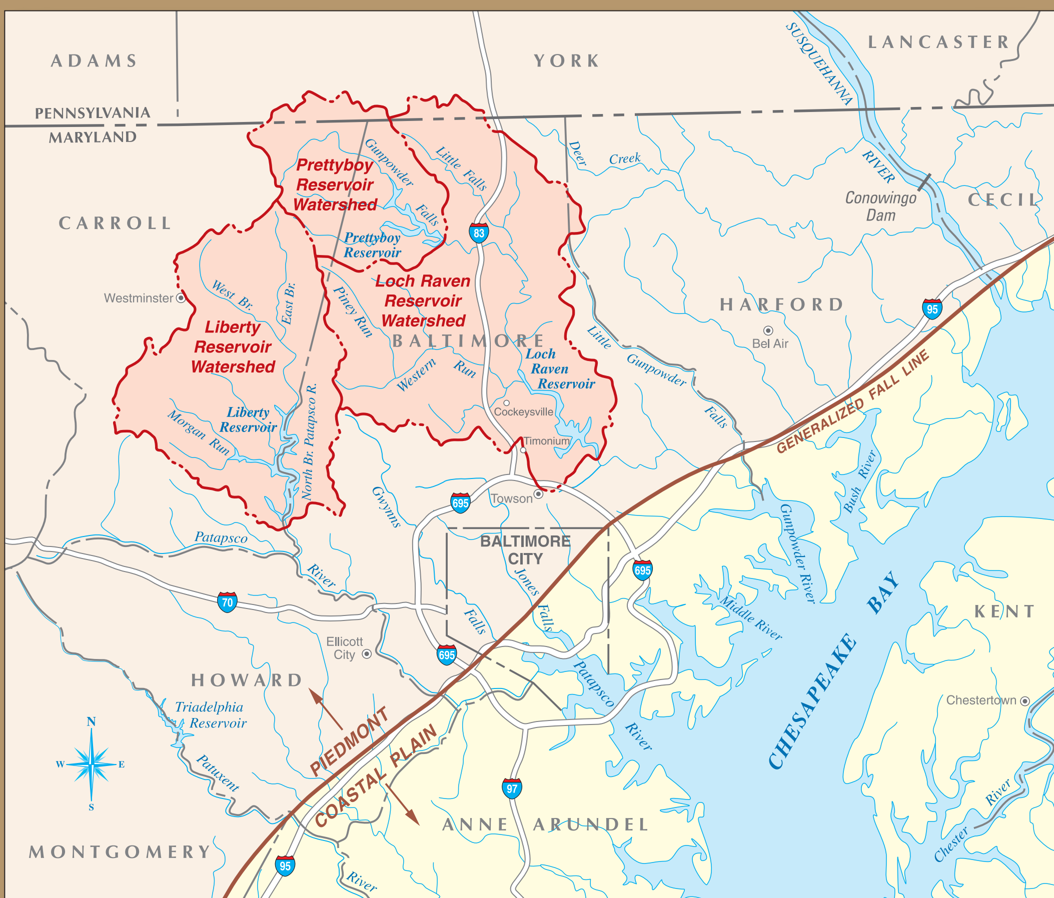
Prepared in cooperation with the
City of Baltimore, Baltimore County, and Carroll County, Maryland

The Water-Quality Monitoring Program for the Baltimore Reservoir System, 1981–2007—Description, Review and Evaluation, and Framework Integration for Enhanced Monitoring



Scientific Investigations Report 2011–5101

U.S. Department of the Interior
U.S. Geological Survey

Cover. Map showing location of reservoirs and watersheds of the City of Baltimore, Maryland.

The Water-Quality Monitoring Program for the Baltimore Reservoir System, 1981–2007—Description, Review and Evaluation, and Framework Integration for Enhanced Monitoring

By Michael T. Koterba, Marcus C. Waldron, and Tamara E.C. Kraus

Prepared in cooperation with the
City of Baltimore, Baltimore County, and Carroll County, Maryland

Scientific Investigations Report 2011–5101

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Koterba, M.T., Waldron, M.C., and Kraus, T.E.C., 2011, The water-quality monitoring program for the Baltimore reservoir system, 1981–2007—Description, review and evaluation, and framework integration for enhanced monitoring: U.S. Geological Survey Scientific Investigations Report 2011–5101, 133 p.

ISBN 978-1-4113-3170-9

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons (Ggal)	3,785,000	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day per square mile [(Mgal/d)/mi^2]	1,461	cubic meter per day per square kilometer [(m^3/d)/km^2]
billion gallons per day (Ggal/d)	43.81	cubic meter per second (m^3/s)
billion gallons per day per square mile [(Ggal/d)/mi^2]	1,461,000	cubic meter per day per square kilometer [(m^3/d)/km^2]
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Specific conductance (conductivity) is given in micromhos per centimeter (micromhos/cm).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water year for surface-water supply is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends and includes 9 of the 12 months.

Abbreviations

α	Accepted statistical significance level
BMC	Baltimore Metropolitan Council
BMP	Best Management Practice
CWA	Clean Water Act
DBP	Disinfection by-product
DPW	Department of Public Works, Baltimore, Maryland
DEPRM	Baltimore County Department of Environmental Protection and Sustainability (formerly Resource Management)
HAA	Haloacetic acid
ICPRB	Interstate Commission on the Potomac River Basin
MDE	Maryland Department of the Environment
NPDES	National Pollution Elimination Discharge System
p	Statistical power of test
RTG	Reservoir Technical Group
SDWA	Safe Drinking Water Act
SRBC	Susquehanna River Basin Commission
THM	Trihalomethane
RWMA	Reservoir Watershed Management Agreement
RWPC	Reservoir Watershed Protection Committee (earlier version of RTG)
RWPS	Reservoir Watershed Protection Subcommittee (earlier version of RWPC)
USEPA	U.S. Environmental Protection Agency
WWTP	Waste Water Treatment Plants

The Water-Quality Monitoring Program for the Baltimore Reservoir System, 1981–2007—Description, Review and Evaluation, and Framework Integration for Enhanced Monitoring

By Michael T. Koterba, Marcus C. Waldron, and Tamara E.C. Kraus

Abstract

The City of Baltimore, Maryland, and parts of five surrounding counties obtain their water from Loch Raven and Liberty Reservoirs. A third reservoir, Prettyboy, is used to resupply Loch Raven Reservoir. Management of the watershed conditions for each reservoir is a shared responsibility by agreement among City, County, and State jurisdictions. The most recent (2005) Baltimore Reservoir Watershed Management Agreement (RWMA) called for continued and improved water-quality monitoring in the reservoirs and selected watershed tributaries. The U.S. Geological Survey (USGS) conducted a retrospective review of the effectiveness of monitoring data obtained and analyzed by the RWMA jurisdictions from 1981 through 2007 to help identify possible improvements in the monitoring program to address RWMA water-quality concerns.

Long-term water-quality concerns include eutrophication and sedimentation in the reservoirs, and elevated concentrations of (a) nutrients (nitrogen and phosphorus) being transported from the major tributaries to the reservoirs, (b) iron and manganese released from reservoir bed sediments during periods of deep-water anoxia, (c) mercury in higher trophic order game fish in the reservoirs, and (d) bacteria in selected reservoir watershed tributaries. Emerging concerns include elevated concentrations of sodium, chloride, and disinfection by-products (DBPs) in the drinking water from both supply reservoirs. Climate change and variability also could be emerging concerns, affecting seasonal patterns, annual trends, and drought occurrence, which historically have led to declines in reservoir water quality.

Monitoring data increasingly have been used to support the development of water-quality models. The most recent (2006) modeling helped establish an annual sediment Total Maximum Daily Load to Loch Raven Reservoir, and instantaneous and 30-day moving average water-quality endpoints for chlorophyll-*a* (chl-*a*) and dissolved oxygen (DO) in Loch Raven and Prettyboy Reservoirs. Modelers cited limitations in data, including too few years with sufficient stormflow data, and (or) a lack of (readily available) data, for selected tributary and reservoir hydrodynamic, water-quality, and biotic conditions. Reservoir monitoring also is too infrequent to adequately address the above water-quality endpoints.

Monitoring data also have been effectively used to generally describe trophic states, changes in trophic state or conditions related to trophic state, and in selected cases, trends in water-quality or biotic parameters that reflect RWMA water-quality concerns. Limitations occur in the collection, aggregation, analyses, and (or) archival of monitoring data in relation to most RWMA water-quality concerns.

Trophic, including eutrophic, conditions have been broadly described for each reservoir in terms of phytoplankton production, and variations in production related to typical seasonal patterns in the concentration of DO, and hypoxic to anoxic conditions, where the latter have led to elevated concentrations of iron and manganese in reservoir and supply waters. Trend analyses for the period 1981–2004 have shown apparent declines in production (algal counts and possibly chl-*a*). The low frequency of phytoplankton data collection (monthly or bimonthly, depending on the reservoir), however, limits the development of a model to quantitatively describe and relate temporal variations in phytoplankton production including seasonal succession to changes in trophic states or other reservoir water-quality or biotic conditions.

Extensive monitoring for nutrients, which, in excessive amounts, cause eutrophic conditions, has been conducted in the watershed tributaries and reservoirs. Data analyses (1980–90s) have (a) identified seasonal patterns in concentrations, (b) characterized loads from (non)point sources, and (c) shown that different seasonal patterns and trends in nutrient concentrations occur between watershed tributaries and downstream reservoirs. A lack of data for total nitrogen and (or) available phosphorus limits direct comparisons of temporal or spatial variations in nutrient availability (comparable forms or ratios) between watershed tributaries and reservoirs.

Eutrophic conditions in the shallow water layer (30 feet in depth or less) in each reservoir have been assessed with four Carlson Trophic State Indices (TSIs)—derived from concentrations of chl-*a*, total phosphorus (TP), or DO, and (Secchi disc) transparency data. The frequency of eutrophic conditions for the entire period from 1982–2000 differed within each reservoir, and among the reservoirs, depending on which TSI index was used. The use of each index to compare trophic conditions among the reservoirs, however, possibly is biased because of the manner by which TSI data were collected, aggregated, or analyzed. In addition, no analyses of these indices were encountered that assessed possible trends in the frequency of eutrophic or mesotrophic conditions during this period.

Analyses of suspended-sediment data (1982–mid-90s) indicate that tributary concentrations and loads varied markedly within a year, and from year to year, but were clearly highest in wet years. Most sediment is carried by storm- as opposed to dry-weather (low) flow. Sediment transport has reduced reservoir capacity by 3 to 11 percent, and remains the major source of the TP load to the reservoirs. The role of this sediment as a source of available phosphorus (unmeasured) for phytoplankton production, however, has not been adequately addressed.

Manganese and iron are frequently monitored in water-supply intake waters during reservoir stratification and initial turnover. Elevated concentrations of these metals often occur at the supply intakes following their release from reservoir bed sediments under anoxic conditions, which can result from the decomposition of algal bloom residues. Monitoring in the reservoirs is too infrequent (monthly to bimonthly) to provide sufficient advanced warning of their occurrence at the intakes.

Elevated concentrations of mercury in game fish in the reservoirs are considered the end result of atmospheric deposition and beyond the control of RWMA jurisdictions. The submergence of terrestrial plants established on reservoir bed sediments exposed during droughts could enhance methylmercury production and biological uptake during reservoir recovery. However, this cannot be determined by conventional synoptic monitoring for mercury in game fish.

Fecal coliform bacteria have occurred at elevated counts in selected reservoir watershed tributaries, but counts in supply-reservoir intake waters consistently have been below the State recreational water-contact standard. Depending on results from synoptic surveys conducted by RWMA jurisdictions in the watersheds, the State could require routine monitoring of bacteria in the tributaries.

Among emerging concerns, trihalomethanes (THMs) and haloacetic acids (HAAs) are DBPs created by chlorination that are present in the drinking-water distribution systems of both supply reservoirs. Analysis of DBP data (2003–08) by the USGS indicates that the total concentrations of THMs and HAAs could exceed Federal standards under a pending rule change on approximately 19 percent and 40 percent of the sampling dates, respectively, at one or more monitoring stations in each water-distribution system. THM concentrations in drinking water varied seasonally, whereas HAA concentrations did not. There was little correlation between total concentrations of THMs and HAAs at a given monitoring station, or between monitoring-station concentrations of either DBP and total organic carbon (TOC) in intake waters. Monitoring of TOC alone will not identify intake waters associated with high concentrations of DBPs after chlorination.

In 2003, sodium and chloride concentrations at supply intakes were three-to-four-times greater than in the 1970s. Concentrations generally peaked during the winter months. Watershed and reservoir monitoring do not include the collection of sodium data. Monitoring also is too infrequent to provide either advanced warning of elevated sodium and chloride concentrations at the supply-reservoir intakes, or timely information on reductions in their concentrations if management activities are implemented to reduce road-salt use—the suspected source of the recent increases.

Projected changes combined with the inherent variability in climate in the Mid-Atlantic region indicate more intense storms with heavy precipitation and more frequent drought conditions. These changes imply increases in storm-borne contaminants (nutrient, sediment, salt, and bacterial loads), which could adversely affect reservoir water quality, particularly during recovery from drought conditions. Monitoring of stormflow does not appear to be adequate to address climate change and variability.

The 2007 Baltimore Reservoir System monitoring program could be improved in three major areas: (a) the monitoring design framework, (b) the temporal and spatial resolution of water-quality assessments in the major tributaries and reservoirs, and (c) the management and archival of data. Improvements in the framework design could include adoption of a quantitative phytoplankton model, such as the Phytoplankton Ecology Group model. Such models describe intra-seasonal, seasonal, and annual variations in phytoplankton abundance and succession. The model data can be analyzed in relation to temporal variations in nutrients or TSIs. The characterization of these biotic and water-quality conditions could be evaluated in relation to temporal variations in climate by the collection of climatic and water-quality data that reflect the full range in tributary flows and reservoir hydrodynamics within a year and from year to year. The minimal monitoring data would include daily temperature (mean), daily precipitation (total and type), continuous or partial records of streamflows depending on the type of tributary monitoring station, and daily water levels, withdrawals, and releases from each reservoir. To aid in this evaluation, the monitoring framework could incorporate the routine use of statistical and modeling methods to help define, aggregate, analyze, and interpret data.

Improvements in spatial and temporal assessments of water-quality conditions could be realized with two major and selected minor modifications to historical monitoring. First, to quantify water-quality conditions for the full range in tributary flows in the reservoir watersheds, sampling could include 3 to 15 pre-defined high (or storm-) flows per year at each of seven stations—three historical stations in each of the two supply reservoirs and one new station on a tributary to Prettyboy Reservoir. Pre-defined base-flow conditions could be sampled at each station on a monthly fixed time interval. Second, two fixed-station continuous monitors could be established in each reservoir to provide daily 5-foot-depth-increment profiles for selected parameters—water temperature, DO, pH, specific conductance, chl-*a*, turbidity, and depth of measurement. Data from these monitors could be transmitted to water-treatment staff to provide advanced warning of potential problems with supply intake waters.

A comprehensive quality-assurance program and plan (QAPP) with clear lines of responsibility could help ensure collection of the correct type and quality of data. The QAPP would include the following: (a) clear and concise definitions of the data and data-quality requirements for each water-quality concern; (b) field and laboratory methods and analytical procedures to obtain and provide the required data; (c) procedures to archive, clearly remark, and qualify data, including quality-assurance and control data; (d) procedures to routinely evaluate collected data in relation to data requirements; and (e) procedures to modify and document changes in field and laboratory methods.

Introduction

The City of Baltimore, Maryland (hereafter referred to as the City) supplies drinking water obtained from three reservoirs to approximately 1.8 million people in the City and parts of five Maryland Counties (Anne Arundel, Baltimore, Carroll, Harford, and Howard). Contributing watersheds to these reservoirs are primarily located outside the City in two Maryland counties (Baltimore and Carroll). The City is primarily responsible for managing and monitoring the reservoirs, monitoring in the major watershed tributaries, and assessing reservoir and major tributary conditions that affect the quality of drinking water. As the reservoir watersheds lie largely outside the jurisdiction of the City, however, managing and assessing reservoir-watershed conditions that could affect reservoir water quality is shared by City, County, and State governments. This shared responsibility is outlined in a voluntary Reservoir Watershed Management Agreement (RWMA) and related Reservoir Watershed Action Strategy (RWAS).

Implementation of the RWMA and RWAS involves the Baltimore Metropolitan Council (BMC), which provides staff for RWMA coordination. Management of the RWMA is conducted by a Watershed Protection Committee (WPC), which informs the BMC (Management Committee) of ongoing work. The WPC also provides policy guidance to a Reservoir Technical Group (RTG), and reviews their technical work. The RTG, a professional advisory body, is responsible for guiding day-to-day operations of the RWMA under the RWAS. It also provides technical advice, assistance, and recommendations to the WPC and RWMA signatories or their designees.

The most recent (2005) RWMA and RWAS reflect knowledge gained in part from routine water-quality monitoring in the reservoirs and selected reservoir watershed tributaries, which began in the early 1980s. The resulting monitoring data have served a wide range of purposes. For example, data routinely collected by drinking-water purveyors, primarily on raw water obtained through intakes in each water-supply reservoir, coupled with knowledge gained from their long-term monitoring and treatment of reservoir waters, helps guide daily decisions on which intakes to use to withdraw water from the reservoirs in order to provide suitable potable water at reduced costs. Data obtained from routine monitoring in the reservoirs are used for periodic assessments of reservoir water quality in relation to designated recreational uses (water-contact activities such as fishing and non-motorized boating, where permitted) and in relation to the general ecological health or trophic state of each reservoir. Routine monitoring in the reservoirs and selected watershed tributaries provides data to periodically characterize states, changes, or trends in water quality in the reservoirs and tributaries, and target management and restoration activities in the watersheds. Monitoring data also have aided in the development of watershed-reservoir models, which are used to guide management strategies to improve water quality in the watersheds tributaries and reservoirs.

As with most long-term monitoring efforts, the City and its RWMA partners recognize that the design and scope of the monitoring program require periodic evaluation. The purpose of this report is to aid the RWMA partners, and, in particular, the RTG, in an evaluation of the monitoring program as follows:

a) To describe the long-term and emerging monitoring-related RWMA water-quality concerns for the Baltimore reservoir system;

b) To evaluate the historical (1981–2007) and current (as of 2007) monitoring program in relation to its ability to provide suitable, relevant, and technically sound data to characterize water-quality conditions directly related to long-term and emerging water-quality concerns and in relation to expressed 2005 RWMA goals and action strategies; and

c) To provide a framework to identify continuing and additional monitoring that could enhance the ability of the RWMA partners to address specific water-quality concerns.

The scope of this report focuses on monitoring that was conducted either in the reservoirs or on selected major tributaries (subbasins) of the reservoir watersheds chiefly from the early 1980s (1981 or 1982, depending on the water-quality parameter) through 2007. The scope of this report also is a retrospective by nature, in that the review and evaluation are conducted mainly on the basis of an examination of dozens of historical investigative and technical reports produced through 2007, which discussed the production, analysis, or utilization of monitoring data, described findings, and possibly recommended modifications to improve the monitoring program.

The reports used in this retrospective review and evaluation were obtained during interviews and (or) by follow-up requests to agencies within or contracted under 2005 or past reservoir agreements and action strategies to provide data and (or) information relative to the Baltimore Reservoir Drinking-Water System. The reports include internal as well as published documents produced over several decades from a variety of agencies and organizations. As a result, the historical documents differed in the level of technical and scientific analysis, and in the manner and form in which monitoring data or interpretive analysis were reported and described (tables or figures). Limitations in the former are noted in this report where applicable. Modifications to the latter, where presented in this report for illustrative purposes, were minimal, and were used to improve visual quality and (or) maintain consistency in the names of reservoirs, reservoir watersheds, monitoring stations, or other place names used throughout this retrospective report.

Baltimore Drinking-Water Reservoir System

Drinking water for the City and all or parts of five Maryland counties is supplied by three surface-water reservoirs—Liberty, Loch Raven, and Prettyboy—and their contributing watersheds, which are entirely located in the Piedmont Physiographic Province in central Maryland (fig. 1). Water for consumptive use is withdrawn at intakes located in two of the reservoirs—Liberty and Loch Raven, which hereafter are collectively referred to as the water-supply reservoirs. The third reservoir, Prettyboy, is mainly used to provide additional storage and to re-supply the Loch Raven Reservoir. In addition, and generally during drought conditions, supplemental water supplies are obtained from the Susquehanna River upstream of Conowingo Dam, which is located approximately 45 mi (miles) northeast of the City (fig. 1).

Watershed and Reservoir Characteristics

Liberty Reservoir watershed covers 164 mi^2 (square miles; fig. 1, table 1), mainly in Carroll County and partly in Baltimore County, Maryland. Major land uses in the watershed are agriculture (43 percent), forest (32 percent), and developed land (22 percent; Maryland Department of Planning, 2000a; Winfield and Sakai, 2003). Agricultural lands are mainly cropland and pasture (37 percent and 6 percent, respectively). Developed lands include major transportation corridors and areas with predominantly industrial, commercial, and (or) residential infrastructure. Surface water to the reservoir is primarily supplied by the North Branch Patapsco River. Reservoir property covers 9,200 acres (table 1)—or 9 percent of the total watershed area—of which 3,100 acres is open water at reservoir capacity, estimated to be 37.7 Ggal (billion gallons) in 2001.

Loch Raven Reservoir watershed, excluding the Prettyboy Reservoir and watershed (fig. 1), covers 223 mi^2 (table 1), mostly in Baltimore and Carroll Counties, with small parts in Harford County, Maryland and York County, Pennsylvania. Major land uses are forest (38 percent), agriculture (27 percent), developed (21 percent), and mixed open (15 percent) (Maryland Department of Planning, 2000b; Maryland Department of the Environment, 2004a). Agricultural lands are mainly pasture and cropland (17 percent and 10 percent, respectively). Surface water to the reservoir is supplied primarily by the Gunpowder River. Reservoir property covers 8,000 acres—or 5.7 percent of the total watershed area—of which about 2,400 acres is open water at reservoir capacity, estimated to be 19.1 Ggal as of 1998.

Prettyboy Reservoir watershed covers 80 mi^2 (table 1), mostly in Baltimore and Carroll Counties in Maryland, with a small part in York County, Pennsylvania (fig. 1). Major land uses in the Maryland part of the watershed include agriculture (50 percent), forest (38 percent), and developed (13 percent) lands (Baltimore County Department of Environmental Protection and Resource Management, 2008). Agricultural lands are primarily cropland and pasture (39 percent and 11 percent, respectively). Surface water to the reservoir is supplied primarily by the Gunpowder River. Reservoir property covers 7,380 acres—or 14.3 percent of the total watershed area (table 1)—of which 1,500 acres is open water at reservoir capacity, estimated to be 18.4 Ggal in 1998.

Reservoir Watershed Management and Reservoir Operation

The City owns, and through its Department of Public Works (DPW), operates the three reservoirs to provide treated drinking water from the Liberty and Loch Raven water-supply reservoirs to approximately 1.8 million residents of the City and parts of five adjacent counties—Anne Arundel, Baltimore, Carroll, Harford, and Howard. Exclusive rights to surface water in the reservoirs and the Maryland part of their contributing watersheds have been granted to the City by the State legislature. However, only approximately 8 percent (table 1) of the total watershed area that drains into the three reservoirs actually is owned and under direct control of the City. Since the mid-1970s, the City DPW has been aided in its efforts to maintain the quality of water supplies by signatory City, County, and State organizations to a series of reservoir and watershed protection agreements and action strategies leading to the (2005) RWMA and RWAS.

The water-quality related goals of the 2005 RWMA for the program are as follows (Reservoir Watershed Management Agreement, 2005, p. 5–6):

a) To ensure the three reservoirs and their respective watersheds will continue to serve as:

1) Sources of high-quality raw water for the Baltimore metropolitan water-supply system; and

2) Areas where the surface waters will continue to support existing environmental, wildlife-habitat, and aesthetic purposes, as well as beneficial recreational uses.

b) To ensure that water quality in the three reservoirs and their tributaries consistently meet all applicable water-quality standards established by Federal and State regulations.

c) To ensure continued satisfactory water quality in the reservoirs themselves, by adopting the following specific technical goals:

1) Maintain existing water quality in the reservoirs and their tributaries, and reduce phosphorus, sediment, bacterial, sodium and chloride loadings to the reservoirs (and their tributaries) to acceptable levels[1], in order to:

(i) Eliminate existing, and prevent future, water-quality impairments, as defined under the Federal Clean Water Act (CWA), Section 303(d);

(ii) Prevent health and nuisance (taste and odor) conditions from developing in the treated water; and

(iii) Assist Baltimore City and Anne Arundel, Carroll, Harford, and Howard Counties (as water providers) to meet the Federal Safe Drinking Water Act (SDWA) requirements.

2) To improve the safety and security of the metropolitan water supply by reducing the risk of hazardous material contamination of the reservoir watersheds.

d) To commit program participants to promote certain types of land use and certain stewardship practices within the watershed that are intended to minimize the delivery of certain types of pollutants (including sediment and nutrients) to the three reservoirs.

The 2005 RWMA is accompanied by the 2005 RWAS (Reservoir Watershed Management Agreement Action Strategy, 2005). This strategy includes and encourages program participants to continue a multi-decadal effort to promote land use and stewardship practices within the watersheds that are intended to reduce the delivery of selected pollutants (for example, nutrients and sediment) to the reservoirs.

Whereas the 2005 RWMA and RWAS are designed primarily for management of the reservoir watersheds, the City manages and operates the reservoirs to provide drinking-water supplies. Drinking water from Liberty Reservoir is produced at the Ashburton treatment facility, and drinking water from Loch Raven Reservoir is produced at the Montebello treatment facility.

[1] "Acceptable" is not explicitly defined in the agreement, but can be considered guided by elements (i), (ii), and (iii).

Water levels in the three reservoirs vary seasonally in response to climatic conditions and withdrawals for supplies. Summer seasonal drawdowns in water levels are a normal part of reservoir operations; however, recovery from high demand or climate stresses is slow, particularly in the case of Liberty Reservoir. For example, it can take several months or more for the reservoirs to recover after a substantial decrease in water levels (Valcik, 1975; Winfield and Sakai, 2003). Therefore, variations in water levels guide daily management decisions on withdrawals from each water-supply reservoir and releases of water from Prettyboy Reservoir. To reduce the duration and extent of drawdown in any reservoir, and particularly in Liberty Reservoir, the City employs what is officially referred to as their "firming program," which represents the documented procedure that utilizes water levels to govern reservoir withdrawals (Loch Raven and Liberty Reservoirs) or releases (Prettyboy Reservoir) to meet supply demands (Winfield and Sakai, 2003). This term will be used hereafter in this report.

Under the firming program, and assuming that all reservoirs have sufficient reserves, withdrawals for drinking water generally are made from both Liberty and Loch Raven Reservoirs. Daily withdrawals are incrementally reduced from Liberty Reservoir, however, as a function of seasonal demand and its water levels. For example, during the period of highest demand (generally June through September) and assuming all reservoirs are near capacity, withdrawals from Liberty Reservoir are typically 160 Mgal/d (million gallons per day) or more. Withdrawals from this reservoir are incrementally reduced, however, when the water level near the intakes in the lower part of this reservoir falls below 415 ft (feet) to as little as 60 Mgal/d if the water level falls below 370 ft. Increased withdrawals from Loch Raven Reservoir are used to make up the shortfall in demand. If demands result in water levels falling below approximately 236 ft near the intakes in the lower part of Loch Raven Reservoir, water is released from Prettyboy Reservoir, which is approximately 18 mi upstream on the Gunpowder River, to resupply Loch Raven Reservoir. The DPW also can release water from Prettyboy Reservoir as necessary during warmer low-flow periods to help maintain the aquatic habitat for stocked trout along the Gunpowder River between the two reservoirs.

The primary goal of the City in withdrawing water from either water-supply reservoir is to obtain the highest quality of raw water in order to minimize treatment costs (Winfield and Sakai, 2003). This is achieved by withdrawing water from one or more vertical intakes located at different depths at gatehouses in the middle (Loch Raven Reservoir only) and (or) at the lower end of each water-supply reservoir. City staffs at each reservoir treatment facility generally decide which intake(s) to use to withdraw raw water, and, if multiple intakes are used, the mixing ratio of intake waters. Their decisions are guided by routine (daily-to-weekly) monitoring of intake waters coupled with knowledge obtained from the long-term monitoring and treatment of reservoir waters.

During extended dry periods, water demands could result in continued declines in water levels in all three reservoirs.

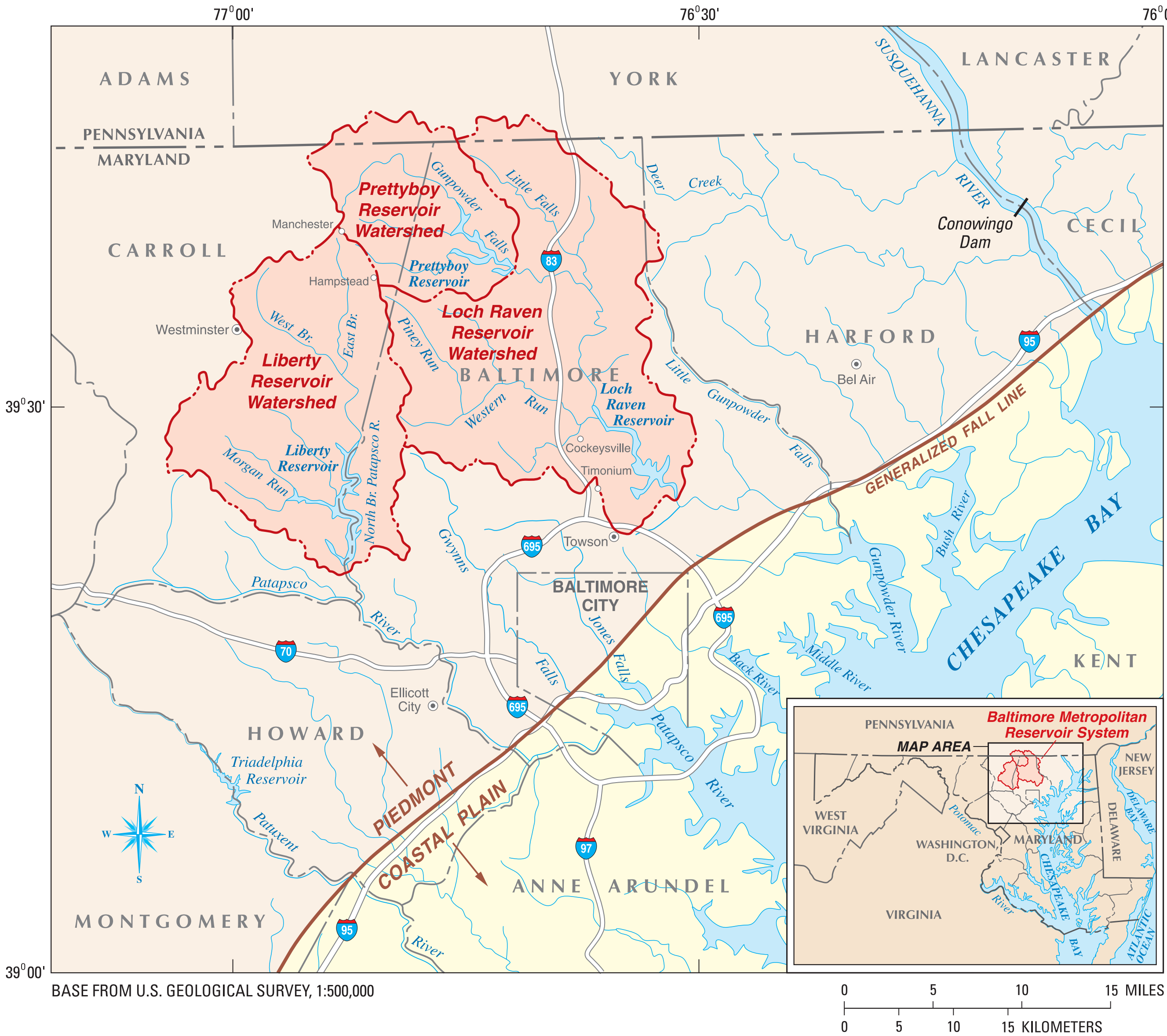


Figure 1. Location of reservoirs and watersheds for the City of Baltimore, Maryland (modified from Baltimore Reservoir Technical Group, 2004).

The firming program generally has been able to circumvent this problem. Under extended withdrawals from all three reservoirs, water is released from Prettyboy Reservoir until the reservoir is at 50 percent of its capacity, whereupon the City can exercise its option to obtain water from the Susquehanna River at the Conowingo Dam (fig.1). Under an agreement with the Susquehanna River Basin Commission (2006), and dependent upon river flows to the Conowingo Dam, the City is permitted to pump from 64 to 240 Mgal/d on the basis of a 30-day average. The drainage area of the Susquehanna River Basin is 27,510 mi^2 above the dam (Susquehanna River Basin Commission, 2006), therefore, the low-flow limitation on City withdrawals typically only becomes a factor under prolonged regional droughts.

Generally it is the quality of the Susquehanna River water, and the added costs to the City to obtain, pump (transport), and treat this water, that limit its use. For example, during a severe drought in 2001–02, the City was able to obtain water of reasonably good quality from the Susquehanna River to help meet demands; nevertheless, major withdrawals and drawdowns ultimately occurred in all three reservoirs. During and upon recovery in 2003, however, the quality of water in the Baltimore Reservoirs declined in relation to selected water-quality conditions relative to pre-drought conditions (Baltimore Reservoir Technical Group, 2004). During a recent but less severe drought and recovery in 2005–06, the City also chose to use water from the Susquehanna River, but soon after the drought began, rather than withdrawing water solely

Table 1. Reservoir and watershed characteristics for the City of Baltimore, Maryland, drinking-water supply system.

Reservoir/watershed	Characteristics[1]
Liberty	Area of watershed: 164 square miles
	Area of land owned by City: 9,200 acres or 14.4 square miles
	Storage capacity: Initial (1913) estimate, 40.0 billion gallons
	Storage capacity: Recent (2001) estimate, 37.7 billion gallons
	Length of shoreline at crest elevation: 82 miles
	Normal depth: 132.8 feet
	Flooded area at crest elevation: 3,106 acres
	Built: 1951–53, height 175 feet
Loch Raven	Area of watershed: 223 square miles (less Prettyboy watershed area)
	Area of land owned by City: 8,000 acres or 12.5 square miles
	Storage capacity: Initial (1913) estimate, 21.4 billion gallons
	Storage capacity: Recent (1997–98) estimate, 19.1 billion gallons
	Length of shoreline at crest elevation: 50 miles
	Normal depth: 76 feet
	Flooded area at crest elevation: 2,400 acres
	Built: 1912–14; crest raised: 1921–22, height 101 feet
Prettyboy	Area of watershed: 80 square miles
	Area of land owned by City: 7,380 acres or 11.4 square miles
	Storage capacity: Initial (1933) estimate, 19.9 billion gallons
	Storage capacity: Recent (1998) estimate, 18.4 billion gallons
	Length of shoreline at crest elevation: 46 miles
	Normal depth: 98.5 feet
	Flooded area at crest elevation 1,500 acres
	Built: 1933, height 155 feet

[1] Compiled from Ortt and others, 2000; Banks and LaMotte, 1999; Weisberg and others, 1985; and R. Ortt, Maryland Geological Survey, written commun., 2001.

from the reservoirs. The quality of river water in 2005–06 was notably poorer than the quality of river water in 2001–02, however, and use of this water was quickly discontinued (Michael Kohler, City of Baltimore, Department of Public Works, written commun., 2010).

As of 2007, the City firming program is under review (Michael Kohler, City of Baltimore, Department of Public Works, written commun., 2010). Decisions on when to begin reducing withdrawals from Liberty Reservoir, increase withdrawals from Loch Raven Reservoir, release water from Prettyboy Reservoir, or obtain water from the Conowingo Dam on the Susquehanna River, are still dependent upon the quality and available volumes of water. Comparing the costs to obtain, transport, and (or) treat each source of water for drinking water to provide the lowest-cost drinking water is becoming increasingly important to consider as part of the firming program. In addition, following the drought of 2001–02, the Susquehanna River Basin Commission (SRBC) initiated legal action to limit City withdrawals of water from the Conowingo Dam (Baltimore Reservoir Technical Group, 2004; Winfield and Sakai, 2003). The SRBC also is conducting an independent review of its basin management plan (Susquehanna River Basin Commission, 2006) because of increased demands for river water by upstream, in-lake, and downstream users, particularly during drought conditions.

Ultimately, how the City manages the reservoirs could possibly affect the quality of water in the reservoirs during their recovery following major droughts. During major droughts, the City maintains daily withdrawals of the best available quality of water for supplies to reduce treatment costs and limit consumer complaints about the quality of treated water. After recovery from droughts, there typically is a decline in the quality of reservoir waters, which could be exacerbated by the repeated removal of only the best available quality of water, as well as a considerable quantity of water, during drought conditions.