Public Health Effects of Inadequately Managed Stormwater Runoff

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Objectives. This study investigated the scale of the public health risk from stormwater runoff caused by urbanization.

Methods. We compiled turbidity data for municipal treated drinking water as an indication of potential risk in selected US cities and compared estimated costs of waterborne disease and preventive measures.

Results. Turbidity levels in other US cities were similar to those linked to illnesses in Milwaukee, Wis, and Philadelphia, Pa. The estimated annual cost of waterborne illness is comparable to the long-term capital investment needed for improved drinking water treatment and stormwater management.

Conclusions. Although additional data on cost and effectiveness are needed, stormwater management to minimize runoff and associated pollution appears to make sense for protecting public health at the least cost. (*Am J Public Health.* 2003;93:1527–1533)

Residents in the United States generally can depend on safe water for drinking, food production, and recreation, thanks to effective water treatment and protective environmental policies. Despite these safeguards, waterborne illnesses are prevalent and may increase because of the strain of climate change, population growth, and changing land use.[1] Expansion of urban areas is creating more impervious surfaces, such as roofs, roads, and parking lots, that collect pathogens, metals, sediment, and chemical pollutants and quickly transmit them to receiving waters during rain and snowmelt events. This nonpoint source pollution is one of the major threats to water quality in the United States[2] and is linked to chronic and acute illnesses from exposure through drinking water, seafood, and contact recreation. Impervious surfaces also lead to pooling of stormwater, increasing potential breeding areas for mosquitoes, the disease vectors for dengue hemorrhagic fever, West Nile virus, and other infectious diseases.

Traditional strategies to manage stormwater and treat drinking water require large infrastructure investments and face difficult technical challenges. Reducing stormwater runoff and associated nonpoint source pollution is a potentially valuable component of an integrated strategy to protect public health at the least cost.

WATERBORNE DISEASE

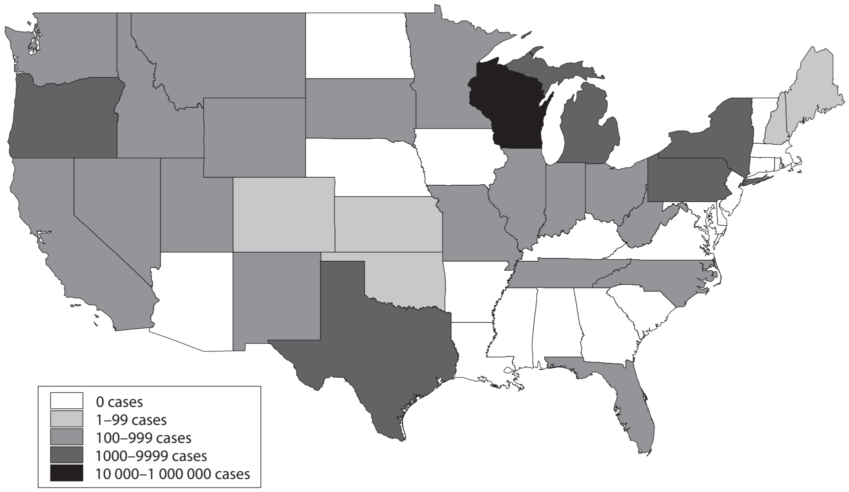
Acute illnesses can result from consuming water contaminated with protozoan oocysts, viruses, and bacteria. Between 1991 and 2000, 123 documented outbreaks of waterborne illness in 30 states were linked to pathogens or involved acute gastrointestinal illnesses of unknown etiology (Figure 1).[3–7] Pathogens currently impair 5529 US water bodies (Figure 2) and are the second leading cause of impairment, following sediment.[8] Children, the elderly, pregnant women, and the immunocompromised—20% of the US population—are at the greatest risk for serious illness and mortality from waterborne pathogens.[9] Outbreaks of cryptosporidiosis in Milwaukee, Wis, in 1993 and Las Vegas, Nev, in 1994 caused at least 70 fatalities among the immunocompromised.[4,10–12]

It is widely recognized that the vast majority of waterborne disease cases go unreported because of difficulties in diagnosing the cause of illness. Approximately 99 million people in the United States have acute gastrointestinal illnesses each year, at a cost of billions of dollars,[13] and 6% to 40% of these illnesses may be caused by contaminated drinking water.[1,14,15] Exposure to *Cryptosporidium* is common; 17% to 32% of people tested have evidence of infection by young adulthood.[16]

Drinking water outbreaks have been linked to runoff; more than half of the documented waterborne disease outbreaks since 1948 have followed extreme rainfalls.[17] Spring rains and snowmelt preceded the Milwaukee *Cryptosporidium* outbreak and may have played a role in transport of the oocysts.[6] Urban and suburban streets, parking lots, and lawns generate large loads of bacteria in stormwater,[18–20] and urban runoff is responsible for an estimated 47% of the pathogen contamination of Long Island Sound.[21] Stormwater drainage pipelines and channels accumulate sediment and block sunlight, inhibiting natural bacteria die-off and creating a bacterial reservoir,[22,23] and combined storm and sanitary sewer systems discharge untreated sewage into receiving waters when runoff volumes overwhelm their treatment capacity.

Inflows of runoff to surface water bodies, indicated by increased turbidity from suspended soil particles eroded from the landscape, are associated with elevated concentrations of bacteria, *Giardia*, *Cryptosporidium*, and other microorganisms.[24,25] Small increases in the turbidity of treated drinking water have been linked to increased occurrence of acute gastrointestinal illnesses among children and the elderly in Milwaukee and Philadelphia, Pa, even though the water is in compliance with Environmental Protection Agency standards.[26–28]

Fecal coliform bacteria in surface waters commonly exceed standards for recreation,[29] and exposure to bacteria and parasites from swimming and other forms of recreation in water contaminated with urban runoff has caused numerous cases of illness, including ear and eye discharges, skin rashes, and gastrointestinal problems.[30–32] Consumption of seafood from contaminated waters is linked to diarrheal and paralytic illnesses caused by the hepatitis A and Norwalk viruses, *Vibrio* species, and marine biotoxins formed by algal blooms.[31,33–36] Excess nitrogen from urban



Note. Wisconsin reported the maximum number of cases, with 403 000 caused by the cryptosporidiosis outbreak of 1993.
Source. Compiled from Centers for Disease Control and Prevention data.[3–7]

FIGURE 1—Reported waterborne illnesses linked to pathogens or involving gastrointestinal illnesses of unknown etiology, 1991–2000.

and agricultural sources exacerbates harmful algal blooms.[37] Major sources of nitrogen from urban and suburban areas may include fertilizers carried by stormwater, vehicle exhaust, and septic systems.[38,39]

Nitrogen also poses direct health threats. Exposure to nitrate in drinking water increases the risk of methemoglobinemia, causing shortness of breath and blueness of the skin, especially for infants.[40,41] Consumption of water with elevated nitrate is also suspected to increase miscarriage risk.[42]

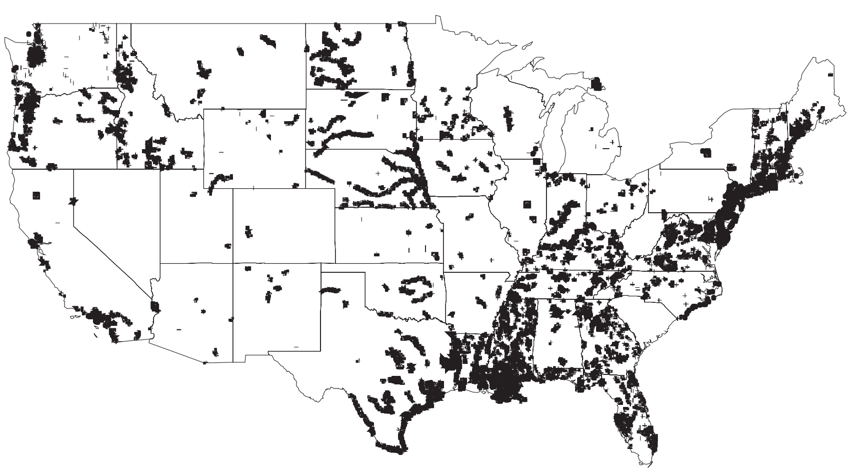
Various pollutants are commonly found in urban and suburban stormwater. Runoff from roofs, roads, and parking lots can contain significant concentrations of copper, zinc, and lead,[19,38] which can have toxic effects in humans. Insecticides occur widely in sediment and fish in urban streams at levels considered harmful to wildlife,[43] raising concerns about carcinogenic effects and disruption of hormonal systems in humans.[44] Increased traffic volume in recent decades has resulted in higher concentrations of polyaromatic hydrocarbons—known human carcinogens—in urban lake sediments, with concentrations commonly exceeding levels set to protect aquatic ecosystems.[45]

DRINKING WATER TREATMENT

Community drinking water supplies are commonly disinfected with chlorine and, if the source is surface water, filtered to remove sediment and associated pollutants. Several common microorganisms, including *Cryptosporidium*, are resistant to treatment with chlorine and filtration,[46] although the effectiveness of filters varies with their pore size. Suspended sediment in source waters further reduces the effectiveness of chlorine. A 1995 study found that 13% of the samples of drinking water filtered and treated with chlorine still contained *Cryptosporidium* oocysts.[47] Ozone is increasingly being used for disinfection instead of or in addition to chlorine. High ozone doses can inactivate *Giardia* and *Cryptosporidium*; however, neutralizing the ozone after treatment presents technical difficulties, and addition of ozone to water containing bromide can form bromate, a potential human carcinogen.[48]

The need for disinfection must be weighed against growing evidence of carcinogenic and other health effects related to disinfection byproducts. Trihalomethanes and other disinfection byproducts form when chlorine reacts with organic carbon associated with sediment or produced by algal and bacterial growth, which can be enhanced by nitrogen and phosphorous in runoff.[49] The Environmental Protection Agency estimates that ingestion of disinfection byproducts in drinking water leads to 1100 to 9300 cases of bladder cancer each year,[50] and trihalomethanes are linked to neural tube defects, small size for gestational age, and spontaneous abortions.[51]

Approximately 42 million people in rural and suburban areas use their own private water supplies, typically shallow groundwater wells that are not covered by the Safe Drink-



Source. Compiled from US Environmental Protection Agency data.[8]

FIGURE 2—Pathogen-impaired water bodies, 1998–2000.

ing Water Act and are rarely treated or monitored.[52] Concerns include cross-contamination from runoff and surface water and contamination by nitrates and pathogens from septic systems.

EFFECTS OF COMMUNITY DESIGN

Community design has a major effect on stormwater volumes and quality, as well as treatment methods and costs. The total area of impervious surfaces in a community is 1 of the most common measures used to assess the effects of community design on stormwater runoff.[53] Also important is the degree of connection between impervious surfaces and the storm drainage system; surfaces that drain directly to vegetated areas produce less runoff and are considered to have a lower effective impervious area.

Urbanization of the landscape adds to strain on water resources by expanding the area covered by impervious surfaces that shed virtually all rainfall and snowmelt. Hydrologic models predict large increases in runoff for urbanizing areas,[54,55] with runoff volume increasing linearly with impervious surface area.[56] Long-term stream-flow monitoring has shown that development leads to higher flood peaks[57] and to increases in annual runoff volumes of 2 to 4 times previous levels for suburban areas and 15 times previous levels for highly urban areas.[58,59]

Increased runoff volume generates greater pollutant loads.[60] In response to an 18% increase in urban area in a watershed near Indianapolis, Ind, between 1973 and 1991, annual average runoff volume increased by 80%, and average annual loads for lead, copper, and zinc increased by more than 50%.[61] High proportions of urban land cover and steep slopes—predictors of high runoff volumes—correspond with high fecal coliform levels in South Carolina watersheds.[62] Elevated fecal coliform levels also have been detected in suburban streams.[63]

Although low-density development with large lawns leads to a low proportion of impervious cover within individual lots, the total impervious surface area of low-density residential and commercial developments, on the regional scale, is typically much larger than that of higher-density developments.[64,65] This high proportion of impervious surface area is largely a result of roads and parking lots, which can account for more than 60% of a low-density development's impervious area.[66] Although large lawns might seem capable of absorbing runoff from adjacent surfaces, they are typically compacted by construction equipment and can generate up to 90% as much runoff as pavement.[67,68] Runoff measured from suburban developments has been shown to be 1.5 to 4 times greater than that from rural areas,[69,70] although low-density development may produce less runoff than do some intensive agricultural land uses.[71]

Moreover, construction of low-density developments disturbs the soil over larger land areas, accelerating transport of sediment and associated pollutants into water bodies. Stripping the protective vegetation cover from construction sites accelerates soil erosion to a rate up to 40 000 times higher than before the soil was disturbed.[72] During brief periods of active construction, sediment yield from watersheds can increase 5-fold, with additional deposition in stream channels providing a continual sediment source during subsequent storms.[73] This accumulated sediment can harbor large populations of bacteria and other pathogens.[74]

There is widespread concern that increased runoff from impervious surfaces contributes to the depletion of groundwater aquifers. Unfortunately, few detailed studies of urban groundwater recharge have been performed to evaluate this concern. Leaks from aging water distribution networks and infiltration in stormwater ponds and channels may add appreciably to aquifer recharge.[75] However, infiltration ponds have a high failure rate because of fine sediment that settles to the bottom and forms a hydraulic barrier,[76] and improvements in construction materials for water pipelines probably lead to reduced leakage in new developments.[77] Nearly half of the US population drinks groundwater from wells,[52] and widespread drops in groundwater levels have contributed to water quality problems, including increased arsenic concentrations.[78]

METHODS

Because turbidity is an indicator of runoff and was associated with increased illness in Milwaukee and Philadelphia,[26–28] we compiled turbidity data for treated drinking water of selected cities in 2001 for comparison. We obtained this information from annual consumer confidence reports published by each water utility. Many of these systems reported turbidity values for water mixed from multiple sources and treatment facilities.

An important consideration in deciding how to address waterborne illness is the cost associated with different options. Unfortunately, available data are inadequate to fully assess these costs. In this article, we present estimates of some of the costs associated with (1) managing current levels of waterborne illness, (2) improving drinking water treatment, and (3) improving stormwater management. Although incomplete, such estimates illustrate the magnitude of these costs and underscore important unanswered questions.

We estimated the annual cost of gastrointestinal illnesses related to drinking water by multiplying the estimated cost of all infectious gastrointestinal illnesses for 1985[13] by the fraction of these illnesses (6%–40%) attributed to drinking water in the literature.[1] Cost estimates for drinking water treatment and stormwater management were taken from Environmental Protection Agency surveys of 20-year capital investment needs.[79,80] We did not extrapolate the annual cost of illness over the same 20-year period, because this estimate was based on data from only 1 year. All costs were converted to 2002 dollars.

RESULTS

Table 1 lists annual minimum, mean, and maximum turbidity values based on daily samples of treated drinking water for selected cities. All of these systems were in compliance with the Environmental Protection Agency requirements in effect at that time that no sample exceed a turbidity of 5 nephelometric turbidity units and that no more than 5% of daily samples show turbidity greater than 0.5 nephelometric turbidity unit. In 2002, these standards were reduced to 1 nephelometric turbidity unit and 0.3 nephelometric turbidity unit, respectively.

The low and high estimates of the annual cost of gastrointestinal illnesses related to drinking water (Table 2) differ by nearly a

TABLE 1—Turbidity Values for Treated Drinking Water Reported by Selected Cities for 2001

	Drinking Water Turbidity (NTU)		
City/Treatment System	Minimum	Maximum	Mean
Ann Arbor, Mich	NR	0.2	NR
Atlanta, Ga	NR	>0.5	NR
Austin, Tex	0.01	0.34	0.08
Baltimore, Md			
Ashburton filtration plant	NR	0.39	NR
Montebello filtration plants	NR	0.41	NR
Chicago, Ill	NR	NR	0.34
Corvallis, Ore	0.02	0.08	0.04
Dallas, Tex	0.04	0.2	0.08
Denver, Colo			
Marston filtration plant	<0.05	0.07	0.04
Foothills filtration plant	0.04	0.05	0.04
Moffat filtration plant	0.04	0.07	0.05
Detroit, Mich	NR	0.48	NR
Houston, Tex, main system	<0.01	0.5	0.07
Los Angeles, Calif			
Los Angeles Aqueduct filtration plant	0.1	0.37	0.12
Diemer filtration plant	0.05	0.07	0.06
Weymouth filtration plant	0.06	0.08	0.07
Milwaukee, Wis	0.06	0.23	0.08
New York, NY			
Catskill–Delaware system	0.8	1.7	1.1
Croton system	1.3	1.6	1.4
Philadelphia, Pa	NR	0.08	0.06
Seattle, Wash			
Cedar system	0.3	3.9	0.8
Tolt system	0.04	0.3	0.07
Washington, DC	NR	0.19	NR

Note. NTU = nephelometric turbidity unit; NR = not reported.

TABLE 2—Comparison of Costs of Options for Addressing Waterborne Illness

Option	Estimate	Cost, in Billions of 2002 Dollars	Source
Continue to manage waterborne illnesses	Annual cost of waterborne gastrointestinal illnesses	2.1–13.8[a]	Estimate of total cost of endemic gastrointestinal illness in 1985[13] and range of these illnesses attributed to drinking water[1]
Improve drinking water treatment	20-year capital needs to meet current and proposed drinking water standards	33.0[b]	1999 Drinking Water Infrastructure Needs Survey[79]; "regulatory needs" for compliance with current and future regulations
Improve stormwater management	20-year capital needs for runoff control	9.3[c]	1996 Clean Water Needs Survey[80]; categories VI (stormwater) and VIID (urban runoff)

[a]Adjusted for inflation by multiplying by factor of 1.50.
[b]Adjusted for inflation by multiplying by factor of 1.06.
[c]Adjusted for inflation by multiplying by factor of 1.11.

factor of 10 because of uncertainty in identifying the cause of illness. These estimates do not include other acute effects, chronic illnesses, or illnesses related to recreation or consumption of contaminated seafood or produce. The higher estimate is comparable to the 20-year capital costs for enhanced drinking water treatment and stormwater management. Operation and maintenance over the 20-year period are not included in these estimates; however, a reasonable assumption is that these costs will be similar to the capital investment.[81,82]

DISCUSSION

Although it is highly likely that Figure 1 greatly underestimates the burden of disease caused by waterborne pathogens, it does indicate widespread occurrence of such disease. Because of underreporting issues and the poor geographic resolution of the state-level illness data, it is difficult to directly compare Figures 1 and 2.

The turbidity of drinking water in many US cities (Table 1) is similar to the level of turbidity linked to illnesses in Milwaukee and Philadelphia (where the mean turbidity was <0.2 nephelometric turbidity unit).[26–28] Although these data alone are insufficient to define the level of risk, they underscore the need for additional research into the complex relations between turbidity, pathogen loads, drinking water treatment, and illness. Assessment of risk and early warning of contamination would be greatly aided by more rapid and accurate testing methods for microbiological contaminants.[83]

Given the limited information in Table 2, the costs of drinking water treatment and stormwater management appear reasonable compared with the burden of waterborne illness. The economic benefits of drinking water treatment have been established previously.[84] Better data regarding the cost and effectiveness of stormwater management options as well as on the true cost of waterborne illness are needed to make fully informed decisions.

Conventional urban stormwater management requires a large investment in infrastructure. For example, the Milwaukee Metropolitan Sewage District has reduced, but not eliminated, combined sewer overflows since 1994 by spending $716 million to construct a tunnel to store excess stormwater during runoff events, allowing it to be treated later.[85] Consequently, it makes sense to use alternative strategies that reduce the volume and improve the quality of stormwater. Planning on the regional scale that integrates community design and watershed function can reduce stormwater volumes and effects. On the local scale, further reduction can be achieved through compact site design and best management practices that remove pollutants, detain stormwater, and reduce runoff volume by enhancing infiltration into the soil.

Watershed planning strategies that effectively protect water quality include maintaining vegetated buffer strips and setback distances of at least 150 m for impervious areas along water bodies[63,86] and preserving forests and other highly pervious land covers.[87] New York City has chosen to spend $1.4 billion over 10 years as part of a strategy to protect its Catskill–Delaware water supply by purchasing land as a buffer against development, thus avoiding the need for a filtration plant that would cost $6 billion to construct and would have an annual operating cost of $300 million.[88,89]

Compact site designs include narrow streets, reduced parking requirements, mixed land uses, increased residential densities, and open space. The city of Olympia, Wash, determined that a 20% reduction in impervious area would not require exceptional changes.[66] A stormwater ordinance passed by the city of Columbus, Ohio, includes reducing street widths and commercial parking to minimize impervious surfaces and enhance open space.[90] Runoff simulations of proposed community designs suggest that a compact development with significant open space may generate only half the increased stormwater volume generated by a conventional, large-lot development.[91]

Best management practices can reduce but not eliminate pollutant loadings of common stormwater pollutants. Designs that collect runoff and allow it to infiltrate the soil have the highest documented pollutant-removal efficiency, eliminating nearly all lead, zinc, and solids and more than 50% of total nitrogen and phosphorus. Ponds and wetlands, which allow contaminants to settle out of the water column or be broken down by sunlight and biological activity, can remove more than 70% of bacteria but are less effective for other pollutants. Drainage ditches and swales appear to have very limited pollutant-removal capabilities.[92] Pollutant modeling indicates that street sweeping once a week on highways and every 3 days in residential areas removes 10% to 60% of solids and nutrients.[93] Modern street sweepers that use vacuum systems may result in higher and more consistent pollutant-removal effectiveness, although potential negative side effects, such as air and noise pollution, also must be considered. Managing urban pet and wildlife waste may reduce pathogen loads, although more research on parasite and bacteria infection rates in animals is needed.[83]

Low-impact development techniques are gaining popularity for supplementing traditional best management practices and reducing infrastructure needs. Low-impact development measures route runoff from impervious surfaces to natural or constructed features where it can infiltrate the soil. Connecting roof drains to a yard, garden, or infiltration trench can double the amount of precipitation that infiltrates the soil.[94] Diverting roof downspouts from sanitary sewers to yards in a Michigan community reduced storm flows in sewers by 25% to 62%, resulting in cost savings that matched the cost of the conversion in only 2 months.[95] Buildings with green roofs (roofs covered with soil and live vegetation to absorb precipitation) have been used for years in Europe and have been successfully constructed in the United States.

Protecting public health by reducing urban stormwater runoff and associated nonpoint source pollution makes sense as a complement to water treatment infrastructure and health care interventions. In fact, stormwater management needs to be integrated into a comprehensive water management scheme that addresses water supply and sewage treatment. We believe that such integrated programs are necessary to adequately protect public health at the lowest cost. ■

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Contributors

S.J. Gaffield led the design and implementation of the study and the writing of the article. R.L. Goo helped to conceptualize ideas, plan the analysis, and write the article. L.A. Richards assisted with the literature review, study design, and writing of the article. R.J. Jackson conceived of this article and assisted with planning and writing.

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Human Participant Protection

No human participants were involved in this study.

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