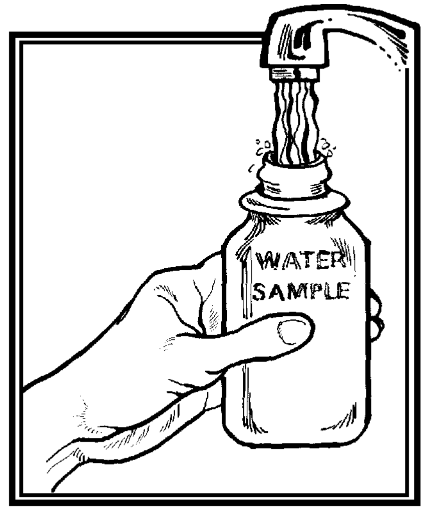
Managing Lakes for Pure Drinking Water

by Anne Kitchell



"Lakes are the reservoirs into which rivers and other streams empty, and their waters are not widely different from their sources of water supply. They are the receptacles of all the waste products of the inhabitants of the district; they receive the contents of sewers, cess pools, and privies; the offal of the distilleries, slaughter-houses and tanneries, and the refuse of factories."

Willis Tucker, 1885a

"*In the United States, 30,000 people die annually from typhoid fever. The mortality from typhoid fever in many of the eastern cities is proportional to the quantity of sewage which enters the water supplies*."

Floyd Davis, 1889

"*In the absence of positive knowledge, we had best err, if err we must, on the safe side, and avoid the use of polluted waters*."

Willis Tucker, 1885b

As these historical quotes remind us, public health authorities have always had an acute interest in the purity of their drinking water, an intuitive understanding of the watershed concept, and an aggressive pursuit of ever-cleaner source waters. Over the past hundred years, these trends have continued. If any threat to source waters can be established, even imperfectly, and a reasonable remedy to treat or eliminate the threat found, it will usually be undertaken. Witness the progressive engineering "firsts" that have occurred in water supply watersheds: storage reservoirs, filtration, disinfection, wastewater treatment, watershed planning, land regulation, spill contingency plans, stormwater treatment practices and buffers, to name but a few. Indeed, arguably the earliest known watershed ordinance was enacted in Chicago in 1833, when authorities declared it to be unlawful to throw or put into the Chicago River... "any carcass of any dead animal or animals, under a penalty of three dollars per offense" (CBH, 1871).

The progressive adoption of these sanitary engineering strategies certainly ranks among the greatest public health achievements of our era; outbreaks of waterborne infectious diseases such as typhoid fever, cholera, shigellosis and salmonellosis have virtually been eliminated as a result. Still, the quest to provide a pure supply of drinking water never ceases, as science continuously reveals new risks to public health, such as *giardia*, *cryptosporidium*, disinfection by-products, and a wide spectrum of pollutants and potential carcinogens.

In recent years, water supplies have gradually recognized that improved water treatment, while necessary, is not sufficient by itself to protect public water supplies. Watershed management is also needed to protect source waters, particularly so for communities growing outward into previously undeveloped water supply watersheds.

> Improved water treatment, while necessary, is not sufficient by itself to protect public water supplies.

This article reviews the current state of watershed practice in reservoirs used for water supply. It begins by reviewing some of the unique concerns facing reservoir managers in these watersheds, and then reports on a detailed survey of trends in watershed treatment practices used to protect more than 20 large water supply reservoirs in the U.S. Finally, the article recommends ways in which watershed practices could be improved to meet ever-tighter drinking water standards, and how recently required source water assessment plans could be better integrated into local watershed planning.

Impact of Watershed Development on Surface Water Supplies

For much of this century, water supply reservoirs were intentionally located in areas of little or no watershed development. In the last three decades, however, many communities have begun experiencing considerable growth pressures within the watersheds of their water supply reservoirs. Managers are quickly realizing that they must clearly understand the impact land development can have on the quality of their source waters. This realization has been prompted by increasingly tight drinking water standards under the Safe Drinking Water Act (see Table 1 for a summary of these new requirements), as well as by new research on the impact of stormwater runoff on reservoir water quality. The following section reviews recent research on key contaminants in reservoir watersheds.

Disinfection By-Products

Nearly all water supplies inject chlorine or bromine to treated waters as an effective last line of defense against pathogens. However, if the source water has high concentrations of organic matter, the disinfection process can create a series of disinfection by-products (or DBPs) under the right conditions. These DBPs include up to 30 different compounds such as trihalomethanes (THMs), haloacetic acids (HAAs) and chloroform, many of which are suspected to adversely affect human health.

DBPs present a severe challenge for reservoir managers, since they are formed at the end of the treatment process.

Recent research has shown a strong association between the consumption of treated water containing DBPs and the occurrence of bladder cancer, and possibly rectal cancer. By some estimates, as many as two to 17% of bladder cancer cases in the U.S. and up to 14 to 16% of bladder cancer cases in Canada could be attributed to the presence of DBPs in drinking water (King and Marret, 1996 and Wigle, 1998). While epidemiologists caution that the research does not prove a causal relationship, the strength of the relationship has prompted the EPA to issue tougher rules on DBPs (US EPA, 1998).

DBPs present a severe challenge for reservoir managers, since they are formed at the end of the treatment process, and few practical alternatives to disinfection currently exist. The primary strategy for reducing DBPs is precursor control, which in simple terms seeks to reduce the amount of organic carbon in source waters prior to treatment (particularly humic and fulvic acids, NRC, 2000). In a practical sense, precursor control is simply another name for watershed treatment to reduce organic carbon and phosphorus loads to a reservoir.

Watershed development makes precursor control very difficult for two reasons. First, stormwater runoff from urban areas often dramatically increase phosphorus loads delivered to a lake, and in turn, increase algal levels (see Caraco and Brown, this issue). Decomposition of algae in the reservoir can help drive up organic carbon concentrations. Thus, the increased eutrophication that often occurs in urban lakes creates an internal source of organic carbon that make it difficult to control DBP levels at the treatment plant. As a consequence, many regulators are setting more stringent limits on the maximum amount of in-lake phosphorus or chlorophyll *a* concentrations allowed with a water supply reservoir, which often translates into limits on watershed phosphorus loadings. For example, some communities have established in-lake chlorophyll limits ranging from five to 15 ug/l and in-lake phosphorus concentrations ranging from 0.01 to 0.05 mg/l. As Caraco (this issue) observes, few urbanizing watersheds can meet such limits given current watershed treatment technology.

The second reason why precursor control is difficult in urban watersheds is that stormwater runoff can deliver significantly higher loads of both total and soluble organic carbon, in comparison to other watershed land uses. Although not much data has been historically collected on total organic carbon (TOC) concentrations in urban stormwater runoff, the Center recently derived a mean TOC concentration of 17 mg/l (median 15.2, range: 5.3 to 41.3 mg/l) based on 19 urban catchments contained in a national STP monitoring database (Winer, 2000).

The primary source of TOC appears to be the decomposition of leaf and other organic matter in curbs, storm drains and streets, along with some combustion by products. Data on dissolved organic carbon (DOC), which is thought to be the main precursor for DBPs, are even more sparse in the stormwater literature. A handful of studies suggest that DOC concentrations in the three to 7 mg/l range for untreated stormwater runoff. Only three studies have monitored DOC removal in stormwater ponds or wetlands, and these suggest that they have little or no DOC removal capability, and may actually increase DOC levels (SWAMP, 2000). Meyer and Couch (2000) report that annual DOC loads were higher in urban streams than in forested or agricultural streams in the southeastern Piedmont.

Turbidity

> *"It is believed that an excessive turbidity, caused by sand or clay, is productive of intestinal difficulties, indigestion, dyspepsia and diarrhea."*
>
> Davis, 1889

Turbidity has been used for more than a century as a measure of water clarity and a standard for both the purity of drinking water and the efficient operation of filtration systems in drinking water treatment plants. In addition, turbidity is also used as a surrogate measure to predict pathogen removal. The EPA has recently issued tighter standards on the permissible amount of turbidity in drinking water, shifting from 1.0 to 0.3 NTUs (nephelometric turbidity units, see Table 1).

Watershed development greatly increases the turbidity to reservoirs in three distinct ways. First, turbidity increases as fine particles are washed off impervious surfaces during storm events. The average turbidity of

Table 1. Condensed Summary of Recent Federal Drinking Water Regulations (NRC, 2000; US EPA, 2001a)		
Year	**Regulations**	**Key Components**
1974	Safe Drinking Water Act (SDWA)	• Contains provisions for assessing and preventing biological and chemical contamination of drinking water supplies • Targets specific contaminants in water supplies
1986	SDWA Amendments	• Regulates 83 specified contaminants • Sets goal of adding 25 new contaminants every three years
1989	Surface Water Treatment Rule (SWTR)	• Requires filtration for all surface water systems unless it can be proven unnecessary • Outlines conditions for filtration avoidance based on source water quality, disinfection criteria and site-specific criteria • Improved treatment criteria for *Giardia* and viruses • Introduces metrics of log removal of microbes and CT (product of disinfectant concentration and contact time) as control parameter for disinfection
	Total Coliform Rule (TCR)	• Criteria to prevent waterborne microbial diseases • Requires suppliers to test drinking water for harmful microorganisms • Set stringent limits on total coliform
1991	Lead and Copper Rule (LCR)	Requires increased evaluation of treatment processes used to control corrosion
1996	Information Collection Rule (ICR)	Mandates that suppliers collect water quality data to form a national database, particularly pathogens and DBPs
	SDWA Amendments	Establishes Source Water Assessment Program (SWAP) to develop and implement a watershed approach to source water improvement/protection by delineating watersheds that supply drinking water and assessing their susceptibility to known contaminants
1998	Drinking Water Contaminant Candidate List (CCL)	• List of 50 chemical and 10 microbiological (non-regulated) contaminants known/or anticipated to occur in drinking water • Prioritizes contaminants for future research, additional data needs, and as regulatory candidates
	Stage 1 Disinfectants/Disinfectants By-Products Rule (D/DBP)	• Updates MCLs for Total THMs; new MCLs for 5 HAAs, chlorite, and bromate and sets residual levels for chlorine compounds • Sets levels for TOC as DBP precursor
	Interim Enhanced Surface Water Treatment Rule (IESWTR)	• Requires tightening of turbidity requirements for filtered systems from 0.5 NTU to 0.3 NTU • Final rule incorporates microbial benchmarking ; require systems to show that filtration and disinfection are reducing *Cryptosporidium*; requires unfiltered suppliers to amend watershed control programs to control for *Cryptosporidium*
2000	Public Notification Rule	Sets requirements for how and when public notification required; Notification required when water utility fails to meet drinking water standards, or is facing a public risk situation
	Radionucleotides Final Rule	• Sets MCL for uranium at 30ug/l • MGCL of 0 for all radionucleotides
2001	Filter Backwash and Recycling Rule (FBRR)	• Requires recycled filter backwash, sludge thickener supernatant, and liquids from dewatering process to be returned to 1st stage of direct filtration/treatment process • First attempt to govern backwash situation that may compromise microbial control

urban stormwater runoff typically ranges about 100 to 200 NTUs, according to the NURP study. The second source of turbidity in urban watersheds comes from sediments eroded from active construction sites. The median turbidity in construction site runoff in Maryland was reported to be about 450 NTUs (range: four to 8,200 NTUs). Even after effective erosion and sediment control practices were applied to construction sites, median turbidity still exceeded 200 NTUs (Schueler and Lugbill, 1990). The third source of turbidity in urban watersheds is caused by stream channel erosion during large storm events, with concentrations frequently ranging from 200 to 1,000 NTUs, depending on the intensity of the storm event. While turbidity levels in reservoirs often decline due to dilution and settling, they still represent a chronic problem for drinking water treatment plant operators.

Several recent studies have detected high levels of both *cryptosporidium* or *giardia* in stormwater runoff.

Drinking water treatment plants can usually meet the new turbidity standard even when their source waters become highly turbid using a combination of coagulation, flocculation and filtration, but it is neither easy nor inexpensive to do so. Plant operators must carefully monitor the spikes or plumes of turbidity in the reservoir after storms, and then administer the precise dose of chemicals and filter run times to reduce them. As a result, the cost of drinking water treatment increases, and the reliability of treatment can decline within urban watersheds.

Loss of Reservoir Capacity

A more long term concern of watershed managers is the gradual loss of reservoir capacity due to sedimentation. Urban land uses often produce higher sediment loadings than other land uses, with the possible exception of agricultural row crops. How much reservoir capacity will be lost over time is usually a function of a reservoir's depth, and its drainage area to surface area ratio (DA/SA). When a reservoir is relatively shallow, has a DA/SA ratio of 50 or more and is highly urban, it is likely that sedimentation could result in a significant loss of capacity within a matter of several decades.

Pathogens

A pathogen is a microbe that is actually known to cause disease under the right conditions. Examples of bacterial pathogens frequently found in stormwater runoff include *Shigella spp*. (dysentery), *Salmonella spp*. (gastrointestinal illness), and *Pseudonomas auerognosa* (swimmer's itch). Other species can cause cholera, typhoid fever and staph infections. The actual risk of contracting a disease from a pathogen depends on a host of factors such as the method of exposure or transmission, pathogen concentration, incubation period and the age and health status of the infected party.

Cryptosporidium* and *Giardia

In the last several decades, the two most common waterborne diseases in the U.S. have been *cryptosporidium* and *giardia* (NRC, 2000). *Cryptosporidium* was the protozoan responsible for the largest waterborne disease outbreak in the U.S. (Fox and Lytle, 1996). To infect new hosts, these protozoans create hard casings known as cysts (*giardia*) or oocysts (*cryptosporidium*) that are shed in feces, and travel through surface waters in search of a new host. The cysts or oocysts are very durable, and can remain viable for many months.

Sand filtration at drinking water plants has not been found to be fully effective in removing all cysts and oocysts (LeChevallier *et al.*, 1991, 1995), although it is not clear whether the cysts that pass through sand filters remain viable. A series of studies have found that back flushing of sand filters at drinking water treatment plants resuspend protozoa, and can become a significant source of cysts/oocysts (LeChevallier *et al*., 1995). Chemical disinfection can inactivate cysts and oocysts, but typically requires chemical pretreatment, higher doses, and longer contact times than when used to inactivate fecal coliforms.

Until recently, the major sources of protozoa in surface waters were generally thought to be human sewage, dairy runoff and wildlife. However, several recent studies have detected high levels of both *cryptosporidium* or *giardia* in stormwater runoff (Stern, 1996; Xiao *et al*., 2000, 2001). David Stern (1996) monitored a series of agricultural and urban watersheds within the New York City water supply reservoir system, and found urban subwatersheds had slightly higher rates of *giardia* and *cryptosporidium* detection than agricultural subwatersheds, and a higher rate of confirmed viability. Graczyk and his colleagues (1998) recently discovered that migratory Canadia geese were a vector for both *giardia* and *cryptosporidium* in the Mid-Atlantic region. It is intriguing to speculate whether the large populations of resident geese found in many urban ponds might be a source of *cryptosporidium* transmission, and more research is warranted.

Total and Fecal Coliforms

Public health authorities have traditionally used total coliforms or fecal coliform bacteria as an indicator of potential microbial risk, and have set stringent standards for both drinking water supplies and finished water (see Table 1). Watershed development tends to greatly increase coliform levels in source

Table 2. National Event Mean and Median Concentrations for Chemical Constituents of Stormwater and Maximum Contaminant Goals and Levels					
Constituent	Units	Source of Data	EMCs		MCL[1]
			Mean	Median	
Copper	mg/l	(1)	0.0133	0.0111	1.3 (a)
Lead	mg/l	(1)	0.0675	0.0507	0.015 (b)
Cadmium	mg/l	(2)	0.0007		0.005
Chromium	mg/l	(3)	0.004		0.1
Nitrate	mg/l	(1)	0.658	0.533	10
Turbidity	ntu	(2)	50		1.0
Fecal Coliform	col/100 ml	(5)	15,038		5%
Atrazine	mg/l	(6)		0.000023	0.003
Simazine	mg/l	(6)		0.000039	0.004
Cryptosporidium	cysts	(7)	37.2	3.9	(c)
Giardia	cysts	(7)	41.0	6.4	(c)

(1) Smullen and Cave, 1998; (2) EPA, 1983; (3) Brush *et al.,* 1995; (4) Barrett and Malina, 1998; (5) Schueler,1999; (6) USGS, 1998 (baseflow); (7) Stern, 1996

Shaded rows indicate contaminants found in significant concentrations in urban stormwater, which could potentially threaten maintenance of water quality standards.

[1] Maximum Contaminant Level (MCL) The highest level of a contaminant allowed in drinking water. MCLs are enforceable and are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration.
(a) Lead and copper are regulated by a Treatment Technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level (1.3 mg/l for copper, and for 0.015 mg/l for lead), water systems must take additional treatment steps.
EPA s surface water treatment rules require systems to meet the following criteria (as of January 1, 2002):
(b) Turbidity: may never exceed 1 NTU and must not exceed 0.3 NTU in 95% of the daily samples in any month.
(c) Cryptosporidium: 99% removal; *Giardia lambia*: 99.9% removal/inactivation

waters. For example, the mean concentration of fecal coliforms in urban stormwater runoff is nearly 15,000 counts per 100 ml (Schueler, 1999). The coliforms are generated from a diverse set of sources in an urbanizing watersheds, and may take many complex pathways to reach a reservoir. For a complete discussion of urban bacteria sources, the reader should consult Schueler (1999).

Once coliforms reach a reservoir, they are subject to die-off, and are further reduced by filtration and disinfection at the drinking water treatment plant. Nevertheless, the coliform loading in urban watersheds can make plant operations more expensive, and can exacerbate the DBP problem if greater levels of disinfection are needed to meet coliform standards.

Organic and Inorganic Chemicals

The U.S. EPA has established primary drinking water standards for 69 different organic and inorganic chemicals that are known or suspected to cause health problems (US EPA, 2001a). Each of these chemicals has a maximum contaminant level or MCL that must be achieved in the finished water, and water utilities must frequently monitor these levels.

Many of these organic and inorganic chemicals have been detected in urban stormwater runoff or baseflow, but in most cases, they are present in concentrations well below the MCL. Table 2 compares the median pollutant concentrations in urban stormwater runoff with the established MCL for finished drinking water. With the exceptions of lead, turbidity and coliforms, the median concentration of most pollutants found in urban stormwater are about an order of magnitude lower than the MCL. It is important to note that it is probable that the *maximum* reported concentrations could equal or exceed the MCL during some extreme runoff or snowmelt events.

The EPA has also identified several chemicals of critical concern for which it is considering developing MCLs as well. Several of these chemicals have been detected in urban stormwater or streamflow, most notably MBTE, diazinon, chloropyrifos and several other pesticides (Table 3). The USGS (1999) detected one or more pesticides in 99% of urban stream samples in a recent national water quality assessment. They found that insecticides and herbicides were detected more often and at higher concentrations in urban streams than any other watershed land use (including agriculture).

Taste and Odor

Various chemicals, organic carbon and algal growth present in source waters can influence the taste and odor of finished water, and consumers are often quick to notice and complain about them. For this reason, the EPA (2001b) has recently issued voluntary guidelines about the taste, odor and appearance of drinking water. Table 3 compares the typical concentrations for some of these pollutants found in urban stormwater runoff against these recommended limits. With the possible exception of chloride levels in snowmelt runoff, most urban pollutants remain below the established limits. It is important to note that the greater algal growth, turbidity, and organic carbon found in urban source waters can impart disagreeable tastes and odors to finished water, often as a result of the greater treatment required at the plant.

Spills, Leaks and Accidents

Urban development can increase the risk of spills, leaks and accidents in a reservoir watershed, whether it be a tanker accident discharging into a highway storm drain, the derailment of a train carrying hazardous wastes, a fire at an industrial site, a shutoff valve breaking on a pipeline or storage tank, a slowly leaking landfill, pesticides dumped in a storm drain or any number of other nightmare scenarios. In a larger urban watershed, it is usually not a matter of whether one of these scenarios will happen, but when, and how quickly the utility can react to it. It is for this reason that nearly every utility has developed contingency plans for spill response, and often seeks to restrict or exclude as many of these risks as possible within a watershed.

Watershed Management for Water Supply Reservoirs

Given the potential impact of watershed development on the quality of water supply reservoirs, it is not surprising that most communities have sought to strictly regulate how and where new development occurs in water supply watersheds. Under the Safe Drinking Water Act, communities must perform a Source Water Assessment for surface and subsurface water supplies to identify potential sources of contamination for water supplies. It is interesting to note that of the 33 sources of potential water contamination that the EPA has recommended for investigation as part of this assessment, 55% are directly or indirectly associated with urban development in a watershed (see Box 1). Clearly, communities will need to greatly improve the effectiveness of watershed practices in reservoir watersheds where growth and development are anticipated. The following section analyzes some of the key trends in managing reservoirs watersheds across the country.

Survey of Watershed Practices in Water Supply Reservoirs

The Center intensively surveyed 22 surface water supply reservoirs, out of a total of 900 surface water supplies of similar size in the country (van der Leeden *et al.*, 1990). The purpose of the survey was to examine

Table 3. Potential Pollutants of Concern Based on Concentration and Detection in Urban Stormwater

Constituent	Units	Source of Data	Median EMCs	Concentrations of Concern
Total Dissolved Solids	mg/l	various	150	500 [a]
Zinc	mg/l	(1)	0.129	5 [a]
Chloride (snowmelt)	mg/l	(2)	116	250[a]
Organic Carbon	mg/l	(3)	11.9	4 [b]
MTBE	ug/l	(4)	1.6	20 to 40 [c]
Diazinon	mg/l	(5) (6)	0.00025 0.0055	0.0006 [c]
Prometon	mg/l	(5)	0.00031	0.001 [c]

(1) Smullen and Cave, 1998; (2) Oberts, 1994; (3) CWP Database, unpubl.; (4) Delzer, 1996; (5) USGS, 1998 (baseflow); (6) Brush *et al.*, 1995

[a] Secondary Maximum Contaminant Level (SMCL) Aesthetic guidelines to assist public water systems in managing their drinking water.
[b] EPA Disinfection By-Products Rule -- <2mg/l TOC for treated water and <4mg/l in source water
[c] Contaminant Candidate List (CCL) EPA list of contaminants known or anticipated to occur in public water systems, and may require future regulations under the Safe Drinking Water Act

trends in watershed management for surface water supplies across the country, and to identify innovative practices to protect drinking water supplies from watershed development. While our survey sample encompassed less than 3% of surface water supplies of similar size nationally, it still represents the most widespread survey of watershed practices for surface water supplies since Robbins *et al*. (1991). We used the following criteria to select our sample of reservoir watersheds:

1. The reservoir must be used primarily as a source of drinking water
2. The reservoir must serve a population greater than 50,000
3. The contributing watershed must currently be experiencing land development
4. Respondents in the watershed must be willing to supply detailed information and review our case studies for accuracy

It should be noted that over 10,000 smaller surface water supplies exist in the U.S., and that these survey results may not be transferable to these smaller reservoirs. The basic profile of our reservoir sample is provided in Table 4, and its geographical representation is provided in Figure 1. More details on the survey results and individual case studies can be found in Table 5 and in Kitchell (2001).

Box 1. Partial List of Potential Sources of Contamination Found in Wellhead Protection Areas and in Watersheds

Related to Watershed Development:	Not Development Related:
Atmospheric deposition	Agriculture
Collection system failure	Contaminated sediment
Combined sewer overflow	Debris and bottom deposits
Construction	Domestic water lagoon
Erosion from derelict land	Groundwater loadings
Habitat modification	Groundwater withdrawal
Highway maintenance and runoff	Internal nutrient cycling
Industrial point sources	Natural sources
Land disposal	Recreation and tourism activities (other than boating)
Leaking underground storage tanks	Resource extraction
Marinas and recreational boating	Sediment resupsension
Municipal point sources	Silviculture
Salt storage sites	Sources outside state Jurisdiction or borders
Sewer line (leaking)	Unknown source
Spills (accidental)	
Urban runoff/storm sewers	
Waste storage/storage tank leaks (above ground)	

Source: US EPA, 1998

The service population of the reservoir watersheds ranged from 60,000 to seven million (median: 450,000). Most of the reservoir watersheds had experienced relatively modest development, with a mean of 8.5% impervious cover (range two to 21%). The actual amount of watershed development is probably somewhat higher, given that only half of the reservoirs surveyed had recent land cover data for their contributing watersheds, and very few explicitly tracked impervious cover over time as an index of watershed development.

Less than 20% of the reservoir watersheds were completely contained within a single local political jurisdiction; the mean number of local jurisdictions was 4.8. About a third of the reservoir watersheds had adopted some form of intergovernmental agreement or legislation that formally established how the local jurisdictions would cooperate together to protect the water supply. The majority of reservoirs utilized filtration, although three unfiltered water supplies were also analyzed.

Watershed Planning and Management

Surprisingly, only 10% of the reservoir watersheds were covered by a comprehensive watershed management plan. Instead, most localities relied on a progressively stringent series of ordinances, regulations and zoning actions adopted over several decades. A major reason for the lack of comprehensive watershed planning was the need to coordinate among a large number of political jurisdictions and the traditional disconnect between the water utilities who are responsible for meeting drinking water standards and local government(s) who are responsible for regulating land use change in the watershed. On the positive side, water utilities exercised some form of local development review authority in about a third of the surveyed watersheds.

Watershed Zoning

Zoning was the primary planning tool to protect the water supply, and this tool was utilized in more than 90% of the reservoir watersheds surveyed. Large lot residential zoning was the primary planning tool relied on to reduce the overall density in the watershed. For example, 68% of the reservoir watersheds restricted development to lots of one acre or more in size. In addition, 48% of reservoir watersheds directly or indirectly excluded commercial or industrial development through their current zoning. Even where these uses were allowed, they were a minor component of the watershed land use distribution.

Overlay districts were the preferred mechanism to guide and regulate land use in the reservoir watersheds (60%), whereas regular zoning was used in the remaining watersheds. Overall, nearly 40% of all reservoir watersheds had down-zoned portions of the watershed to reduce the overall intensity of development. No reservoir watershed reported that they had established a watershed-wide impervious cover limit, although about 38% had imposed stringent impervious cover limits for individual lots.

In many cases, continued land acquisition was being used as a defensive strategy to counter rapid watershed development.

A unique element of water supply watersheds is that they often exclude or restrict certain land uses or activities that pose a potential water pollution risk or hazard. Eighty percent of surveyed watersheds excluded one or more land uses or activities, including the following:

Frequently Excluded

- New point source discharges
- Commercial or industrial land uses that generate, store or dispose of hazardous wastes
- Any commercial or industrial development
- Above or below ground petroleum storage tanks
- Land application of sewage sludge
- New landfills or solid waste disposal facilities
- Confined animal feeding operations

Less Frequently Excluded

- Gas stations, service stations, junkyards
- Dry-cleaning establishments
- Golf courses
- Use of reclaimed waters
- Cemeteries
- Asphalt and concrete plants
- Combined sewers
- Sewer extensions
- Septic systems
- Sale of detergents that contain phosphorus

About a third of the sampled watersheds emphasized stormwater runoff treatment over land use control as the major thrust of their watershed protection strategy. These communities tended to allow more development in the watershed in exchange for more stringent phosphorus limits for runoff from individual sites.

Land Conservation

Land conservation was a major watershed protection strategy for all of the reservoir watersheds. This is reflected by the fact that forest cover was the dominant watershed land use in nearly all of the reservoir watersheds (Mean 50%: range five to 95%). In general, a large fraction of forest or open space had been acquired over time by the water utility or municipality, although there was a great deal of variability in how much land was retained in public ownership, as shown here:

- 48% owned less than 10% of watershed land
- 19% owned from 10 to 25% of watershed land
- 33% owned more than 25% of watershed land

Shoreline buffers were the key priority for land acquisition in the reservoir watersheds, as 90% of the reservoir watersheds reported that they owned and managed extensive areas of shoreline buffer. These publicly owned buffers ranged in distance from 150 to 2000 feet from the reservoir shoreline.

It is also interesting to note that 72% of reservoir watersheds were still actively acquiring land or obtaining conservation easements. In many cases, the continued land acquisition was being used as a defensive strategy to counter rapid watershed development.

Shoreline and Stream Buffers

Every reservoir in the survey either owned the shoreline buffer or required extensive shoreline buffers for new development. In addition, 90% of the watersheds also required buffers on tributary streams to the reservoirs. The median width of shoreline buffer was 150 feet, but the range was very wide: from 25 to 2,000 feet. In general, the widest shoreline buffers were owned by a municipality or utility. The median buffer for tributary streams was 100 feet (range: 25 to 500 feet). The shoreline buffers often had specific vegetative targets (70%), and a wide range of prohibited or restricted uses within the shoreline buffer (80%). A list of the more common uses excluded from shoreline buffers includes the following:

- Impervious cover
- Septic tanks or drain fields
- Clear cutting
- Structures
- Commercial or industrial parking lots
- Grazing or livestock
- Land disturbance
- Pesticide application
- Generation, storage or disposal of hazardous materials

Table 4: General Characteristics of Drinking Water Watersheds Surveyed				
Reservoir Name	Watershed			Drainage/ Reservoir Surface Area Ratio
	Area (mi^2)	(%) Impervious	Political Entities	
Unfiltered Supply				
Wachusett, MA	111	1.6 [1]	9	17.9
Croton Reservoirs, NY	374	--	21	7.7
Kensico, NY	13.2	19	5	4.0
Filtered Supply				
Dog River, GA	78	5.0	4	221.9
Heads Creek, GA	27	11	2	38.4
University Lake, NC	30	4.5	3	90.1
Swift Creek (Lake Benson), NC	66	9	5	93.9
Lee Hall, VA	14.2	6.5	2	18.4
Occoquan, VA	592	12.0[1]	6	210.5
South Fork Rivanna , VA	258	5.7 [1]	1	423.4
Swift Creek, VA	65	5-10	2	24.5
Loch Raven, Pretty Boy, & Liberty, MD	466	--	6	42.6
Patuxent Reservoirs, MD	132	4 [1]	4	52.8
Hoopes, DE	1.9	6.0 [1]	1	6.4
Hemlocks, Easton, &Trap Falls, CT	91	--	12	--
Lake Vadnais, MN	23	17.0	8	9.1
Lake Whatcom, WA	57	<5	2	7.3
Nicasio, CA	36	< 5	1	26.5
Sweetwater, CA	184	21	1	--
Lake Dillon, CO	329	<< 5	4	65.6
Lake Austin,TX	41	10 [1]	4	16.4
Town Lake, TX	158	13 [1]	5	224.2

Notes:
[1] *Actual impervious values; remaining values were estimated by survey respondent or the Center*

Figure 1. Reservoir Locations

It should be noted that septic systems were often required to be located well outside of the designated shoreline buffer zone in many reservoirs. In general, shoreline and stream buffers used to protect water supplies were consistently more stringent than buffer requirements used to protect other water resources, as reported in a national survey of stream buffers (Heraty, 1992).

Better Site Design

Better site design refers to a series of design techniques that reduce the impervious cover and increase the natural cover associated with individual development sites. Nearly 70% of the reservoirs surveyed reported that they encouraged better site design in their watersheds, although the same proportion indicated that they could do much more in this respect. The two most common better site design techniques applied in reservoir watersheds were open space or cluster subdivisions (48%) and capping impervious cover for residential lots (38%). Many of the residential impervious cover limits were quite low (median: 12%; range: six to 30%).

Treatment of stormwater runoff quality was required in all but one of the reservoir watersheds surveyed.

It is interesting to note that these two better site design techniques can work against each other. In practice, however, many reservoir watersheds exempted cluster subdivisions from impervious cover limits if it could be demonstrated that the total impervious cover for a subdivision would be lower with clustering than without it. What is more important, many localities were willing to extend sewers or allow shared septic systems in order to make cluster development feasible.

Erosion and Sediment Control

Erosion and sediment control (ESC) practices during new construction were required in every reservoir watershed in our survey. However, ESC performance requirements were no more stringent in a reservoir watershed than in the surrounding locality 75% of the time. Slightly more than a third of localities (36%) did report more stringent requirements in regard to ESC plan review or inspections. Many of these localities shared development review and inspection authority with the water utility.

Stormwater Treatment Practices

Treatment of stormwater runoff quality was required in all but one of the reservoir watersheds surveyed. It was also noteworthy that 64% had more stringent stormwater requirements within the reservoir watershed than in the surrounding locality. In addition, 71% of the reservoir watersheds indicated that they had started or were planning to start a stormwater retrofit program to treat runoff from existing development.

Requirements for New Development

In general, reservoir watersheds require designers to treat a greater volume of stormwater runoff than non-reservoir watersheds. Sizing requirements ranged from one to two watershed inches of treatment, which is about twice the typical treatment volume used elsewhere. Wet ponds were the most frequently used type of stormwater treatment practice in reservoir watersheds. About 25% of the reservoir watersheds required designers to meet a specific phosphorus removal target. Examples of these targets include the following:

- 0.22 lbs/ac/yr
- 50 to 65% phosphorus removal
- Maintenance of predevelopment phosphorus loading

Only a handful of reservoir managers reported that they inspected stormwater treatment practices more frequently within a reservoir watershed.

Treating Existing Development

Stormwater retrofitting is becoming an increasingly common practice to treat existing developed areas within reservoir watersheds. For example, 38% of the reservoir watersheds had actually installed stormwater retrofits to improve the quality of runoff from existing development, and another 33% were considering pursuing a stormwater retrofit strategy. However, with the notable exception of the Kensico Reservoir, most watersheds had retrofitted only a small fraction of existing developed areas to date.

Wastewater Management

Surface Wastewater Discharges

New wastewater discharges were explicitly prohibited in 85% of reservoir watersheds. Three watersheds did have major wastewater discharges to the reservoir, but each relied on advanced tertiary treatment. Nearly all of the reservoirs used sewers to collect wastewater from at least a portion of their watersheds, but 85% pumped the sewage out of the watershed. Further, a third of the reservoir watersheds reported that they had extended sewers to relieve areas prone to failing septic systems.

Septic Systems

Septic systems were extensively utilized in about 67% of the surveyed watersheds. They were discouraged or prohibited in 14% of our sample. Many respon-

Table 5. Survey Results *(n =17-22)*			
Watershed Protection Measure	**%yes**	**Watershed Protection Measure**	**%yes**
Watershed Planning		***Erosion and Sediment Control***	
Have comprehensive watershed plan	10%	Require ESC during construction	100%
Utilize zoning as primary land use tool	90%	Have more stringent ESC criteria for reservoir protection	26%
Have protection overlay district	60%	Report more intensive review or inspection inside watershed	36%
Use large lot zoning (1 acre or more)	68%	***Stormwater Treatment***	
Rely primarily on stormwater treatment practices	32%		
Exclude specific uses/activities from watershed	80%	Require stormwater treatment	95%
Exclude new commercial or industrial uses (directly or by zoning)	48%	Have more stringent criteria for water supply watershed	64%
Have down zoned portions of watershed	37%	Require designer to meet specific phosphorus removal target	25%
Requirements take distance to intake into account	42%	Require specific practices or larger treatment volumes	67%
Dominant land use is forested/open space	59%	Have installed retrofits for existing development	38%
Dominant land use is commercial/industrial	5%	Are considering pursuing a retrofit strategy	33%
Have recent land use data (since 1996)	55%	***Non-Stormwater Discharges***	
Track impervious cover	37%		
Land Conservation		Have septics in watershed	100%
		Have sewers in watershed	95%
> 10% of watershed owned by utility/public	48%	Have reservoir specific criteria for septics	76%
10-25% of watershed owned by utility/public	18%	Require minimum septic setbacks at least 100ft	89%
>25% of watershed owned by utility/public	33%	Mandate inspections/cleanout	46%
Have a land acquisition/conservation easement program	72%	Exclude wastewater discharges from watershed	86%
Shoreline and Tributary Buffers		Regulate hazardous material storage/disposal/generation in watershed	73%
		Report having a spill contingency plan	95%
Require or own shoreline buffer	100%	***Stewardship***	
Require tributary buffers	90%		
Minimum shoreline buffer is greater than 100ft	80%	Monitor tributary and watershed lands	90%
Minimum tributary buffer is greater than 100ft	50%	Some form of education and outreach for watershed stewardship	86%
Specify vegetative targets for buffer area	70%	Prohibit swimming in reservoir	90%
Specify allowable or prohibited uses	85%	Prohibit gasoline engines in reservoir	90%
Better Site Design		Restrict public access to reservoir	27%
Mandate impervious cover at the site	38%		
Mandate BSD in watershed	4%		
Have active clustering/open space development	48%		
Encourage BSD	68%		
Admit that they could do more	65%		

dents indicated concerns about septic systems as a possible pollutant source, and nearly all had developed reservoir-specific regulations for them. The most frequent regulations included larger setbacks, that ranged from 50 to 600 feet in distance. Just less than half of the reservoir watersheds required mandatory inspection and pumpouts. In addition, many of the reservoirs recently adopted innovative programs to improve the performance of septic systems in their watersheds, including the following:

- Free inspections
- Requirements for non-discharge units
- Reservoir setbacks of up to 600 feet
- Requirements that innovative septic systems be used with higher nitrogen removal capability
- Proof of pumpout required to maintain public water service
- Utility monitoring to detect failing systems
- Sewering of failed septic systems
- Drain field rotation

Watershed Stewardship

Watershed Education

While 86% of the surveyed reservoirs reported that they had some kind of watershed education program, most were relatively modest in scope. For example, less than half of the outreach programs devoted full-time staff to watershed education. Even fewer had developed an overall strategy to guide their watershed outreach efforts (e.g., targeting specific watershed behaviors or conducting pollution prevention training).

We recommend that every source water assessment measure the amount of current watershed impervious cover.

Spill Response

The potential risk of spills or leaks of hazardous material in the watershed has always been a concern for reservoir managers. More than 90% of the surveyed watersheds reported that they had developed and tested a spill contingency plan. In most cases, these plans focused on potential spills from transportation corridors, such as highways or railroads. Most reservoir watersheds (76%) regulated the generation, storage and disposal of hazardous wastes within their watershed, usually by excluding these types of industrial uses, or requiring setbacks from the shoreline. However, few reservoirs had any kind of reporting program to track existing sources of hazardous materials in the watershed.

Monitoring

Robbins *et al*. (1991) noted that few reservoir watersheds were monitoring their watersheds and tributary streams, but this has changed greatly in the last decade. According to our survey, 90% of the reservoir watersheds indicated that they were monitoring within their watersheds and tributary streams. Only a handful, however, reported that they were monitoring the effectiveness of treatment practices, such as stormwater ponds.

Reservoir Restrictions

Reservoir managers often restrict public access to the reservoir itself. While only 27% of survey respondents indicated that they completely prohibited public access to the reservoir, nearly all of the reservoirs restricted access or use in some manner. The most common restrictions were to prohibit swimming (90%) and the use of gasoline engines within the reservoir (90%).

Overall Findings

Based on our survey, it is evident that nearly all reservoirs apply the eight watershed protection tools described above, at least in some form (Figure 2). Water supplies have traditionally been heavily regulated, given the paramount public health concern and increasingly stringent drinking water standards. It is fair to say that no other kind of watershed has regulated development to the extent seen in water supply watersheds.

Given this, it is surprising that only 10% of the reservoir watersheds had developed a comprehensive watershed plan. And despite the fact that development was expected to continue in nearly all of the watersheds, none had established a maximum upper limit on the total amount of watershed development that could occur in the future. This shortcoming reflects the disparity between water utilities who want clean source water and local government(s) who want growth, and are responsible for regulating land use in the watershed. Still, the lack of watershed land use planning is disturbing, given that watershed development is at the root of most potential sources of drinking water contamination.

And indeed, many reservoir managers acknowledged shortcomings in their watershed management programs. Most notable were consistent concerns about the long term maintenance of stormwater practices, septic systems, and buffers. Others reported chronic problems with the actual implementation of watershed practices in the field. The cumulative impact of inadequate staffing, waivers, infrequent inspections, poor

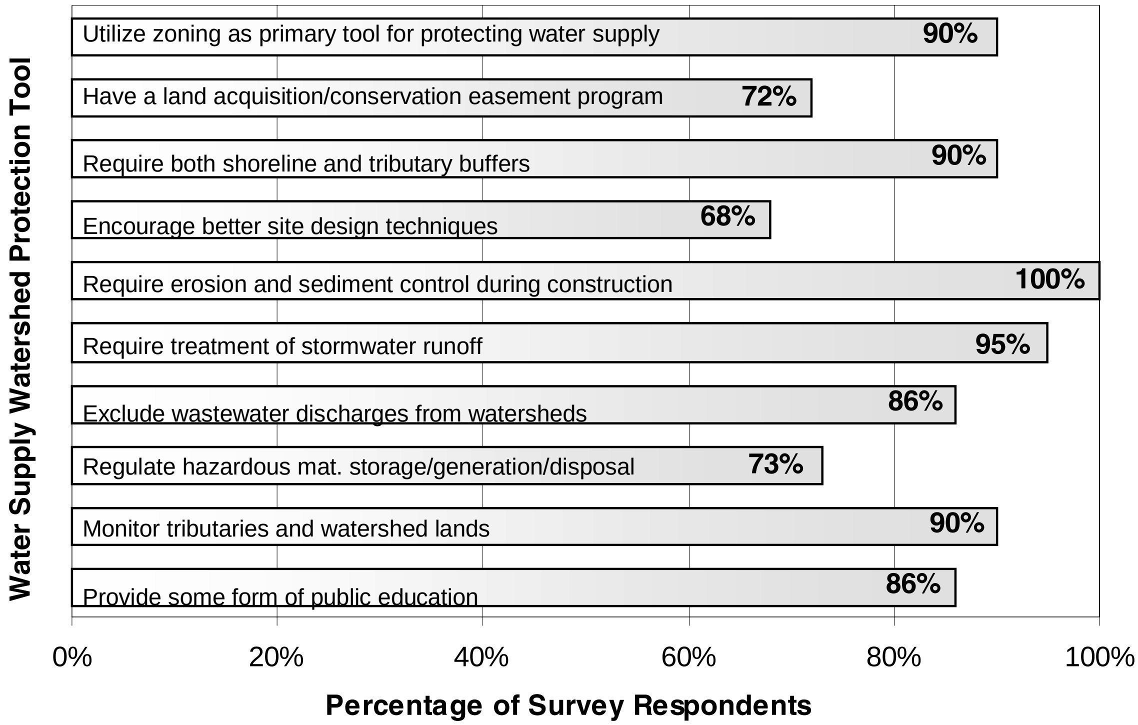


Figure 2. Percentage of Survey Respondents Utilizing Watershed Protection Tools

design standards and limited enforcement was believed by many to compromise the overall effectiveness of watershed protection programs. Some managers also lamented the lack of actual performance data for watershed treatment practices, at both the site and watershed level.

Integrating Watershed Planning Into Source Water Protection

One of the key requirements of the 1996 Safe Drinking Water Act Amendments is for water providers to conduct a *source water assessment plan* (SWAP) to identify potential contaminants, and then develop a *source water protection plan* (SWPP) to minimize these risks. Most states have just developed guidance on the minimum elements that water providers need to incorporate into these plans (see also a national manual developed by NEIWPPC, 2000). The major components of a SWPP are public involvement, use of regulatory and non-regulatory practices to manage drinking water contaminants and adoption of spill response contingency plans.

While state and federal water regulators clearly endorse a watershed approach for developing SWPPs, and, in particular, promote stakeholder involvement and intergovernmental partnerships (US EPA, 1999), they do not mandate that the cumulative impact of current or future watershed development be explicitly considered in the planning process. As a consequence, it is not likely that many water providers will be able to develop effective watershed land use plans. To some extent, this reflects the fact that not all reservoir watersheds are experiencing development, and both water regulators and water providers are reluctant to interfere with the land use prerogatives of local governments.

We recommend that every source water assessment measure the amount of current watershed impervious cover, and forecast the amount of new impervious cover to be created over the next 20 or 30 years. If current or future impervious cover is expected to exceed 10% in the watershed, we strongly recommend that communities adopt more stringent treatment practices for new development. Table 6 summarizes the critical elements of a source water protection plan we recommend for water supply watersheds expected to exceed 10% impervious cover. These recommendations are based on results from the watershed population we surveyed; smaller systems may want to take a simpler approach. These recommendations are a general framework to integrate watershed management into source water protection plans, and should be modified for unique watershed conditions such as unfiltered supplies, lake geometry, and amount of impervious cover.

Table 6. Elements of a Source Water Protection Plan for Urban Surface Water Supplies	
Watershed Protection Tool	**More Than 10% Watershed Imperviousness**
Watershed Planning, Management and Zoning	Adopt a comprehensive watershed plan that can provide consistent implementation across all jurisdictions Establish an ongoing watershed management structure Update land use and development trend analysis track land use and impervious cover every four years. Designate a watershed manager for the reservoir Create a reservoir protection overlay district and/or ordinance (see Cappiella and Schueler, this issue) Exclude or restrict pollutant hotspots (i.e industry, WWTP, and land fills) Establish maximum level of watershed development/impervious cover
Land Conservation	Prioritize land acquisition to critical water supply protection areas (i.e. corridors, streams, and intakes) Maintain rural land through conservation easements
Shoreline and Tributary Buffers	Require, or acquire, wide shoreline (minimum 300 ft) and tributary (minimum 125 ft.) buffers Maintain natural shoreline vegetation and establish allowable uses
Better Site Design	Set impervious cover caps for individual zoning categories Allow cluster design for residential subdivisions to conserve open space
Erosion and Sediment Control	Make inspection and enforcement efforts more stringent for construction sites
Stormwater Treatment Practices	Size and design stormwater treatment practices for maximum phosphorous removal Use environmentally-sensitive design on lake-front properties to minimize creation and concentration of stormwater runoff (see Cappiella and Schueler, this issue) Consider retrofitting existing development where necessary
Wastewater Management	Prohibit new WWTP discharges in watershed; require advanced tertiary treatment of existing discharges or pump out of watershed Enforce tighter regulations for septic system design, siting, and maintenance if non-sewered development allowed Perform regular surveys to identify failing septic systems Establish minimum 150 ft setbacks from tributaries Mandate regular clean out and inspection of septic systems
Watershed Stewardship	Expand monitoring efforts to include tributary monitoring and watershed land assessments Target education efforts towards relevant pollution prevention activities such as lawn care and contractor education for proper fertilizer and pesticide usage Establish a spill response contingency plan and tracking system for existing sources Restrict recreational activities and gas motorboats

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