of use by visitors, their pets, and their pack animals. Thresholds of use need to be identified, above which adverse effects on water quality become pronounced and unacceptable. We need a better understanding of how site variables influence susceptibility to contamination and whether water-contact activities, such as swimming, are a significant concern at the low densities typical of dispersed recreation sites.
3. Research is needed to develop techniques capable of distinguishing between human and other sources of pathogens. Finally, we should assess (1) the validity of rules of thumb managers use to develop management prescriptions and (2) the effectiveness of techniques managers develop to mitigate contamination.
4. More research is needed on the decomposition rates of human feces, on variables that influence decomposition rates, and on how pathogens disperse in and over the soil. This information could contribute to better educational material about where and how to bury feces, and to better decisions about where sanitary facilities are needed.

## Key Points

1. Since dispersed recreation can contribute to contamination, every affordable effort should be made to educate visitors in appropriate human waste disposal and to provide well-designed and appropriately located facilities for the disposal of human waste. Surface water from wildlands including wilderness, can contain pathogens that cause human disease unless drinking water is adequately treated. For public water supplies, adequate treatment may be expensive.
2. Where recreation use is high and water contamination is too high, sanitary facilities need to be developed or improved, and/or use of the area must be restricted. Where it is clear that dispersed recreation use is low, use restrictions and the provision of sanitary facilities are not worth the costs involved. In areas of moderate use, our understanding is inadequate to suggest whether it is worth the costs of limiting access, restricting behavior, or investing in sanitary facilities. Inadequate understanding also makes it difficult to identify use thresholds above which (1) rudimentary sanitary facilities are needed or (2) developed sanitary facilities are needed.

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## Chapter 9

# Roads and Other Corridors

W.J. Elliot<sup>1</sup>

### Introduction

The focus of this chapter is on the impact on drinking water quality of roads and other corridors, such as trails, utility rights-of-way, railroads, and airfields in forest and grassland watersheds. These corridors are essential for a wide range of access including residential, recreational, and managerial (U.S. Department of Agriculture, Forest Service 1998). They can be public and managed by Federal, State, or local agencies or private and managed by individuals or industries.

Roads, railroads, and similar corridors are major features in most watersheds. Figure 9.1 is a diagram of a typical insloping forest road in steep terrain. Water from the roadway is diverted to the ditch, and then directed to a culvert or surface drain. In less steep areas, or for larger roads, there are usually ditches on both sides of the road to collect and channel runoff. The runoff is then delivered to vegetated slopes for infiltration or to a natural channel that is part of the stream system (Packer and Christensen 1977).

Roads and similar corridors can adversely affect water quantity and quality in several ways. Runoff is low from undisturbed forests, but runoff rates from rainfall and snowmelt are greater from compacted road surfaces than from less disturbed parts of watersheds (Elliot and Hall 1997). The roadway, the ditch, and in some cases, the waterway below a road culvert are the main sources of detached sediment (fig. 9.1) from erosion depending on road surface material (Elliot and Tysdal 1999). The cutslopes and fillslopes erode mainly by mass wastage.

Eroded sediment is usually deposited on the undisturbed surface below the road (Elliot and Tysdal 1999, McNulty and others 1995, Packer and Christensen 1977). Establishing a buffer zone of undisturbed forest between a corridor and a stream is helpful, but if runoff from roads or other disturbances is channeled, or filter strips are too narrow, then buffer zones cannot be expected to eliminate sediment movement to streams. Most surface water contaminants

enter streams at stream crossing by roads, railroads, or pipelines, or places where other disturbances are close to streams. Corridor-related disturbances also can degrade ground water from shallow wells, particularly in highly porous geologies, such as karst (Gilson and others 1994, Hubbard and Balfour 1993, Keith 1996).

Excavation at the bottom of a cutslope can intercept ground water, creating instability of the road or the cutslope and altering hydrology (Jones and others, in press). This intercepted ground water may also be affected by acid drainage (chapter 18). All of the excavated surfaces revegetate slowly and are prone to erosion (Burroughs and King 1989, Grace and others 1998).

When roads or other compacted corridors are abandoned, they can continue to be sources of sediment through chronic surface erosion or mass failure (Elliot and others 1996). Compaction of a disturbed surface frequently restricts vegetation regrowth. Bare surfaces are susceptible to erosion, and steep areas without trees are susceptible to landslides. In some cases, local frost heaving or minor slumping of fill shoulders can cause surface water to collect, leading to saturation of the fill and an increased risk of mass failure. Both surface erosion and mass failure can lead to

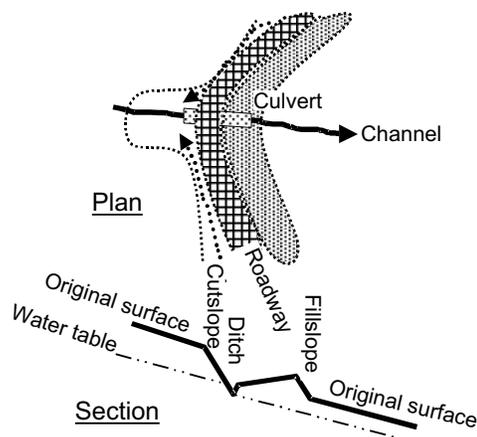


Figure 9.1—Surfaces and flow paths associated with a road cross section.

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increased sediment loads in streams (McClelland and others 1998).

Runoff and seepage from roads and rights-of-way can contain elevated levels of sediment, metals, and complex hydrocarbons from the highway material and traffic. They may also contain traces of pesticides or other undesirable substances. Chemicals may be dissolved in the runoff water, but they frequently are attached to the eroded sediment particles.

## Altered Hydrology

### Issues and Risks

The presence of roads in a watershed may increase the frequency and magnitude of peak runoff discharges, particularly on small watersheds. Roads may also increase total runoff and decrease the time to peak runoff from major storms or snowmelt.

### Findings from Studies

Roads have a number of impacts on hydrology. They intercept precipitation and snowmelt and, because they have lower infiltration rates, divert it as surface runoff to channels (Packer and Christensen 1977). Cutslopes (fig. 9.1) can also tap into ground water and divert it, increasing runoff. In a study of spring snowmelt in the northern Rockies, 58 percent of the runoff from a road was due to intercepted subsurface flow (Burroughs and Marsden 1972). Megahan (1983) found that road segments on granitic soils in central Idaho collected about 8.4 inches [21 centimeters (cm)] of water in subsurface flow from the area above the road. Road ditches can extend the stream network, increasing the volume of water available during the early part of a storm. The presence of roads can also shorten the time to peak flow during a runoff event (Wemple and others 1996). This diversion of ground water can dry out hillsides below the road, altering vegetation, and reducing water yield during dry periods later in the year.

If a road culvert is too small, or becomes blocked, water can be diverted from one subwatershed to another. Severe ditch and channel erosion may result (Megahan 1983; U.S. Department of Agriculture, Forest Service 1998). The cumulative effect is an increase in frequency and magnitude of peak discharges (Jones and Grant 1996; Megahan 1983; U.S. Department of Agriculture, Forest Service 1998).

Adding gravel to the road surface increases the porosity and roughness of the road, increasing the conductivity from

under 1 millimeter (mm) per hour to 3 mm per hour or more (Foltz 1996). This results in decreased runoff rates from low-intensity rain and snowmelt. Gravel addition will have less impact during high-intensity storms. Ripping closed roadways can increase infiltration rates, but studies show that rates do not reach undisturbed levels (Luce 1997). Culverts or surface drainage structures to deliver water to hillsides rather than to channels will also reduce the hydrologic impacts of roads (Elliot and Tysdal 1999).

### Reliability and Limitations of Findings

Generally, roads will have the same types of impacts on hydrology regardless of climatic or soil differences, but the magnitude of impact may vary substantially (Elliot and others 1999a). Impacts of disturbances and benefits of mitigation measures will be greater in wetter climates. Interception of subsurface flows depends on slope position, depth to the water table, and availability of subsurface flow. The greatest challenge in applying the hydrologic findings is that landscapes are highly variable, making differences in hydrology due to the presence of roads difficult to isolate.

### Research Need

The main research need is watershed scale studies to compare relatively undeveloped watersheds to similar watersheds with greater disturbances due to roads. Such sites are difficult to find, so hydrologic predictive models need to be developed and verified.

### Key Point

Roads in a watershed may increase the amount of runoff and the peak runoff rate.

## Sedimentation

### Issues and Risks

On most forested watersheds, sediment is the most troublesome pollutant and roads are a major source of that sediment (Appelboom and others 1998; Megahan and Kidd 1972a, 1972b; Patric 1976; Reid and Dunne 1984; Yoho 1980). Sediment can adversely impact water quality by increasing turbidity, prematurely plugging filters and other components of treatment systems. Suspended sediment can also carry undesirable chemical pollutants, such as phosphates, pesticides, and other hydrocarbons into surface water and ground water (Gilson and others 1994, Patric 1976, Thomson and others 1997). See chapter 3 for additional impacts of sediment.

Sediment may be from surface erosion, which is generally more likely to carry pollutants. On steep watersheds, more sediment may be from mass wasting, which tends to bring greater volumes of soil to the stream.

### Findings from Studies

Numerous researchers and managers throughout the United States have identified roads as a major source of sediment in otherwise relatively undisturbed watersheds, such as forests and rangelands (table 9.1). Table 9.1 presents some typical erosion rates for different regions in the United States for different types of disturbance. Note that some investigators have reported erosion rates for roads, ranging from 5 to 550 tons per acre [11.2 to 1232 metric tonnes (Mg) per hectare] per year, whereas others have reported erosion rates of watersheds containing roads in the range of 0.02 to 2 tons per acre (0.045 to 4.5 Mg per hectare) per year. The wide range results from differences in measuring erosion (at the road or at the watershed outlet) and in the factors causing erosion, including the presence, density, and design of the road network on the watershed.

In a mixed rural and urban watershed in northern Idaho, roads covered only 1 percent of a watershed, but they contributed 8 percent of the sediment to streams (Idaho Division of Environmental Quality 1997). Megahan (1974) estimated that, in central Idaho, the sediment yield from watersheds without roads was about 0.07 tons per square mile (0.025 Mg per square kilometer) per day, whereas the presence of roads increased this yield by a factor of 5. McNulty and others (1995) attributed the majority of sediment from a forested watershed in the Southeast to unpaved roads.

Immediately after roads are constructed, erosion rates from bare slopes and road surfaces are high (fig. 9.2). Erosion rates can drop rapidly as exposed slopes revegetate and stabilize. Erosion reductions of 90 percent or more are common as a road ages (Burroughs and King 1989, Ketcheson and Megahan 1996). Road surfaces, however, will likely continue to be a source of sediment as long as traffic or maintenance prevents the establishment of vegetation (Elliot and others 1996, Swift 1984b). Applications of high-quality gravel to unpaved roads can decrease erosion rates by up to 80 percent (fig. 9.2) (Burroughs and King 1989, Swift 1984a), but reductions may be less for poorer quality aggregates (Foltz and Truebe 1995).

In a study attempting to isolate the specific sources of sediment, Burroughs and King (1989) identified the cutslope, the roadway, and the fillslope (fig. 9.1). For each of these components they suggested mitigation measures,

including application of mulch, geotextiles, seed, and sod. Many other studies have demonstrated the effectiveness of these treatments (table 9.2), and they are recommended in many States. Luce and Black (1999), however, were not able to measure any differences in sediment from roads for bare and vegetated cutslopes of different heights in the Oregon Coast Range. They concluded that the roadway and the road ditch were the only significant sources of sediment.

Wemple and others (1996) and Elliot and Tysdal (1999) found that the roads can influence a wider zone of erosion than previously thought. Slopes and channels downhill from the road can be sites of deposition, or the major source of sediment from a given segment of road. The excess runoff from roads can overload ephemeral channels, resulting in significant downcutting of the channel.

Poor road drainage can also lead to saturation of road beds and mass failure. In steep terrain, abandoned roads that do not shed surface water can become saturated, increasing the likelihood of failure. In areas of high rainfall, such as the Coast Range in Washington and Oregon, more sediment comes from roads due to landslides associated with roads than from road surface erosion. Beschta (1978) reported that watershed sediment yields increased from around 300 tons per square mile [105 Mg per square kilometer (km)] per year before roads and harvesting, to about 400 tons per square mile (140 Mg per square km) per year after installing roads and harvesting timber. Much of the increase in watershed sediment yield in this high-rainfall area was from mass failure. In a recent study in the Clearwater National Forest in Idaho, 58 percent of the landslides that occurred were associated with roads (McClelland and others 1998). Recent studies in Oregon, however, suggest that road impacts may have been overestimated (Robinson and others 1999), and that sediment from landslides in undisturbed areas is similar to that in areas with roads. While surface erosion is a chronic source of sediment associated with numerous precipitation or snowmelt events every year, landslides tend to contribute large amounts of sediment during very wet years and no sediment during normal and dry years. Landslide scars can also be sources of sediment until they are revegetated. McClelland and others (1998) calculated that the amount of sediment from the worst landslides in 20 years was about 10 times a background erosion rate, while the ongoing contribution from roads in the basin was about 2.5 times the background rate.

In addition to roads, other rights-of-way such as pipelines, are potential sources of sediment (Gray and Garcia-Lopez 1994, Sonett 1999). Any construction that exposes bare mineral soil, particularly on sites that are adjacent to ditches or streams, is likely to increase sedimentation. Once

**Table 9.1—Typical erosion rates observed for different types of land use in the United States**

Location	Surface cover	Erosion rate	Reference
		<i>Tons/ac/yr</i>	
Eastern watersheds	Forests	0.003– 0.32	Patric 1976
Fernow NF, West Virginia	Observed bare and graveled roads	6.0 – 52.5	Kochenderfer and Helvey 1987
Appalachian Trail	Trail	4 – 60	Burde and Renfro 1986
Southeast	Roads	5 –144	Swift 1984a, 1984b
Southern watersheds	Forests	Trace – .32	Yoho 1980
	Meadow	.06 – .1	
	Prescribed burn	.01 – .23	
	Careless clearcut	1.35	
	Roads	16 –150	
Central Arkansas	Roads	6.8 – 33.7	Beasley and others 1984
		4 – 38.5	Miller and others 1985
Southeastern Oklahoma	Roads	8 – 77	Vowell 1985
Western watersheds	Rangeland	.1 – 1.8	U.S. Department of Agriculture 1989
Northern Rockies	Forests	.04	Megahan 1974, McClelland and others 1998
	Forested watershed		
	Undisturbed	0	Megahan and Kidd 1972b
	With roads	.02	
	Roads	7.5 – 22	Ketcheson and Megahan 1996, Megahan and Seyedbagheri 1986, Megahan and Kidd 1972a
Washington Olympics	Roads	46 –550	Reid and Dunne 1984
Oregon Cascades	Forested watershed	.11	Fredrikson 1970 (most of road and harvest erosion attributed to landslides)
	Roads added	.56	
	Harvested	18.4	
	Roads	.22 – 24	Foltz 1996
Oregon Coast Range	Roads	1 – 18	Luce and Black 1999
Oregon coast	Forests	.4	Beschta 1978
Northern California Coast Range watershed	Undisturbed forest	.008	Rice and others 1979
	After roads	.63	
	After roads and logging	1.9	

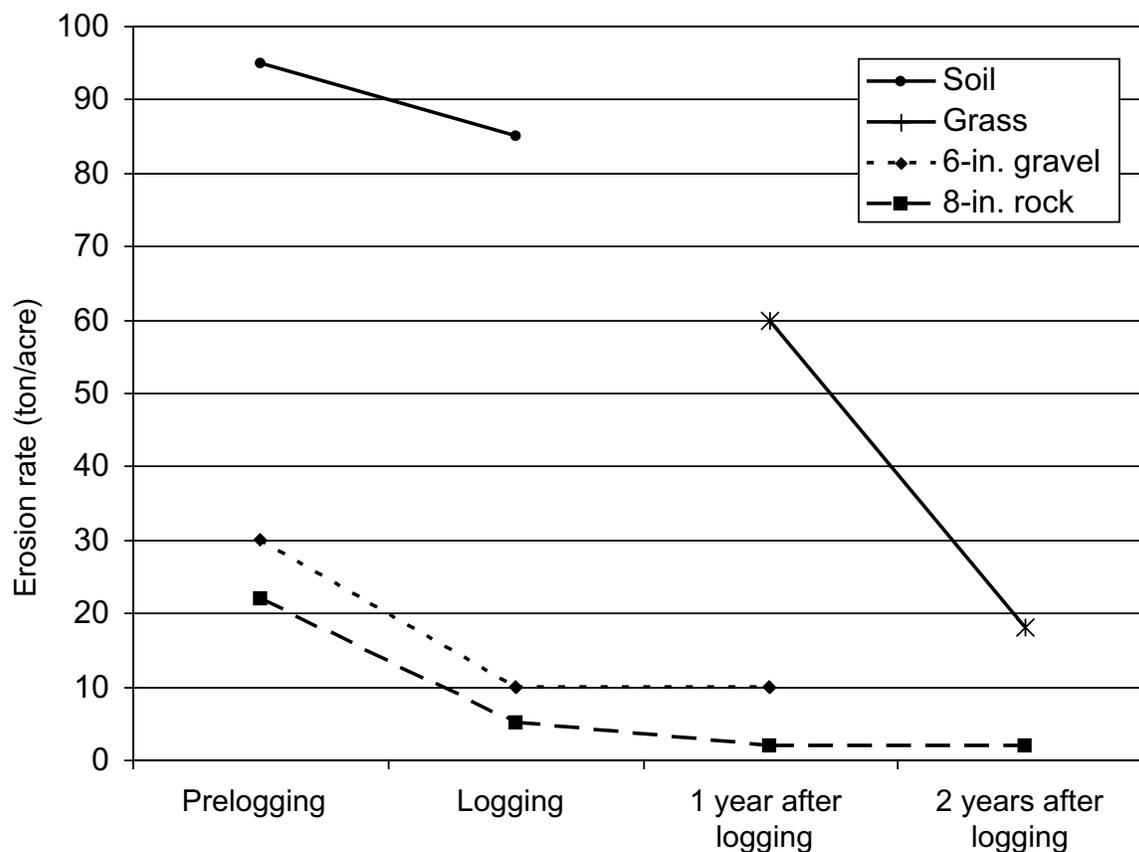


Figure 9.2—Mean soil loss rates for four road surfaces before, during, and for 2 years after logging (based on Swift 1984a).

installed, rights-of-way may continue to be sources of sediment if revegetation or other erosion control practices are not initiated (Gray and Garcia-Lopez 1994). Frequently, off-road vehicle enthusiasts may use rights-of-way for recreation. Also, mechanical and chemical control of vegetation may reduce vegetative cover. Depending on the site conditions, erosion rates from the compacted trails or exposed rights-of-way may be similar to those of roads.

Trails for bicycling, walking, or horseback riding erode at rates similar to roads (Leung and Marion 1996). The total sediment delivered from these trails is generally lower, however, because the total surface area of a narrow trail is less than that of most roads.

Much of the sediment eroded from a right-of-way is rapidly deposited below the right-of-way and never reaches a stream. Rummer and others (1997) found no significant sedimentation effects beyond the clearing limit of the road in a bottomland hardwood study on a floodplain. Numerous scientists have developed equations from field observations to predict how far sediment will travel (Ketcheson and

Megahan 1996, McNulty and others 1995, Packer and Christensen 1977, Swift 1986).

Various mitigation measures to reduce road erosion are commonly prescribed by Federal and State agencies. The most common methods include surfacing the road with gravel, decreasing the spacing of cross drainage, locating roads farther from streams, or limiting road gradients (Burroughs and King 1989, Swift 1984a, Yoho 1980).

**Table 9.2—Effectiveness of erosion mitigation techniques**

Condition	Reduction	Reference
	Percent	
Erosion mat	74– 99	Grace and others 1998
Seeding	82– 95	Grace and others 1998
Grass on fillslope	46– 81	Appelboom and others 1998
Straw and asphalt tack or erosion mats (depends on percent cover)	60– 100	Burroughs and King 1989
Straw	60– 80	Burroughs and King 1989

Treatment of cut and fillslopes has also been effective in reducing sediment delivery from new roads (table 9.2) (Burroughs and King 1989, Grace and others 1998). Sediment production can be reduced by applying higher quality gravel (Foltz and Truebe 1995) or by reducing the pressure in vehicle tires on the road network (Foltz 1994). The installation of vegetated filter strips or slash filter windrows below fills, or sediment basins below culverts, are also management options that have reduced sedimentation. In climates with distinct wet seasons, seasonal closure of roads may be a desirable option to prevent rutting and severe erosion.

In an effort to reduce the impacts of roads and railroads in watersheds, many government management agencies are removing unwanted corridors. In many national forests, watershed restoration is synonymous with removal of excess roads (Elliot and others 1996). Moll (1996) presented an overview of road closure and obliteration methods in the Forest Service. He recommended that watershed managers consider access, drainage, erosion risk, slope stability, and revegetation when planning any road closure or obliteration. Table 9.3 summarizes management options for decommissioned roads. Elliot and others (1996) warn that the disturbances associated with road closure may cause more erosion than simply abandoning a road that has been revegetated and is hydrologically stable.

Surface erosion rates can drop significantly when roads are closed. Figure 9.2 shows the relative impacts of different road surfaces during the first 2 years after abandonment, compared to erosion rates during construction and logging (Swift 1984b). In the Oregon Cascades, Foltz (1996) observed that during the first year of closure erosion rates dropped from 4 to 0.5 tons per acre (9 to 1 Mg per hectare) when marginal quality aggregate was applied, 20 to 2.5 tons per acre (45 to 5.6 Mg per hectare) when good-quality aggregate was applied. Erosion will often drop to background levels as the density of vegetation on an abandoned road surface increases (Foltz 1996, Swift 1984b). Such a decline is unlikely, however, if the abandoned road has unvegetated surfaces and continues to concentrate runoff water.

Several general principles can be applied to analyzing and mitigating potential sediment sources from abandoned corridors. The surface should be covered with vegetation. In order to establish vegetation, it may be necessary to rip or till the surface. In extreme cases, it may be necessary to add topsoil. To encourage infiltration and revegetation, it may be necessary to discourage off-road vehicle traffic by installing permanent barriers to prevent wheeled access to the corridor.

On abandoned roads, culverts can fail or become blocked, causing ponding of water, embankment failure, and major offsite sedimentation (Elliot and others 1994). Many older roads or railroads were built with underdesigned culverts. Some culverts were made from wood that is decaying or metal that is corroding. In either case, most of these culverts will eventually fail unless they are removed or replaced. Culverts that are not regularly inspected can also become blocked with woody debris or sediment. One of the most common practices to minimize the risk of fill failure on abandoned rights-of-way is to remove the culverts.

A number of prediction models have been developed to estimate the amount of sediment that leaves forest roads. Site-specific models were developed in the northern Rocky Mountains by Forest Service hydrologists; the most recent is the Watershed and Sediment Yield Model (WATSED) model (U.S. Department of Agriculture, Forest Service 1990). McNulty and others (1995) presented a Geographical Information System-based method for predicting sediment delivery from a road network, but they observed that additional work with physically based models is necessary to improve the prediction of sediment delivery from roads.

The physically based Water Erosion Prediction Project (WEPP) model is under development for a wide range of conditions including agriculture, range, and forest conditions (Lafren and others 1997). Because it is physically based, the model can be applied whenever the factors that cause erosion can be adequately described. Elliot and Hall (1997) have developed a set of input templates for forest roads and other disturbances. Elliot and others (1999b) developed simplified tools based on the WEPP model to aid managers in estimating the impacts of climate, soil, and topography on the delivery of sediment from roads. These models are available on the Web at <http://forest.moscowsl.wsu.edu/fswepp/>.

### **Reliability and Limitations of Findings**

Researchers worldwide have measured increased sedimentation from roads and similar disturbances. The magnitude of erosion varies considerably with climate, but the relative impacts of soil, topography, and management are generally the same (Elliot and others 1999b). Observed erosion rates are highly variable (table 9.1) due to the high natural variability in the factors that cause erosion. Even a well-designed erosion experiment frequently results in variations from the mean of up to 50 percent. This high variability should be considered when interpreting any research or monitoring results, or any erosion prediction value. Managers should exercise caution when applying any model to an area where it has not received some validation. Predictive technology for one climate, soil, and topography does not

**Table 9.3—Management options for decommissioned roads**

Option	Comment
Close road with barriers, vegetation, ditch, or removal of first segment	Recreational users may still obtain access.
Rip road surface	Runoff is reduced (Luce 1997). Instability may be increased (Elliot and others 1996).
Revegetate road surface	See table 9.2
Remove culverts and restore channels	Mitigation may be necessary on bare, excavated embankments or in channels; remaining road segments may not be accessible for future maintenance (Moll 1996).
Reshape road surface to be outsloping or partially recontoured with regular waterbars	Moll 1996
Install rock buttresses to stabilize cut and fillslopes	Moll 1996
Remove, recontour, or obliterate road prism	Expensive [\$0.60 to 1.50 per lineal ft (Moll 1996)] Increase revegetation rate by excavating until the old topsoil is reached <sup>a</sup>
Mitigate obliterated road prism with slash, mulch, geotextile, or seeding	Moll 1996

<sup>a</sup> Spreiter, T.A. 1999. Road closure experiences of the National Park Service. Presented at the Oregon and Washington engineering workshop; 1999 March 9; Gleneden Beach, OR. Oral presentation.

translate well to other conditions unless the model is able to incorporate those site-specific characteristics.

The technology to remove abandoned roads is well established (Moll 1996). Numerous agencies including the Forest Service (Moll 1996; U.S. Department of Agriculture, Forest Service 1998) and the National Park Service<sup>2</sup> have specialists to provide technical assistance in road closure, stabilization, revegetation, and removal. Many abandoned roads and railroads require site-specific prescriptions for reclamation. The same level of design that went into creating some of these roads may be required to remove them (Elliot and others 1996). Although this design expertise is available, the cost may be prohibitive.

<sup>2</sup> Spreiter, T.A. 1999. Road closure experiences of the National Park Service. Presented at the Oregon and Washington engineering workshop; 1999 March 9; Gleneden Beach, OR. Oral presentation.

### Research Needs

1. Upland erosion and sedimentation are well understood. The long-term impacts of trapping sediment on hillsides between sites of disturbance and streams and movement of sediment within and through stream networks are not well understood. Future research on overland transport and storage of sediment and transport and storage in stream networks will enhance sedimentation prediction.
2. Reports related to problems associated with abandoned roads and railroads focus specifically on culverts or mass failures. Surface and channel erosion may be a chronic source of sediment for many years. Thus, published information is frequently limited to episodic problems rather than solutions to chronic problems. There is a need for research to determine the probability of a failure occurring as well as the probability that no failure will occur.

3. Research is also needed to determine risks of failure or erosion for specific road networks.
4. There is a need to develop field techniques to assist road and watershed managers to make better decisions on which segments of a road network are at the greatest risk of a failure that may impact off-site water quality as well as other resources.
5. Another need is to develop tools to estimate the amount of sediment that may come from road closure activities, both from reshaping or removing the road prism, and from removal of stream-crossing structures.

### Key Points

1. Roads and similar corridors can be a major source of sediment in a forested watershed.
2. Effective measures to reduce sedimentation include surface gravel, careful design of roads and water crossings, and removal of unwanted roads.
3. Abandoned roads may be sources of sediment if they collect or divert surface runoff.

## Hydrocarbons, Cations, and Related Pollutants

### Issues and Risks

Runoff from roads and similarly surfaced sites can contain a host of hydrocarbons and other chemical pollutants, adsorbed to sediments, as particles, or dissolved by the runoff. These chemicals can find their way into surface and subsurface water. Pesticides used to control unwanted weeds can also be a source of pollution, and the reader should refer to chapter 12 for further discussion.

### Findings from Studies

Researchers have identified a range of chemicals in road runoff (tables 9.4, 9.5). Some of the pollutants are from the road material itself, some occur in the soil and rock on the site and are released during construction or subsequent erosion, and many are from vehicles. Traffic and road surfacing may contribute undesirable cations, hydrocarbons, and metals to surface and subsurface water (Maltby and others 1995, Mungur and others 1994). Most studies on the impact of roads and similar disturbances have focused on heavily traveled roads such as major freeways (Mungur and others 1994). If water source areas contain major roads, runoff treatment may be necessary to ensure that undesirable hydrocarbons do not enter the water supply.

Cations released from a road may have a buffering effect on the runoff acidity, which may be beneficial in acid rain areas. Morrison and others (1995) measured pH values from 6.0 to 7.0 in road runoff from small storms, compared to the average rainfall pH of 4.1.

Ions from deicing or dust control chemicals are common pollutants from road surfaces (Church and Friesz 1993, Pugh and others 1996). Road salt contamination of shallow ground water has become a serious problem, particularly in the Northeast and Midwest (Church and Friesz 1993). Church and Friesz (1993) state that during a 7-year period in Massachusetts, there were complaints from 100 of the 341 municipalities about road salt contamination. Nationally, about \$10 million are spent each year for prevention or remediation of problems associated with road salt contamination. Surface water is less vulnerable to such contamination than ground water, because there tends to be much greater dilution and mixing in turbulent channels carrying runoff from roads (Jongedyk and Bank 1999). Calcium magnesium acetate and potassium acetate are deicing chemicals with less serious environmental consequences than sodium chloride because they contain weak biodegradable acids. Sodium chloride, calcium chloride, and magnesium chloride, however, leave residues of chloride ions that may contaminate ground water (Jongedyk and Bank 1999).

Some of these ions (calcium, magnesium, and potassium) can enhance vegetation growth along highways (Pugh and others 1996). In some cases, elevated levels of deicing cations such as sodium in the road runoff, may be adsorbed by the soils near the road, and pose no further concern to the aquatic ecosystem (Shanley 1994). Pugh and others (1996) observed that ion concentrations from an adjacent interstate highway decreased exponentially with distance from the road in a peat bog. Although many thousands of tons of salt are spread annually on highways, because of dilution, salts in runoff are not likely to be a major source of pollution for drinking water except where they use shallow ground water even though impacts on the aquatic ecosystem may be great.

Road dust can transport unwanted chemicals to surface water. Christensen and others (1997) observed recent accumulations of polycyclic aromatic hydrocarbons (PAH's) in a Wisconsin stream, and identified dust from nearby roads as the source of the pollutant.

Oil-based dust suppressants may be environmentally more risky than salt-based products. A literature search for the Forest Service (Heffner 1997) found reports that calcium and magnesium chloride showed some toxicity towards

**Table 9.4—Pollutants that have been observed in runoff from road surfaces**

Pollutant	Comment	Reference
Cd, Cu, Pb, Zn	Treated in wetlands	Mungur and others 1994
Highway deicing salt	Na adsorbed in soil	Shanley 1994
Cu, Zn, hydrocarbons, PAH's	Accumulated in aquatic biota	Maltby and others 1995
PAH's	Altered aquatic communities	Boxall and Maltby 1997
Ca, Mg, Na, K, Cl	Captured in peat bogs	Pugh and others 1996
Total petroleum hydrocarbons, Pb, Zn	Reduced by vegetation	Ellis and others 1994
Heavy metals, petroleum hydrocarbons, pesticides, sediment, nutrients	Treatment ponds can remove up to 95 percent of pollutants.	Karouna-Renier and Sparling 1997

Ca = calcium; Cd = cadmium; Cl = chloride; Cu = copper; K = potassium; Mg = magnesium; Na = sodium; PAH's = polycyclic aromatic hydrocarbons; Pb = lead; Zn = zinc.

plants, whereas ligninsulfonate increased water biological oxygen demand. The study concluded:

based on the literature review and typical application rates for dust abatement, the effects of these compounds on plants and animals would be negligible. For the purposes that the Forest Service uses these compounds, the selection of one over another would be more dependent on cost, availability, and local conditions than effects to the environment.

Some dust inhibitors may also decrease road erosion, decreasing the likelihood of off-site transport of sediment and related pollutants (Ice 1982).

Chemicals used to preserve utility poles and railway crossties are potential sources of pollution. Wan (1994) found that concentrations of PAH's in the soil were higher in the immediate vicinity of utility poles than on surrounding farm or rangeland. Soil concentrations of PAH's dropped rapidly from 550 micrograms ( $\mu\text{g}$ ) per liter to 23.2  $\mu\text{g}$  per liter within 13 feet (4 meters) of a treated pole. Background levels were between zero and 0.8  $\mu\text{g}$  per liter. Such findings emphasize the importance of maintaining vegetated buffers to reduce transport by erosion of contaminated soil between rights-of-way and any sensitive water resources.

Measuring concentrations of many pollutants is tedious and expensive. To reduce the cost, surrogate relationships have been developed between more easily measured pollutants, such as suspended solids (mainly sediment) or dissolved

**Table 9.5—Mean concentrations of a number of pollutants in highway runoff in Minnesota**

Pollutant	Range	Mean
----- Milligrams per liter -----		
Total nitrogen	0.6 – 8.14	1.67
Chloride	1 – 46 000	1 802
Sulphate	5 – 650	45
Sodium	2 – 67 000	3 033
Total phosphorous	.06 – 7.8	.6
BOD	1 – 60	12.6
COD	2 – 3 380	207
Total suspended solids	8 – 950	118
Total dissolved solids	22 – 81 700	10 440
----- Micrograms per liter -----		
Chromium	1.5 – 110	13
Copper	3 – 780	47
Iron	180 – 45 000	4 162
Lead	11 – 2 100	207
Zinc	10 – 1 200	174
Nickel	1 – 57	10
Cadmium	.2 – 12	1.7
Mercury	.08 – 5.6	.49
Aluminum	30 – 14 000	2 694
Arsenic	.1 – 340	19

BOD = biological oxygen demand; COD = chemical oxygen demand.  
Source: Thomson and others 1997.

solids and other pollutants that are difficult to measure (Thomson and others 1997). Such surrogates may be useful if relationships were developed for nearby conditions, but they become less reliable when extrapolated to other regions.

Gilson and others (1994) completed research on the effectiveness of filter systems for highway runoff to improve surface water quality in the karst terrain in Texas. They found that some alternatives to sand filters have higher adsorptive capacities initially, but filtration efficiencies tended to approach that of sand after several runoff events. A Virginia study found that highways in karst areas should be located to avoid polluting surface water that drains into caves (Hubbard and Balfour 1993). This study found raw sewage and petroleum fumes in the cave system. Keith (1996) described extra precautions on road location and drainage designs that were taken in Indiana to minimize the ground water impact of a new road design in a karst area.

Pollutants in runoff can be trapped in natural or artificial wetland areas (Ellis and others 1994, Karouna-Renier and Sparling 1997, Mungur and others 1994). Karouna-Renier and Sparling (1997) found that such treatment systems could remove up to 95 percent of metals, nutrients, and sediment. Monitoring of the performance of such areas is necessary to ensure that they are functioning as desired (Startin and Lansdown 1994).

Another treatment method is a partial exfiltration trench. This type of device filters out the suspended solids that carry many of the undesirable metals and hydrocarbons from road surfaces (Sansalone and Buchberger 1995). The trench improved the quality of both rainfall and snowmelt runoff from roads. Because of the wide range of runoff rates, however, multiple treatment methods may be necessary to decrease the pollutant load from large as well as small storms (Romero-Lozano 1995). Detention basins are needed to catch the first flush of highly polluted runoff. A filtration system is needed to treat the runoff from later in the storm, which is likely to be at a higher flow rate, but requires less treatment.

Sediment basins and similar structures built to contain polluted road runoff can become sources of pollution through seepage into the ground, or through other forms of hydraulic or structural failure. In either case, sediments with large amounts of adsorbed chemicals can enter a stream. The pollutants can become concentrated in these basins, increasing the risk of offsite pollution (Grasso and others 1997, Morrison and others 1995). Grasso and others (1997) observed a lead content of 1392 milligrams per kilogram on one site and recommended soil washing be carried out to

prevent offsite pollution. One of the best defenses against such risks is cleaning and maintaining such structures to minimize the risk of failure.

Past designs of runoff structures tended to collect water and route it directly to a stream. New designs that disperse water to ensure greater infiltration and onsite attenuation of pollutants can improve runoff quality (Elliot and Tysdal 1999, Li and others 1998). Not all sites lend themselves to this approach, particularly where rights-of-way are limited. Another recent innovation to reduce offsite pollution from roads and similar areas is to surface them with permeable pavement (Church and Friesz 1993). Permeable pavement combined with high-infiltration shoulders significantly decreased salt content in nearby ground water (Church and Friesz 1993, Jongedyk and Bank 1999). European researchers found that permeable pavement significantly reduced outflow levels of lead and suspended solids.

### **Reliability and Limitations of Findings**

Much of the research associated with chemical pollution from roads has taken place near large urban centers. The findings are generally reliable for their locality, but care needs to be taken in extrapolating to other conditions, particularly nonurban areas. The water-quality risks associated with hydrocarbon pollution are closely linked to the density of traffic. Watersheds with minimal traffic are unlikely to experience any of the problems discussed. These results should only be applied to more remote watersheds with caution and some form of monitoring.

### **Research Need**

Pollution from main roads that cross sensitive forest and grassland watersheds should be measured. Quantitative data are needed on the benefits of dust abatement chemicals for reducing erosion and pollution of streams near roads.

### **Key Point**

Many pollutants from vehicles, deicing and dust abatement chemicals, and road surfacing material have been measured in runoff from roads. Most of these measurements have been from roads with heavy traffic. Some level of monitoring may be necessary to determine pollution problems. Levels of pollution can often be related to levels of easily measured sediment concentration. Some cations in runoff may be beneficial in buffering acid rain. There are methods to collect and treat or to harmlessly disperse polluted road runoff.

## Fuels and Other Contaminants from Accidental Spills

### Issues and Risks

Accidents are rare on low-use roads and other rights-of-way in remote watersheds. Risks of an accident causing contamination spills are related to the traffic density, quality of road, and frequency of contaminant transport. Railroads pose similar risks, particularly on aging lines, or on busy routes linking industrial centers.

### Findings from Studies

Hazardous chemical spills from vehicle accidents can pose a direct, acute threat of contamination to streams. Risk analysis models have been developed for busy paved roads in nonmountainous terrain, but these models are seldom applicable to low traffic, remote watersheds. Chemicals that may be spilled include fuel, fertilizer, pesticides, and mining chemicals (U.S. Department of Agriculture, Forest Service 1998). Airfields can often be sources of ground water contamination due to spills of fuels and other material (Levine and others 1997).

Accidents may occur anywhere along a given road or railroad, but stream crossings and bridges tend to be frequent sites of accidents due to damage by floods, or a narrowing of the roadway. Whether the pollutant is able to reach a nearby stream is an important concern. Spills at stream crossings have a high likelihood of reaching surface water because of its close proximity. Frequently, transport of the pollutant overland, or through the soil, depends on the local climate, season, and hydrology.

### Reliability and Limitations of Findings

There is little information available on the risk of accidental spills in remote areas. Whatever information can be found is likely to be site-specific, and judgment must be used to apply it elsewhere. Watershed managers will need to develop their own set of potential risks, based on local conditions. Along with those risks, they will need to develop a set of potential mitigation measures, both in the water source area, and in the treatment system.

### Ability to Address Issues

Most counties have established committees to address local emergencies or disasters. An accident that impacts a local water supply is a prime example of such an emergency. Water supply managers should work with local emergency or disaster committees or services to ensure that mitigation

plans and equipment are in place to deal with toxic spills that may occur near a water source.

### Research Need

Because of the site-specific nature of this risk, it is difficult to define a broad research activity for remote watersheds. It is likely that research will continue to study risks associated with busier roads, so monitoring of those results for application to remote watersheds may be beneficial.

### Key Point

The risk of vehicle accidents and spills depends on road hazards and traffic volume. Watershed managers need to evaluate risks on a given watershed and develop prevention or mitigation measures specific to their own conditions.

## Pipeline Failures

### Issues and Risks

Pipelines carrying a wide range of substances, including drinking water, sewage, and petroleum products, can fail, leading to pollution of both surface water and ground water. In the past 15 years, about 200 oil pipeline failures have occurred per year, with an average net loss of about 600 barrels (95 cubic meters) for each spill (U.S. Department of Transportation 1999).

### Findings from Studies

Pipelines tend to have fewer accidents and injuries than other modes of transport (Jones and Wishart 1996). To minimize pollution impacts, most modern pipeline systems are equipped with devices to quickly shut down pumping if a change in flow or pressure is sensed (Ariman 1990).

A number of disturbances increase the likelihood of pipeline accidents (fig. 9.3). Road or construction accidents and damage from boulders are common external causes of damaged pipelines (Driver and Zimmerman 1998, Stalder 1997). Areas prone to severe erosion, landslides, and earthquakes tend to have more accidents (Ariman 1990, Gray and Garcia-Lopez 1994, Hart and others 1995). For example, Hart and others (1995) predicted that the probability of rupture for a pipeline in California increased from 0.0 for earthquakes with a magnitude below 5 to 1.0 for earthquake magnitudes greater than 6.0. They also predicted other probabilities of failure based on pipe length and installation. They recommended numerous design measures including depth of burial, trench design, and pipe wall thickness, to minimize failure due to earthquakes.

Pipelines sometimes fail at river crossings due to erosion of the streambank or bottom (Doeing and others 1995, Teal and others 1995). Pipelines carrying sewage and industrial wastes are frequently located in floodplains and are at particular risk from flood damage, or from overloading due to high runoff rates. Disturbances in a watershed, such as a fire, may cause landslides that lead to pipeline failure. Failure of water supply pipelines or canals can lead to considerable erosion if controls to monitor flow conditions are not in place.

Soil shrinking and swelling and freezing and thawing can lead to pipeline fatigue and premature failure. Corrosion due to electrolysis (Stalder 1997) and stress corrosion cracking can also occur on older pipelines (Wilson 1996). Above-ground pipelines can fail due to wind fatigue (Honegger and others 1985). Any pipeline may experience seam failure (Yaorog and others 1996).

Risk assessment models to aid in pipeline design and operation have been developed (Hart and others 1995, Nessim and Stephens 1998). These models can identify segments of pipe most at risk of failure, and maintenance can be concentrated on those segments. Risk rates of 0.0022 spills per mile per year are quoted in one environmental assessment (U.S. Department of the Interior, Bureau of Land Management 1978).

Table 9.6 shows the extent of contamination from 53 oil pipeline spills. The extent depends on the pipeline characteristics and on the soils and terrain. Risks of failure from normal, predictable events can be reduced to almost zero with adequate pipeline monitoring (Stalder 1997). In addition, technologies have been developed to mitigate the impacts of spills quickly and effectively (Sittig 1978).

Pipeline failures can pollute ground water as well as surface water. Petroleum products tend to float on ground water, but the processes associated with breakdown of oil underground are not well understood. Underground methane generation by anaerobic bacteria is common after a pipeline break.

Substantial amounts of the volatile petroleum hydrocarbons are transported from the surface of the water table through the unsaturated zone as vapor, which subsequently dissipates to the atmosphere or is biodegraded (Revesz and others 1996).

Eganhouse and others (1996) observed that an underground breakdown process from microbial degradation leads to the detection of a plume containing aliphatic, aromatic, and alicyclic hydrocarbons.

Pipelines carrying water and sewage may also be present on watersheds. Although the same principles of failure apply to

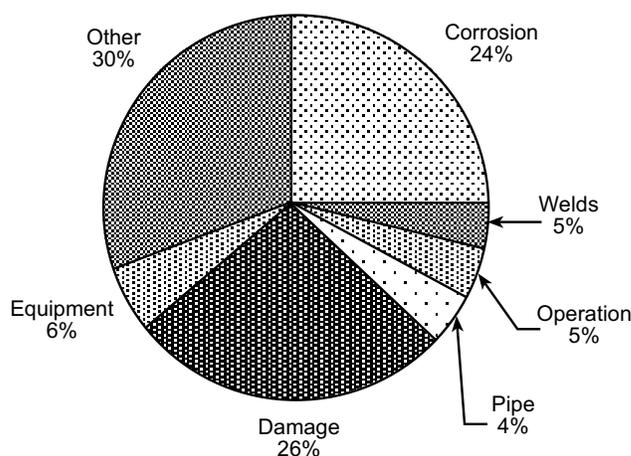


Figure 9.3—Summary of causes of pipeline accidents in 1998 in the United States (U.S. Department of Transportation 1999).

these pipelines, they are generally not as well monitored and may be older and more prone to failure.

### Reliability and Limitations of Findings

These findings are generally reliable because much of the pipeline industry receives close government scrutiny. Pipeline failures tend to be mechanical and predictable and findings are generally applicable to local conditions.

Current technology can address the risks associated with pipeline failure. Technologies to minimize pipeline failure are well established in the petroleum industry, as are controls to minimize pollution of surface and ground water should a failure occur. These same technologies can also be applied to other pipelines in sensitive watersheds. Managers of watersheds containing pipelines should work with

Table 9.6—Extent of soil contamination by 53 oil spills of various sizes in Alberta, Canada

Average volume	Average area	Average film thickness
<i>Barrels</i>	<i>Ft<sup>2</sup></i>	<i>In.</i>
54	8,000	0.4
880	70,000	.8
13,200	600,000	1.6

Barrel = 42 gallons of petroleum.  
Source: U.S. Department of the Interior, Bureau of Land Management 1978.

pipeline managers to minimize risks to water supplies. In addition, the U.S. Department of Transportation has an Office of Pipeline Safety (OPS) to assist in addressing risks associated with pipelines. One of its responsibilities is to identify areas that are unusually sensitive to a hazardous liquid pipeline release. The OPS has an ongoing program that may assist watershed managers in risk management (see Web site).

### Research Need

The oil industry has developed sophisticated systems for managing pipelines. There is a need to develop similar, but less costly, technologies for water and sewer pipelines in sensitive watersheds. The fate of oil pollution in the ground is not well understood, and further research is needed to better understand the chemical and biological processes associated with degradation of petroleum products on and in the soil.

### Key Point

Causes of failures on petroleum pipelines are well understood, and controls are generally in place to minimize environmental risks of failures. Such measures are less developed for water and sewage pipelines, so the risks of the failure of such systems may be higher.

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