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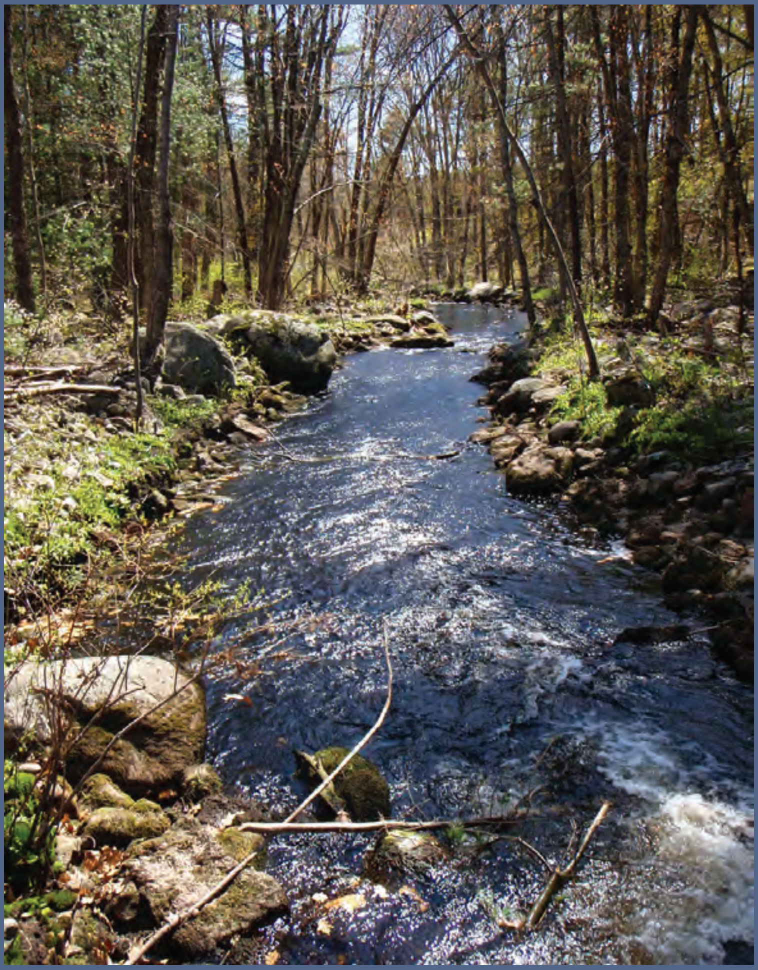
Massachusetts Department of Conservation and Recreation

Indicators of Streamflow Alteration, Habitat Fragmentation, Impervious Cover, and Water Quality for Massachusetts Stream Basins



Scientific Investigations Report 2009–5272
Version 1.8, Revised July 2, 2013

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

Cover. Photograph of Tarbell Brook near Winchendon, Massachusetts, looking downstream.

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By Peter K. Weiskel, Sara L. Brandt, Leslie A. DeSimone, Lance J. Ostiguy, and Stacey A. Archfield

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Conversion Factors, Datums, and Abbreviations

Inch/Pound to Standard International Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-feet (acre-ft)	1,233	cubic meters (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallons per day (gal/d)	3.785	liters per day (L/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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

$$°C=(°F–32)/1.8$$

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

$$°F=(1.8×°C)+32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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

One cubic foot per second (ft^3/s) is equivalent to 0.6465 million gallons per day (Mgal/d).

ABBREVIATIONS USED IN REPORT

AML	Arc Macro Language
CWA	Clean Water Act
DD	dam density
DEM	digital elevation model
GIS	geographic information system
HUC	Hydrologic Unit Code
IC	impervious cover
IHA	Indicators of Hydrologic Alteration
I/I	inflow and infiltration
MDCR	Massachusetts Department of Conservation and Recreation
MDEP	Massachusetts Department of Environmental Protection
MDFG	Massachusetts Department of Fish and Game
MWRA	Massachusetts Water Resources Authority
MWRC	Massachusetts Water Resources Commission
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NLCD	National Land Cover Dataset
NPDES	National Pollution Discharge Elimination System
RND	relative net demand
SR	storage ratio
SWQS	Surface Water Quality Standards
SYE	Sustainable Yield Estimator
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WBD	Watershed Boundary Dataset
WBS	Water Body System

Indicators of Streamflow Alteration, Habitat Fragmentation, Impervious Cover, and Water Quality for Massachusetts Stream Basins

By Peter K. Weiskel, Sara L. Brandt, Leslie A. DeSimone, Lance J. Ostiguy, and Stacey A. Archfield

Abstract

Massachusetts streams and stream basins have been subjected to a wide variety of human alterations since colonial times. These alterations include water withdrawals, treated wastewater discharges, construction of onsite septic systems and dams, forest clearing, and urbanization—all of which have the potential to affect streamflow regimes, water quality, and habitat integrity for fish and other aquatic biota. Indicators were developed to characterize these types of potential alteration for subbasins and groundwater contributing areas in Massachusetts.

The potential alteration of streamflow by the combined effects of withdrawals and discharges was assessed under two water-use scenarios. Water-use scenario 1 incorporated publicly reported groundwater withdrawals and discharges, direct withdrawals from and discharges to streams, and estimated domestic-well withdrawals and septic-system discharges. Surface-water-reservoir withdrawals were excluded from this scenario. Water-use scenario 2 incorporated all the types of withdrawal and discharge included in scenario 1 as well as withdrawals from surface-water reservoirs—all on a long-term, mean annual basis. All withdrawal and discharge data were previously reported to the State for the 2000–2004 period, except domestic-well withdrawals and septic-system discharges, which were estimated for this study.

The majority of the state's subbasins and groundwater contributing areas were estimated to have relatively minor (less than 10 percent) alteration of streamflow under water-use scenario 1 (seasonally varying water use; no surface-water-reservoir withdrawals). However, about 12 percent of subbasins and groundwater contributing areas were estimated to have extensive alteration of streamflows (greater than 40 percent) in August; most of these basins were concentrated in the outer metropolitan Boston region. Potential surcharging of streamflow in August was most commonly indicated for main-stem river subbasins, although surcharging was also indicated for some smaller tributary subbasins. In the high-flow month of April, only 4.8 percent of subbasins and groundwater contributing areas had more than 10 percent potential flow alteration. A majority of the state's subbasins and groundwater contributing areas were also indicated to have relatively minor alteration of streamflow under water-use scenario 2 (long-term average water use, including surface-water-reservoir withdrawals). Extensive alteration of mean annual flows was estimated for about 6 percent of the state's subbasins and groundwater contributing areas. The majority of subbasins estimated to have extensive long-term flow alteration contained reservoirs that were specifically designed, constructed, and managed to supply drinking water to cities. Only a small number of subbasins and groundwater contributing areas (1 percent) were extensively surcharged on a long-term, mean annual basis. Because site-specific data concerning surface-water-reservoir storage dynamics and management practices are not available statewide, the seasonal effects of surface-water-reservoir withdrawals on downstream flows could not be assessed in this study.

The impounded storage ratio (volume of impounded subbasin or groundwater-contributing-area storage divided by mean annual predevelopment outflow from the subbasin or contributing area, in units of days) indicates the potential for alteration of streamflow, sediment-transport, and temperature regimes by dams, independent of water use. Storage ratios were less than 1 day for 33 percent of the subbasins and groundwater contributing areas, greater than 1 month for about 40 percent of the cases, and greater than 1 year for 3.2 percent of the cases statewide. Dam density, an indicator of stream-habitat fragmentation by dams, averaged 1 dam for every 6.7 stream miles statewide. Many of these dams are not presently (2009) being managed. The highest dam densities were in portions of Worcester County and in the Plymouth-Carver region, respectively, reflecting the historical reliance of Massachusetts industry upon water power and agricultural water-management practices in southeastern Massachusetts.

Impervious cover is a frequently used indicator of urban land use. About 33 percent of the state's 1,429 subbasins and groundwater contributing areas are relatively undeveloped at the local scale, with a local impervious cover of less than 4 percent. About 18 percent of Massachusetts subbasins and contributing areas are highly developed, with a local impervious cover greater than 16 percent. The remaining 49 percent of subbasins and contributing areas have levels of

urban development between these extremes (4 to 16 percent local impervious cover). Cumulative impervious cover, defined for the entire upstream area encompassed by each subbasin, shows a smaller range (0 to 55 percent) than local impervious cover. Both local and cumulative impervious cover were highest in metropolitan Boston and other urban centers. High elevated impervious-cover values were also found along major transportation corridors.

The water-quality status of Massachusetts streams is assessed periodically by the Massachusetts Department of Environmental Protection pursuant to the requirements of the Federal Clean Water Act. Streams selected for assessment are commonly located in larger subbasins where some degree of impairment is expected. In the 72 percent of the state's subbasins and groundwater contributing areas with assessed streams in 2002, more than 50 percent of the assessed stream miles were considered impaired. All of the assessed stream miles were considered impaired in 66 percent of the subbasins and groundwater contributing areas with assessed streams. Large streams, such as the main stems of rivers that make up most of the assessed stream miles, also are in many cases the receiving waters for treated wastewater discharges and for this reason may be more susceptible to water-quality impairments than smaller streams. Subbasins and contributing areas with large fractions of assessed stream miles that are listed as impaired are distributed across the state, but are more prevalent in eastern Massachusetts.

Introduction

Humans interact with streams and stream basins in a wide variety of ways. Such interactions include the withdrawal, discharge, and interbasin transfer of water and wastewater, dam construction and operation, stream channelization, urbanization and other types of land-cover change, and anthropogenic climate change (Vörösmarty and Sahagian, 2000; Milly and others, 2005; Walsh and others, 2005; Weiskel and others, 2007). Over time, human interactions with stream basins may alter streamflow regimes, water quality, and the integrity of aquatic habitats, affecting the availability of freshwater for human and ecosystem needs.

In Massachusetts, concern has grown in recent years about all forms of basin alteration, the potential effects of basin alteration on water availability and aquatic habitat, and the need for improved indicators of basin alteration. In 2001, the Massachusetts Water Resources Commission (MWRC) developed an interim "stressed basin" classification, in order to "flag areas [in which proposed development projects] may require a more comprehensive and detailed review of environmental impacts or require additional mitigation" (Massachusetts Water Resources Commission, 2001). The stressed-basin classification was based on an analysis of electronically available streamflow data from 72 U.S. Geological Survey (USGS) gages in the state with more than 25 years of daily record. Three flow statistics—median annual 7-day low flow, median annual 30-day low flow, and the median annual low-flow pulse duration—were compiled for each gaging station and normalized to the basin drainage area at each station.[1] The gaged basins were then ranked according to the magnitude of each statistic. A stress level was assigned to each gaged basin according to the relative ranking of the basin with respect to the three low-flow statistics.

The 2001 Massachusetts stress classification was based entirely on streamflow data from gaged sites, because these were the only relevant data that were available statewide in electronic form at the time of the analysis. This approach imposed several limitations on the 2001 stress designations; these limitations were noted in the MWRC report (Massachusetts Water Resources Commission, 2001). First, the relative contributions of seasonal climate variation, natural basin characteristics, and human factors to streamflow variability could not be distinguished. Second, levels of flow alteration in ungaged basins could not be assessed. Finally, the 2001 report noted the importance of biological, water-quality, and land-cover indicators of basin alteration, but provided no information concerning these factors.

Since 2001, data sets and computer tools have become available that allow several of these limitations to be addressed. For example, the USGS, in cooperation with the Massachusetts Department of Conservation and Recreation (MDCR), defined a set of 61 least altered or index streamgages across southern New England (Armstrong and others, 2008). This set of index stations defined the range of natural streamflow regimes in Massachusetts and informed the development of an index-streamflow guidance document (Massachusetts Water Resources Commission, 2008). In addition, the USGS, in cooperation with the Massachusetts Department of Environmental Protection (MDEP), recently developed a computer application for estimating both natural and water-use-affected daily streamflows at ungaged sites, facilitating statewide analysis of water use in relation to availability (Archfield and others, 2010). As part of this effort, a database of annually reported withdrawal information for public-water-supply sources and other withdrawals regulated under the Massachusetts Water Management Act, as well as treated-wastewater discharge information, was created from MDEP and U.S. Environmental Protection Agency (USEPA) sources. Finally, detailed datalayers of dam locations, impounded water storage, percent impervious cover, and water-quality impairments have recently become available, allowing the statewide mapping of additional indicators of basin alteration not addressed in 2001. These datalayers are described and referenced in appropriate sections of this report.

This report describes the compilation and spatial distribution of a new set of basin-alteration indicators derived from publicly available statewide data maintained in electronic form

[1]The annual low-pulse duration is the number of consecutive days in a specific year during which the flow at a gaging station is less than a set threshold—in this case, the long-term Q_{75}, or the flow that is exceeded 75 percent of the time.

by state and Federal agencies. The indicators address the following types of potential basin alteration (table 1): (1) streamflow alteration caused by human water-use patterns (withdrawals and return flows); (2) alterations of flow and habitat caused by dams; (3) the extent of impervious cover; and (4) known water-quality impairments in streams. The spatial patterns of each indicator are mapped and described, and the limitations and appropriate uses of the indicators are discussed.

Delineation of Massachusetts Subbasins and Groundwater Contributing Areas

In order to assess Massachusetts basin alterations, it is useful to characterize these alterations at scales that are (1) appropriate to the scale of the stream and stream-basin alterations in the state, and (2) practical for use by the water-management community. The 28 state planning basins (fig. 1A) are widely known (Massachusetts Office of Geographic and Environmental Information, 2003), but are generally too coarse to represent many of the alterations described in this study. For example, a basin indicator such as percent impervious cover is generally determined as a spatial average over a particular area. Averaging this indicator over a large area such as a state planning basin can mask subareas where the indicator is either substantially greater or less than the areal average. For this reason, two finer scale sets of basins were chosen for the present study in consultation with the Massachusetts Basin Stress Reclassification Task Force. The first set of basins consisted of the 183 12-digit Hydrologic Unit Code (HUC-12) basins from the Massachusetts portion of the Watershed Boundary Dataset (WBD; Natural Resources Conservation Service, 2009) (fig. 1B). The second was a finer scale set of 1,395 subbasins, newly delineated by USGS

Table 1. Basin-alteration indicators used in this study, by indicator class.

[Unimpacted and water-use-impacted streamflows estimated by the Massachusetts Sustainable Yield Estimator (Archfield and others, 2010); dam storage and density information obtained from the National Inventory of Dams (U.S. Army Corps of Engineers, 1996) and the Massachusetts Riverways Program (C. Leuchtenberg, written commun., 2009); impervious cover and water-quality data obtained from the Massachusetts Office of Geographic and Environmental Information (2007, 2005). See text for further description of indicators and data sources]

Indicator class and indicators	Definition
Potential alteration of streamflow by water use	
Median January flow, percent alteration (no reservoir withdrawals)	See table 3.
Median April flow, percent alteration (no reservoir withdrawals)	See table 3.
Median August flow, percent alteration (no reservoir withdrawals)	See table 3.
Median October flow, percent alteration (no reservoir withdrawals)	See table 3.
Annual 7-day minimum flow, percent alteration (no reservoir withdrawals)	See table 3.
Low-pulse count, percent alteration (no reservoir withdrawals)	See table 3.
Low-pulse duration, percent alteration (no reservoir withdrawals)	See table 3.
Annual relative net demand, in percent (with reservoir withdrawals)	See table 3.
Water-use intensity, in percent (with reservoir withdrawals)	See table 3.
Potential alteration of streamflow and habitat by dams	
Dam storage ratio, in days	Ratio of maximum impounded subbasin storage to long-term mean annual outflow, in days.
Dam density, in dams per stream mile	Number of dams per stream mile.
Impervious cover	
Local percent impervious cover	Average percentage of impervious cover in the local hydrologic unit.
Cumulative percent impervious cover	Average percentage of impervious cover in the entire upstream subbasin.
Water quality	
Assessed stream miles, in percent of total stream length	Percentage of subbasin stream length assessed for water quality by the State.
Impaired stream miles, in percent of assessed stream length	Percentage of assessed stream length listed as impaired by the State.

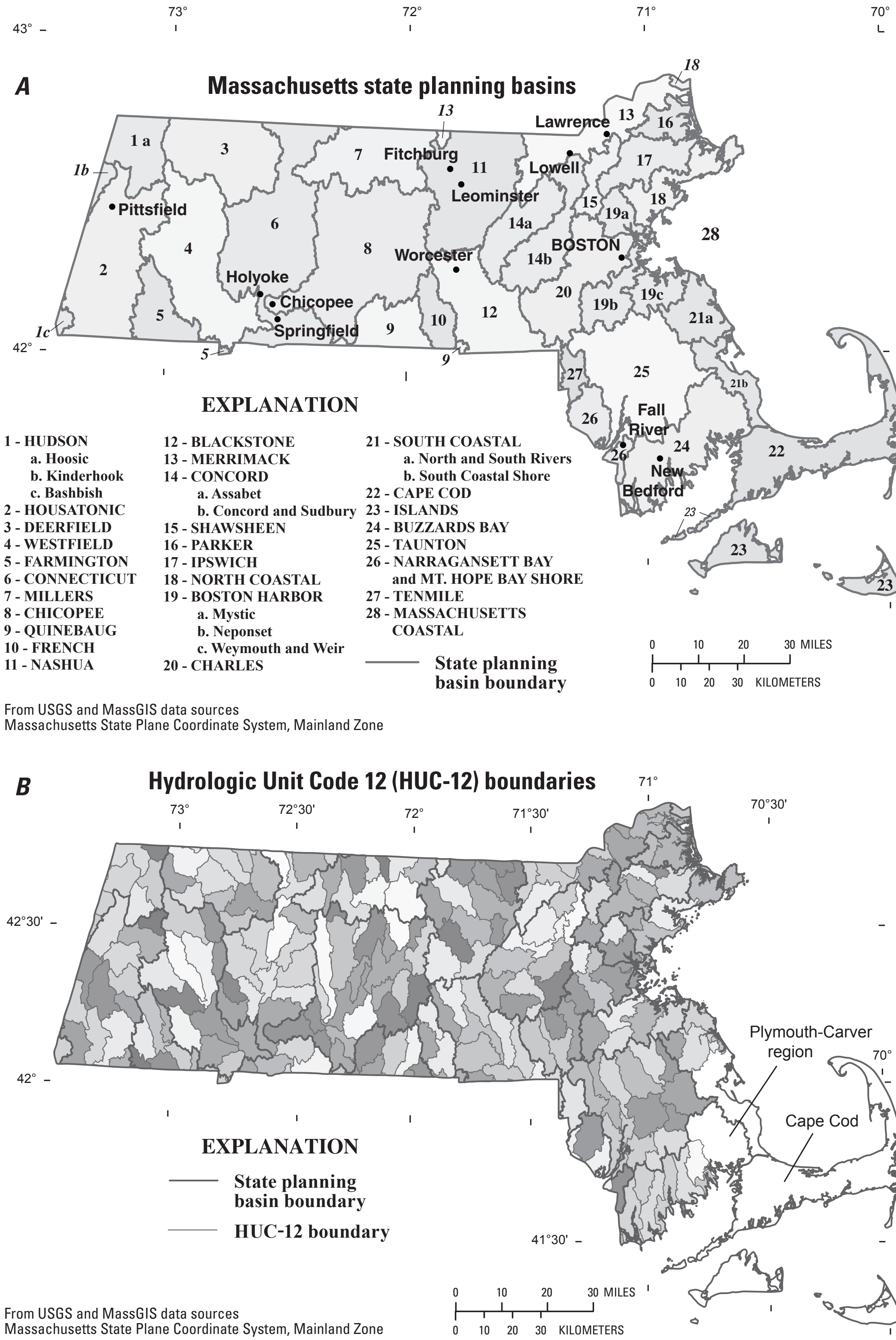
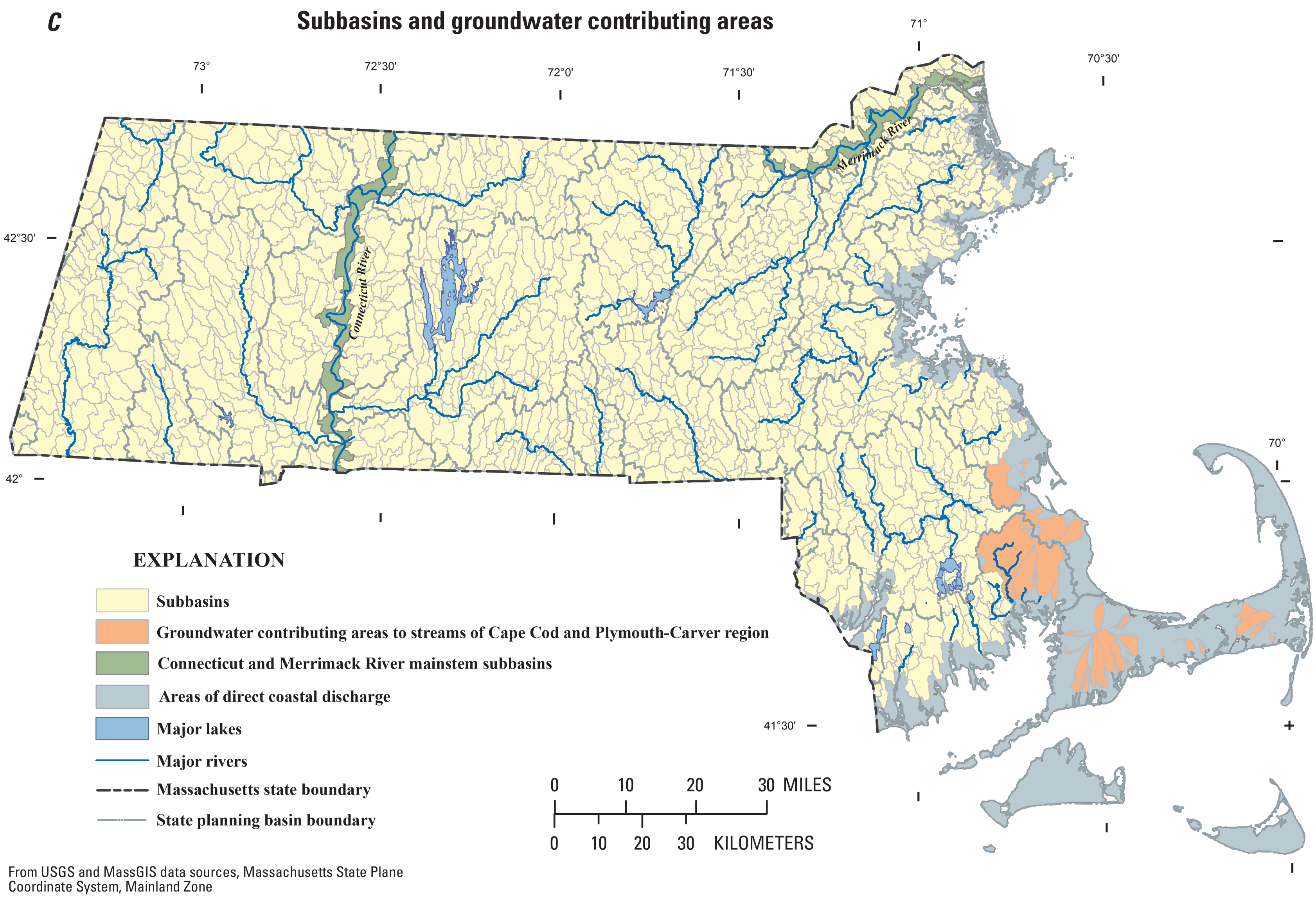


Figure 1. *(A)* Massachusetts state planning basins and major cities, *(B)* Hydrologic Unit Code 12 (HUC-12) basins, and *(C)* subbasins and groundwater contributing areas defined for this study. *(D)* Relations between subbasins and hydrologic units in this study. Hydrologic units are defined as the local land area draining to a particular stream reach or group of reaches; subbasins are defined as the entire upstream land area that drains to a subbasin outlet. Subbasin areas increase in the downstream direction. *(E)* Drainage areas of the HUC-12 basins, subbasins, and groundwater contributing areas defined for this study.



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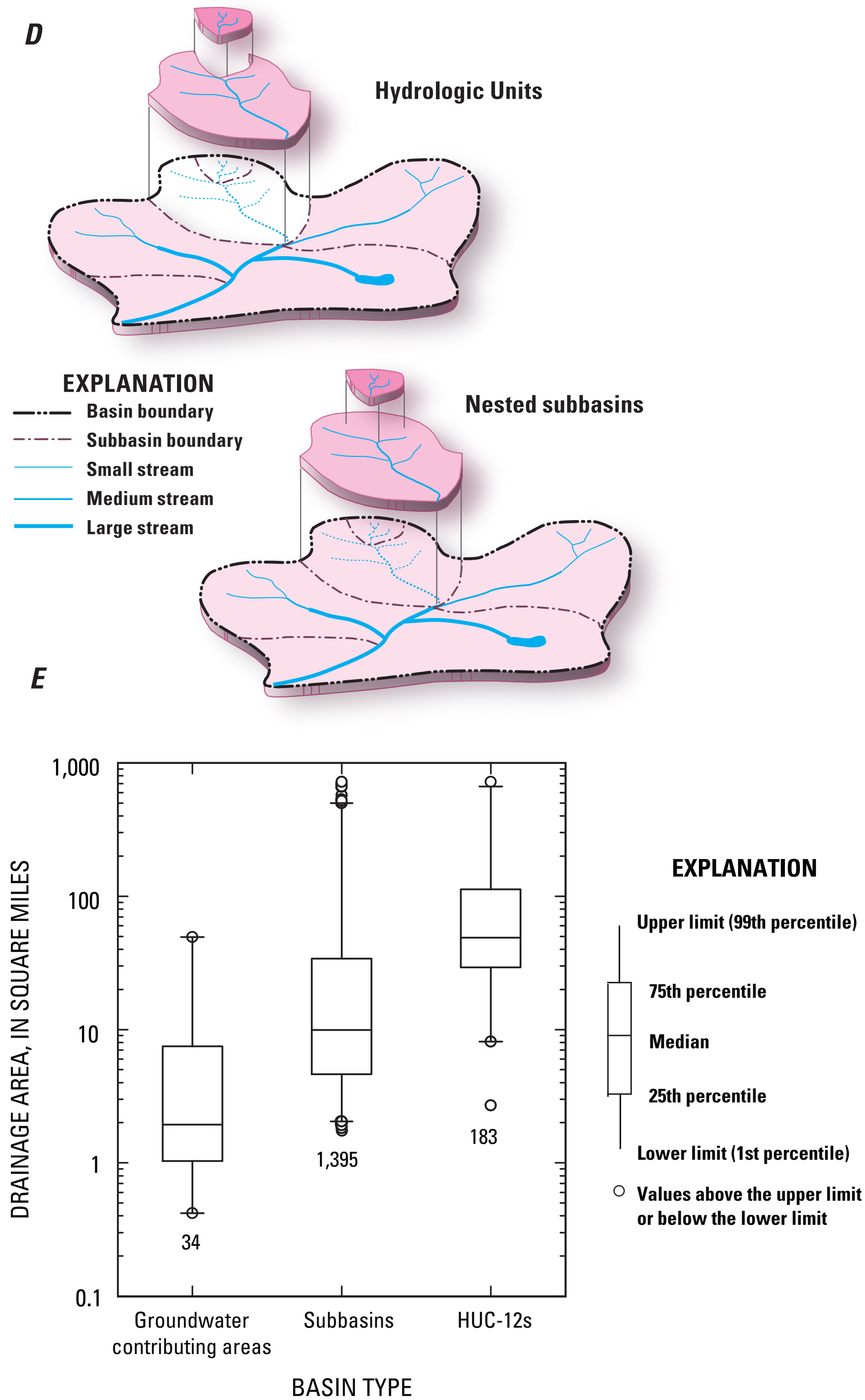

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for the present study (fig. 1C). This set of basins covers all portions of Massachusetts where stream drainage areas can be defined by surface topography. (Contributing areas to streams in groundwater-dominated areas of southeastern Massachusetts are described later in this section.)

For the purposes of this study, a subbasin is defined as the total upstream drainage area (or watershed) that drains to a selected point on a stream. A hydrologic unit is defined as the area that drains to a particular stream reach, or set of reaches, between two subbasin delineation points (fig. 1D). (Coastal HUC-12 basins without a single major outlet to the coastal ocean are excluded.) The first, or headwater, subbasin in an upstream-to-downstream sequence of subbasins coincides with the first hydrologic unit in that sequence. Subbasins are constructed by accumulating successive hydrologic units in a downstream direction; a given downstream subbasin includes all upstream subbasins and hydrologic units. The term “groundwater contributing area” is used to denote the 34 land areas that contribute water to the major streams of Cape Cod and the Plymouth-Carver area, as defined by Walter and Whelan (2004) and Masterson and others (2009).

The subbasins delineated for this study (fig. 1C) were designed to nest completely within the previously published HUC-12 basins (fig. 1B) and state planning basins (fig. 1A). Consequently, the newly delineated set of subbasins encompasses a wider range of drainage areas and a smaller average drainage area than the HUC-12 basins (fig. 1E). The newly delineated subbasins range in area from 1.6 to 723 mi^2 (fig. 1E), have a median area of 10 mi^2, and an average increment of drainage area between subbasins (hydrologic unit area) of 5.3 mi^2. The HUC-12 basins range from 2.8 to 723 mi^2, have a median area of 50 mi^2, and an average hydrologic unit area of 38 mi^2. For simplicity, all of the nested WBD basins in Massachusetts are referred to as HUC-12 basins in this report, although some downstream, nested HUC-12 basins coincide with HUC-10 and HUC-8 basins of the WBD.

Procedures Used to Delineate Subbasins

The high-resolution (1:24,000 scale) National Hydrography Dataset (NHD) stream layer (U.S. Geological Survey, 2008) was used to create the new subbasin datalayer for Massachusetts. The NHD stream layer was processed to remove arcs in braided streams and eliminate divergent stream paths, resulting in a purely dendritic stream network. Strahler stream order was calculated by applying an Arc Macro Language (AML) computer routine to the dendritic stream layer. Stream nodes were selected at the junctions of any two third or higher order streams. Delineation points were placed on each upstream reach of the junction using a 25-m buffer. Delineation points were also placed at the outlets of streams along coastlines and estuaries. Basin boundaries were delineated in batch mode by an automated procedure using ArcHydro Tools in ArcGIS 9.2. Base layers for all delineations were derived from a 10-m-resolution digital elevation model (DEM), resampled from the 30-m National Elevation Dataset (NED). Prior to watershed delineation, the elevation data were further enhanced with a series of preprocessing steps that enforced vector stream and watershed boundary data on the DEM.

Delineation points which resulted in headwater subbasins less than approximately 2 mi^2 in area were removed to comply with the minimum basin size requirements of the Sustainable Yield Estimator (SYE) application (Archfield and others, 2010). In order to produce more uniform spatial discretization, hydrologic units were not allowed to exceed 15 mi^2 in area, except in the case of very large water bodies. In these cases, a delineation point was added at approximately the midpoint of the unit, and the subbasin and hydrologic unit were redelineated. All tributaries with basin areas greater than 2 mi^2 were delineated along the Connecticut and Merrimack Rivers. However, main-stem subbasins for these large rivers were not delineated because the uniform spatial data sets required by the SYE application were not available for these large watersheds.

The dendritic stream layer includes centerlines through water bodies and wetlands. Delineation points within the boundaries of lakes 0.5 mi^2 or greater in area were moved along the centerline to the edge of the lake. In three cases, this led to headwater watersheds that were slightly less than 2 mi^2 in area. These subbasins were kept in the data set despite their small size. In addition, a few delineation points were added to coincide with the outlet points of published WBD basins. Newly delineated subbasin boundaries generally conformed closely to previously published basin boundaries at the 12- and 8-digit HUC levels; however, minor discrepancies resulted from differences in the underlying elevation and hydrography data used for the respective delineations. Physical and climatic characteristics required by the SYE application for all subbasins analyzed in this study were obtained from 30-m gridded data in batch mode, as described by Archfield and others (2010), using ArcHydro Tools in ArcGIS 9.2 (Environmental Systems Research Institute, 2008).

Procedures Used to Delineate Contributing Areas in Groundwater-Dominated Areas of Southeastern Massachusetts

Cape Cod and the Plymouth-Carver region of southeastern Massachusetts are dominated by large sand and gravel aquifers of glacial origin. Areas contributing water to streams in these areas cannot be reliably delineated by surface topography and are generally defined by average groundwater elevations and flow directions. Regional calibrated groundwater models of the two regions (Walter and Whelan, 2004; Masterson and others, 2009) were used to delineate average affected areas and simulate monthly streamflows for 34 streams in the two regions at fixed points located immediately upstream of tidal influence. Contributing areas for streams and basin alteration indicators were determined only at these fixed points (one per stream) and encompassed the entire upstream affected area in each case. The contributing areas ranged in size from 0.4 to 49.4 mi^2 with a median size of 2 mi^2 (fig. 1E). The portions of Cape Cod and the Plymouth-Carver region that drain directly to the coastal ocean were not considered in this study. Because calibrated groundwater-flow models were not publicly available for Nantucket, Martha's Vineyard, and the Elizabeth Islands, these areas were not included in this study.

Statewide, a total of 1,395 nested, topographically defined subbasins were delineated for this study. In this report, the term "subbasin" is used to denote these newly defined basins. The term "hydrologic unit" denotes the land area that drains to a stream reach, or set of reaches, between two subbasin outlets. The term "HUC-12" is used to denote the 183 previously published, nested basins of the Watershed Boundary Dataset located completely or partially within Massachusetts.

Indicators of Potential Streamflow Alteration from Water Use

Natural streamflow regimes help to create and maintain the range of habitat properties required for diverse, well-functioning aquatic communities and ecosystems (Poff and others, 1997). Aquatic ecosystem integrity depends upon the maintenance of an appropriate degree of streamflow variability (Richter and others, 1996). In Massachusetts, natural flow regimes vary substantially in both time and space, and as a function of climate, surficial geology, and hydrologic position in a drainage basin (Armstrong and others, 2001; 2008). Relations between natural flow regimes, human basin alterations, and fish-community composition in Massachusetts are presently being assessed by the USGS in cooperation with the MDCR and the Massachusetts Department of Fish and Game (MDFG).

Several examples of contrasting streamflow regimes in Massachusetts can be described. For example, the relatively cool, high-relief drainage basins of northwestern Massachusetts typically generate low streamflows per unit basin area during winter and high spring flows caused by the rapid runoff of the melting snowpack. By contrast, the relatively warm, low-relief basins of southeastern Massachusetts have higher winter streamflows per unit basin area, lower spring peak flows (because of lower slopes and a smaller snowpack), and less overall flow variability. Statewide, the magnitude of summer flows (per unit basin area) is strongly dependent upon local surficial geology. Relatively high summer streamflows, derived largely from groundwater discharge (base flow), are especially common in the sand and gravel dominated basins of Cape Cod and the Plymouth-Carver region. Base flows in the till-dominated, high-relief areas of the state are often relatively low, whereas streams in valley-aquifer settings show moderate base flows per unit basin area (Ries and Friesz, 2000; Archfield and others, 2010).

Natural streamflows may be altered by water-use practices (withdrawals, return flows, and transfers of water or wastewater), the presence of regulated or unregulated dams, and urbanization or other types of land-cover change. In Massachusetts, the effects of water use on streamflow have received detailed study in several state planning basins (for example, Zarriello and Ries, 2000; DeSimone and others, 2002; DeSimone, 2004; Barbaro, 2007). The effects of land use and impervious cover on streamflow have only begun to be studied in Massachusetts (Carlson and others, 2008). The effects of dams and their impoundments on downstream flows are highly site-specific and depend upon the type of impoundment (hydropower, industrial, flood control, recreation, or water supply), the hydraulics of the outlet structure(s), and impoundment management practices, including the timing and rates of withdrawals from public-supply reservoirs. Because the relative importance of water use, urban land use, and dams in altering natural streamflow regimes in Massachusetts has not yet been assessed, this report presents indicators for all three classes of alteration.

Quantifying Potential Streamflow Alteration from Water Use

In order to assess potential streamflow alteration from water use practices in a basin, it is necessary to characterize both the natural or unaffected streamflow that would be expected from the basin and the affected streamflow resulting from water withdrawals and treated wastewater discharges during a period of interest. The USGS, in cooperation with the MDEP, has developed a desktop computer application, the Sustainable Yield Estimator (SYE version 1.0; Archfield and others, 2010), to allow estimation of unaffected and affected daily streamflows at any site on a Massachusetts perennial stream. The SYE application estimates unaffected flows by relating daily streamflows at an ungaged site to those at an index gage on a minimally altered stream that drains a basin with similar characteristics (see Archfield and others (2010) for a detailed description of the procedure). Affected flows are estimated as follows:

$$A = U - H_{out} + H_{in}\,, \tag{1}$$

where

A is the affected streamflow, in ft^3/s, estimated by the SYE application at the outflow point of a subbasin;

U is the unaffected streamflow, in ft^3/s, at this point;

H_{out} is the total of the reported and estimated withdrawals from the water resources, in ft^3/s, of a subbasin; and

H_{in} is the total reported and estimated discharges to the water resources of a subbasin, in ft^3/s, for a period of interest defined by the user.

Note that surface and groundwater discharges of wastewater to a particular subbasin (H_{in}) may be derived either from local water sources or water sources originating outside a subbasin. Hence, it is possible for H_{in} to be either greater than or less than H_{out} and for A to be either greater than U (surcharged streamflow conditions) or less than U (depleted streamflow conditions) during the period of interest.

Reported Withdrawals and Discharges

The withdrawal and discharge data used by the SYE application was reported previously to MDEP or the U.S. Environmental Protection Agency (USEPA) for the 2000–2004 period (Kari Winfield, Massachusetts Department of Environmental Protection, written commun., 2008), the most recent period for which annual data are available in electronic form. This 5-year period included two years that were drier than average, and three were wetter than average as indicated by 1961–2004 streamflow records from the index gages used by SYE to estimate unaffected flows. Withdrawal data for the 2000–2004 period were provided by MDEP for a total of 4,496 withdrawal points, including 3,781 municipal and non-municipal public-supply sources of all sizes and 715 nonpublic-supply withdrawals greater than 100,000 gal/d. Discharge data were obtained for 1,058 treated wastewater discharges permitted by either the MDEP (a total of 204 groundwater discharges greater than 10,000 gal/d each) or the EPA National Pollutant Discharge Elimination System (NPDES; a total 854 surface-water discharges of all sizes). Withdrawal data for the Quabbin and Wachusett Reservoir intakes were provided to Archfield and others (2010) by the Massachusetts Water Resources Authority (MWRA) for the 2000–2004 period.

All withdrawal and discharge points were georeferenced. The reported annual withdrawal data were disaggregated to a monthly time step using median monthly demand curves developed by Archfield and others (2010) from a subset of Massachusetts municipalities for the 2000–2004 period (table 2; fig. 2). Median monthly withdrawal estimates for each withdrawal point were then disaggregated to a daily time step by assigning a constant median monthly value to each day of a given month. Constant discharge rates, equivalent to the reported mean annual value, were assigned to MDEP-permitted groundwater discharges of treated wastewater. NPDES surface-water discharge data are reported monthly; these monthly data were also disaggregated to a set of constant daily values for each month in the 2000–2004 period. For subbasins with upstream portions in adjoining states, georeferenced, annual withdrawal and discharge data for 2000–2004 were obtained from the respective USGS Water Science Centers, disaggregated as described above, and incorporated into the SYE application, with the exception of the Merrimack and Connecticut River main-stem subbasins. The main-stem subbasins of these river systems were excluded because the SYE application does not provide flow estimates for the main-stem Merrimack and Connecticut Rivers.

Table 2. Typical monthly variation of municipal groundwater and surface-water withdrawals in Massachusetts, expressed as the median monthly percentage of the mean annual withdrawal rate for the 2000–2004 period.

[Derived from monthly 2000–2004 withdrawal data reported to the Massachusetts Department of Environmental Protection by 25 communities served by groundwater supplies and 6 communities served by surface-water reservoirs (from Archfield and others, 2010)]

Month	Monthly groundwater withdrawals, as a percentage of mean annual withdrawal rate	Monthly surface-water reservoir withdrawals, as a percentage of mean annual withdrawal rate
January	89.2	92.5
February	82.3	92.4
March	89.5	91.1
April	95.3	92.0
May	111.5	102.6
June	123.1	112.0
July	122.2	118.6
August	115.5	113.2
September	104.6	102.1
October	93.7	96.9
November	85.4	92.0
December	87.7	93.3

The net effects of time-varying monthly groundwater withdrawals and discharges and of NPDES surface-water discharges on streamflow from each subbasin were assumed to be instantaneous during the period of interest. This approach produces an indicator of potential streamflow alteration from water-use practices under the particular streamflow conditions of interest, for example, under median August flow conditions for the 1961–2000 period. The term “potential” is used to denote a best estimate of streamflow alteration that draws upon all of the electronically available, publicly reported information for a subbasin for the 2000–2004 period. The “potential” alteration is not the maximum possible alteration that could result from permitted withdrawals or discharges. Actual streamflow alterations at the monthly time scale (and alterations of the annual 7-day minimum flow, low-pulse count, and low-pulse duration statistics) could be either greater or less than the calculated potential alteration, depending upon year-to-year streamflow deviations from median conditions, variations in withdrawals and discharges associated with year-to-year climate variations, and differences in monthly water-use patterns among communities.

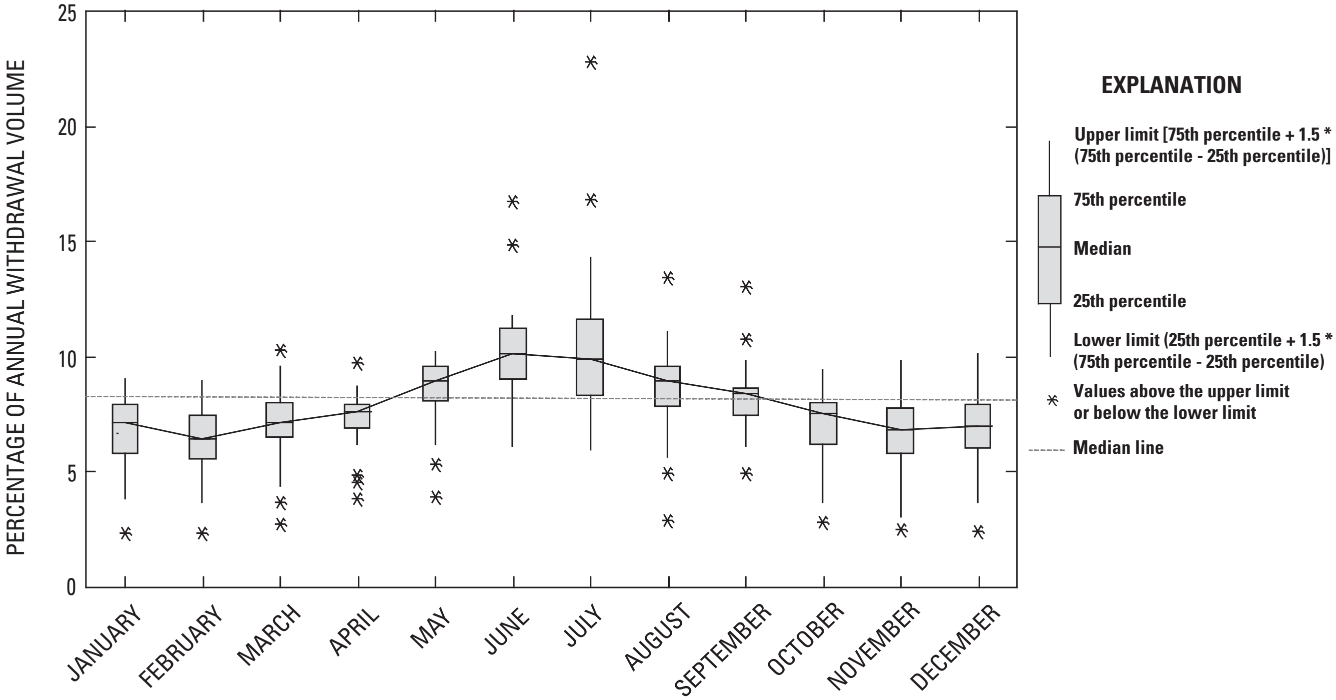

Figure 2. Monthly groundwater withdrawals in Massachusetts, expressed as percentages of mean annual reported withdrawal volumes from 25 communities for 2000–2004. (Modified from Archfield and others, in press).

Unreported Withdrawals and Discharges

Private-well withdrawals for domestic use; self-supplied commercial, industrial, and irrigation withdrawals less than 100,000 gal/d; and domestic wastewater discharges (septic-system discharges) less than 10,000 gal/d are not presently reported to the state. Because these data are not publicly available in electronic form, they are not presently incorporated into the SYE version 1.0 application. This limitation was addressed in the present study by estimating flows in two of the classes above—private-well withdrawals for domestic use, and domestic septic-system discharges—for each subbasin in the state. Although withdrawals and return flows associated with private wells and septic systems generally are smaller in magnitude than state-reported withdrawals and discharges (DeSimone, 2004; Barlow and others, 2009), they likely have detectable effects on the local water balance in some subbasins.

To estimate the net effect of private domestic wells and septic systems on the water balance of each subbasin, the boundaries of approximately 11,000 U.S. Census block groups were obtained for 1990 and 2000 for Massachusetts and for the portions of adjoining states within the watershed areas of this study. The 1990 census tracked the number of households in each block group that were served by public water supplies, individual wells, public sewage collection, and septic systems. (This information was not collected by the 2000 census.) The population percentages served by the respective water-supply and sewage-disposal modalities obtained in the 1990 census then were combined with 2000 population estimates for each block group to obtain estimates of the numbers of persons served by each modality in 2000. Finally, these data were intersected with watershed boundaries to estimate the populations served by private wells and septic systems, respectively, in each subbasin. For any block group that was split between two or more subbasin polygons, the data for that block group were apportioned by block-group area within each subbasin.

An average annual, statewide residential withdrawal rate of 67 gallons per capita per day was obtained from the MDEP (Massachusetts Department of Environmental Protection, 2007a) and applied to each subbasin to obtain the average daily private-well withdrawals for each subbasin. This average was modified by means of the monthly demand curve used by the SYE application (fig. 2; table 2) to reflect seasonal variations in withdrawals.

Rates of septic-system discharge to each subbasin were calculated by multiplying the estimated 2000 population served by septic systems in each subbasin by a constant year-round discharge rate of 57 gallons per capita per day. This rate is equivalent to 85 percent of the 67 gallons per capita per day average annual withdrawal rate noted above and is consistent with recently published estimates of domestic return-flow rates for Massachusetts (Barlow and others, 2009).

Selection of Streamflow-Alteration Indicators

The indicators of hydrologic alteration (IHA) framework of Richter and others (1996) is a widely used set of ecologically important streamflow statistics for characterizing streamflow regimes. In consultation with the Massachusetts Basin Stress Reclassification Task Force, seven distinct IHA indicators were selected to assess estimated changes in streamflow magnitude, frequency, and duration associated with water-use practices in Massachusetts (table 3). The selected IHA indicators were judged to be nonredundant in Massachusetts on the basis of the analysis of Armstrong and others (2008). Changes in flow magnitude were evaluated for median January, April, August, and October flows. Changes in low-flow frequency were evaluated using the low-pulse count, defined as the average number of times per year that flows go below the flow that is exceeded 75 percent of the time under unaffected conditions. Changes in low-flow duration were evaluated by changes in the average magnitude of the estimated unaffected median annual 7-day minimum flow and the estimated unaffected low-pulse duration (the average duration, in days, of the low pulses). Changes in these streamflow statistics were obtained by first using the SYE application to calculate the unaffected (*U*) and water-use-affected (*A*) value of each flow statistic for the outflow point of each subbasin. The potential alteration (P_a), in percent, of each flow statistic was then calculated as follows:

$$P_a = (A / U - 1) * 100 , \quad (2)$$

where

A and *U*, respectively, are the average affected and unaffected flow statistics over the time period of interest at the subbasin outflow point. P_a can range from -100 percent, if net withdrawals equal unaffected outflow from the subbasin, to arbitrarily large positive percentages under surcharged conditions, if affected flows exceed unaffected outflows. In subbasins where net withdrawals exceed unaffected outflows for the time period of interest, P_a was set equal to -100 percent.

Table 3. Streamflow-alteration indicators used in this study.

[Period of record for unaffected flows is 1961–2004. Water-use scenarios 1 and 2 were developed by using withdrawal and wastewater-discharge data for 2000–2004. See text for explanation]

Indicator	Definition	Biological/physical significance
	Water-use scenario 2 (no surface-water withdrawals)	
Median January flow	Percentage of alteration of the median of the January median flows for period of record	Overwintering and salmonid egg development.
Median April flow	Percentage of alteration of the median of the April median flows for period of record	Spring flooding.
Median August flow	Percentage of alteration of the median of the August median flows for period of record	Rearing and growth.
Median October flow	Percentage of alteration of the median of the October median flows for period of record	Fall salmonid spawning.
Annual 7-day minimum flow	Percentage of alteration of the mean of the 7-day annual minimum flows for period of record	Period of high potential temperature, dissolved oxygen, and water-quality stress.
Low-pulse count	Percentage of alteration of the mean number of times per year that flow is below the unaffected Q_{75}	Periods of potential temperature, dissolved oxygen, and water-quality stress.
Low-pulse duration	Percentage of alteration of the mean annual duration (in days) of periods when flow is below the unaffected Q_{75}	Periods of potential temperature, dissolved oxygen, and water-quality stress.
	Water-use scenario 2 (with surface-water withdrawals)	
Annual relative net demand	Ratio of net water use in a subbasin (wastewater discharges – withdrawals) to unaffected mean annual subbasin outflow	Indicates net longterm streamflow alteration caused by water use.
Water-use intensity	Ratio of overall water use in a subbasin (withdrawals + wastewater discharges) to unaffected mean annual subbasin outflow	Indicates overall magnitude of human-induced flows relative to natural flows in a subbasin.

It should be emphasized that potential alteration is a semiquantitative, rather than fully quantitative, indicator of streamflow and stream-ecosystem response to human water use in a subbasin, consistent with the current state of knowledge regarding stream ecosystems in Massachusetts (Armstrong and others, 2001, 2008; Bain and Meixler, 2008; Kashiwagi and Richards, 2009). Continuous functional relations between levels of streamflow alteration and quantitative measures of biological condition (such as fish-species richness, percent fluvial species, or invertebrate-species richness) have not yet been established for the range of natural stream ecosystems in Massachusetts. For example, a stream ecosystem may be more sensitive to a given degree of flow alteration (for example, a 20-percent flow depletion) during the low-flow months of the year or in subbasins where flows are naturally very low in the summer, than during the high-flow months or in subbasins where flows are naturally high in the summer because of high base flow. Although detailed analyses of natural streamflow regimes have recently become available for Massachusetts (Armstrong and others, 2008; Archfield and others, 2010), seasonal and geographic differences among subbasins in stream-ecosystem sensitivity to a constant percentage of flow alteration have not yet been defined. However, studies conducted elsewhere in the eastern United States have shown that key measures of stream-ecosystem health, such as the percentage of fluvial fish, decline in direct proportion to water withdrawals expressed as a fraction of unaffected streamflow (Freeman and Marcinek, 2006), and Massachusetts studies have documented the ecological effects of severe streamflow depletion (Armstrong and others, 2001). For the above reasons, the potential flow-alteration values presented in this report and the thresholds between near-natural, least-altered, altered, and extensively altered flow conditions should be viewed as useful, but nevertheless semiquantitative, indicators of potential ecosystem impact from water-use practices.

Potential Flow Alteration from Water Use

Potential alteration (P_a) values are presented in this section for two water-use scenarios. Water-use scenario 1 is a time-varying water-use scenario that includes median monthly estimates of groundwater withdrawals and discharges; withdrawals and discharges directly from and to streams, respectively; and estimated domestic-well withdrawals and septic-system discharges; but excludes surface-water-reservoir withdrawals. Water-use scenario 2, by contrast, is a constant, long-term average water-use scenario that incorporates long-term, mean annual surface-water-reservoir withdrawals with all of the water uses listed under water-use scenario 1 on a long-term, mean annual basis. Both water-use scenarios, however, employ data that is specific to each of the state's 1,395 subbasins, 34 groundwater contributing areas, and 183 HUC-12 basins.

Surface-water-reservoir withdrawals are excluded from scenario 1 because the relation between a time-varying reservoir withdrawal and outflow from the reservoir is a site-specific function of the stage-storage-outflow relation for each reservoir, the hydraulics of the reservoir outlet structure(s), and reservoir management practices, including possible seasonal releases of water to maintain downstream flows (Waldron and Archfield, 2006). Because this information is not available statewide, the SYE version 1.0 application does not allow a user to simulate the transient response of a subbasin to time-varying reservoir withdrawals in that subbasin. However, surface-water-reservoir withdrawals are appropriate to include in the long-term average, water-use scenario 2, because short-term changes in storage would not be expected to affect sub-basin outflows on a long-term, steady-state basis.

Water-Use Scenario 1—No Surface-Water-Reservoir Withdrawals

Under median monthly conditions, a majority of the 1,429 subbasins and groundwater contributing areas analyzed for this study were estimated to have near-natural streamflow conditions at their outlets. Near-natural streamflow conditions are defined, for the purposes of this study, as a net alteration between -10 and +10 percent under water-use scenario 1 (table 4, fig. 3). The greatest degree of monthly alteration was indicated for August, when 473 (33 percent) of the state's 1,429 subbasins and contributing areas were estimated to have altered streamflows at their outlets—that is, greater than 10-percent potential alteration of streamflow as either net depletion or net surcharging of the natural streamflow. A total of 173 subbasins (12 percent) were indicated to be extensively altered in August (defined, for the purposes of this study, as greater than 40-percent flow alteration), including 46 subbasins (3.2 percent) estimated to have zero flow (100-percent net flow depletion) at their outlets under median August conditions. The smallest degree of alteration was indicated for April, when only 4.8 percent of subbasins were estimated to have greater than 10-percent alteration at their outlets. In January and October, 9 and 24 percent of subbasins, respectively, were estimated to have greater than 10-percent alteration (table 4).

The large differences in streamflow alteration indicated for January, April, August, and October under water-use scenario 1 are caused partly by natural, month-to-month variations in unaffected streamflow (U), and partly by monthly variations in water use, consistent with the A/U term in equation 2. Unaffected monthly streamflows in Massachusetts (U), normalized to basin area, are typically 500 to 1,000 percent higher in the high-flow season (March–April) than in the low-flow season (July–August–September) in a typical year with median monthly streamflows (Armstrong and others, 2008). Groundwater demand is typically about 35 percent higher in the low-flow season of July, August, and September than in the high-flow season of March and April (table 2). Hence, for the

Table 4. Frequency table of flow-alteration indicators for 1,429 Massachusetts subbasins and groundwater contributing areas, water-use scenario 1 (no surface-water reservoir withdrawals).

[For each range of alteration, the number of subbasins or contributing areas and the percentage of the total number is given. Negative alteration values indicate net depletion of outflow from water use; positive values indicate net surcharging from water use. Median January, April, August, and October frequency distributions include the 34 groundwater contributing areas of Cape Cod and the Plymouth-Carver region. The remaining distributions do not include the groundwater contributing areas; <, less than]

Alteration (percent)	Median January	Percent-age	Median April	Percent-age	Median August	Percent-age	Median October	Percent-age	Median annual 7-day minimum	Percent-age	Low-pulse count	Percent-age	Low-pulse duration	Percent-age
-100	0	0	0	0	46	3.22	7	0.49	121	8.67	15	1.08	15	1.08
-100 to <-90	0	0	0	0	3	0.21	3	0.21	11	0.79	0	0.00	0	0.00
-90 to <-80	0	0	0	0	11	0.77	4	0.28	10	0.72	4	0.29	2	0.14
-80 to <-70	0	0	0	0	10	0.70	5	0.35	16	1.15	0	0.00	3	0.22
-70 to <-60	0	0	0	0	14	0.98	7	0.49	10	0.72	2	0.14	1	0.07
-60 to <-50	1	0.07	0	0	16	1.12	11	0.77	11	0.79	5	0.36	0	0.00
-50 to <-40	2	0.14	1	0.07	18	1.26	14	0.98	19	1.36	7	0.50	7	0.50
-40 to <-30	6	0.42	1	0.07	21	1.47	23	1.61	35	2.51	10	0.72	16	1.15
-30 to <-20	12	0.84	3	0.21	55	3.85	37	2.59	34	2.44	25	1.79	25	1.79
-20 to <-10	45	3.15	21	1.47	69	4.83	67	4.69	64	4.59	214	15.34	67	4.80
-10 to <0	575	40.24	737	51.57	635	44.44	537	37.58	502	35.99	995	71.33	680	48.75
0 to <10	730	51.08	623	43.60	321	22.46	557	38.98	221	15.84	5	0.36	383	27.46
10 to <20	34	2.38	26	1.82	94	6.58	83	5.81	81	5.81	93	6.67	103	7.38
20 to <30	9	0.63	6	0.42	43	3.01	33	2.31	53	3.80	5	0.36	48	3.44
30 to <40	4	0.28	4	0.28	18	1.26	7	0.49	51	3.66	8	0.57	29	2.08
40 to <60	9	0.63	6	0.42	26	1.82	11	0.77	57	4.09	5	0.36	13	0.93
60 to <80	1	0.07	1	0.07	5	0.35	5	0.35	26	1.86	0	0.00	3	0.22
80 to <100	1	0.07	0	0	4	0.28	2	0.14	20	1.43	1	0.07	0	0.00
100 to <200	0	0	0	0	11	0.77	15	1.05	28	2.01	1	0.07	0	0.00
200 to <300	0	0	0	0	8	0.56	1	0.07	6	0.43	0	0.00	0	0.00
300 to <400	0	0	0	0	1	0.07	0	0.00	5	0.36	0	0.00	0	0.00
400 to <600	0	0	0	0	0	0.00	0	0.00	6	0.43	0	0.00	0	0.00
600 to <800	0	0	0	0	0	0.00	0	0.00	5	0.36	0	0.00	0	0.00
800 to <1,000	0	0	0	0	0	0.00	0	0.00	2	0.14	0	0.00	0	0.00
1,000 to <1,200	0	0	0	0	0	0.00	0	0.00	1	0.07	0	0.00	0	0.00

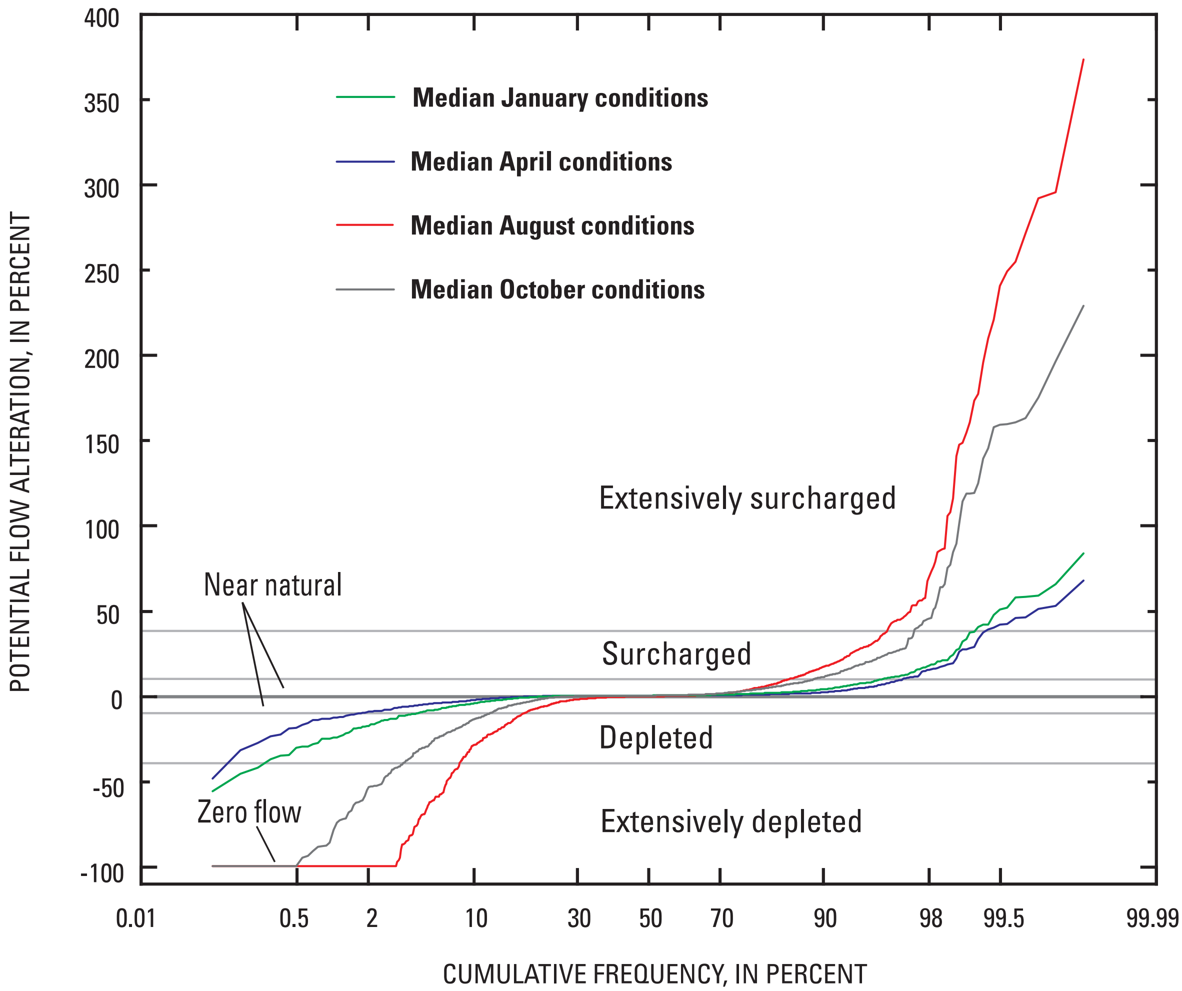

Figure 3. Cumulative frequency distribution of the potential alterations of median January, April, August, and October streamflows in Massachusetts subbasins, water-use scenario 1.

2000–2004 period, most of the monthly variation in the *A/U* ratio under water-use scenario 1, and therefore in potential streamflow alteration, can be attributed to natural variations in unaffected streamflow (*U*) rather than to variations in groundwater demand.

As expected, the median annual 7-day minimum flow was found to be more sensitive than the median August flow to the effects of water-use scenario 1 (table 4; fig. 4) because the unaffected median annual 7-day low flow is considerably lower than the unaffected August median flow. Alteration of the 7-day minimum streamflow (greater than 10-percent alteration) was indicated for 672 of the 1,395 subbasins, or 48 percent of the state's subbasins in a typical year. (The 7-day minimum streamflow and the low-pulse statistics could not be determined for the 34 groundwater contributing areas because the groundwater simulations were limited to a monthly time step.) Extensive flow alteration (greater than 40-percent alteration) was indicated for 353 subbasins, or 25 percent of all subbasins (table 4). Zero-flow conditions (100-percent depletion of streamflow) were estimated for 121 subbasins, or 8 percent of the statewide total, during a typical year.

The low-pulse count is defined as the number of times per year that streamflow goes below the flow that is exceeded 75 percent of the time under unaffected conditions. The low-pulse duration is the average number of days during which the flow remains under this threshold. Under conditions of net streamflow depletion, both statistics would be expected to increase, whereas under net surcharging conditions, both would decrease. Both statistics change as expected in response to scenario 1 (table 4; fig. 5). Overall, the potential alterations

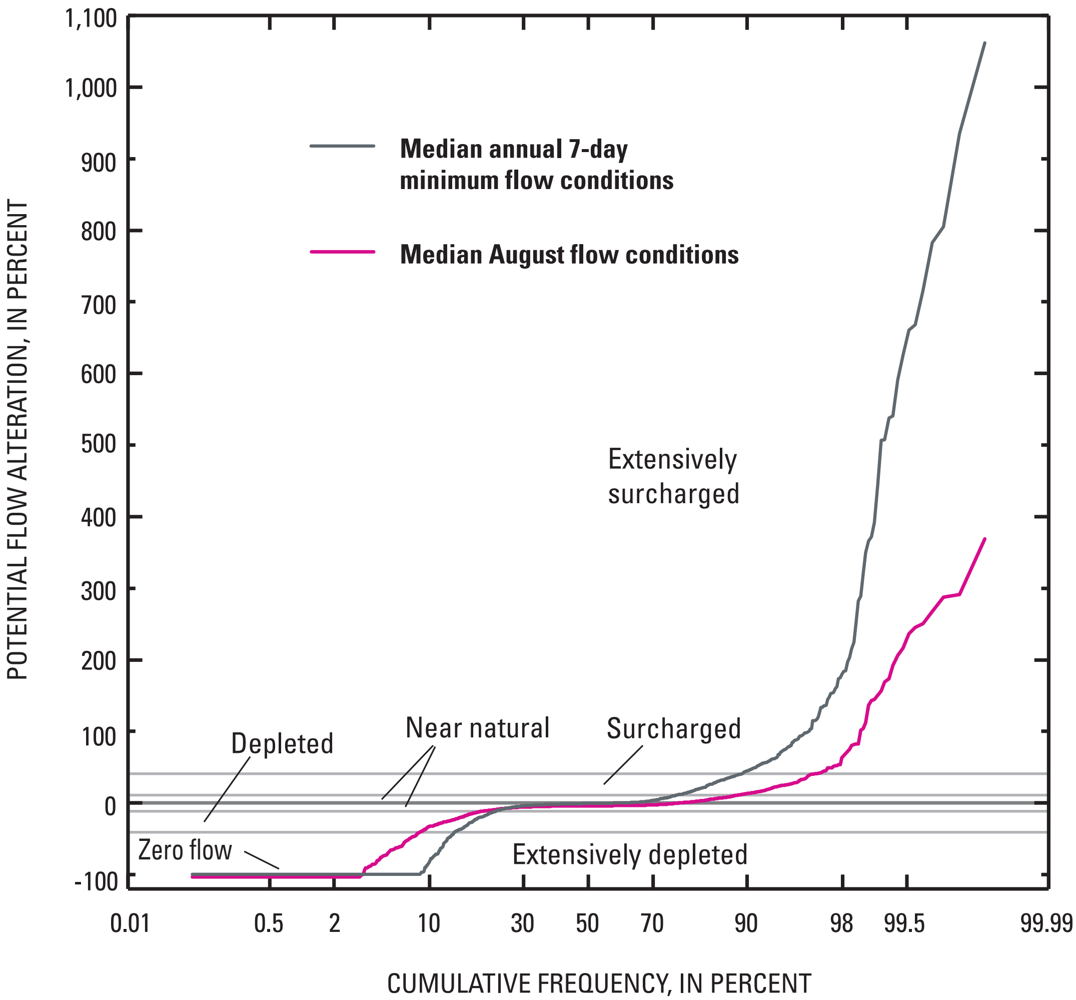

Figure 4. Cumulative frequency distribution of the potential alterations of median August and median annual 7-day minimum streamflows, water-use scenario 1.

in low-pulse count and duration are similar in magnitude, though opposite in sign, to corresponding alterations in the median August streamflows (figs. 4 and 5). That is, potentially depleted subbasins show an increase in low-pulse count and duration, whereas potentially surcharged subbasins show a decrease in these flow statistics. For example, 28 percent of the 1,395 subbasins were indicated to have greater than 10-percent alteration in low-pulse count from water-use scenario 1, which is comparable to the 33 percent of subbasins with the same degree of alteration for August median flows. Similarly, 24 percent of the subbasins show greater than 10-percent alteration in low-pulse duration. However, the percentages of subbasins indicated to have extensive (greater than 40-percent) alteration in low-pulse count and duration are small (2.9 and 3.2 percent, respectively) compared to the 12 percent of basins that were indicated to have extensive alteration in the August median flow.

The potential magnitude and sign of streamflow alteration varies geographically as well as seasonally across Massachusetts. These variations are evident both within and between the state planning basins. For example, large positive alterations (surcharging) of January flows were indicated for subbasins of the Nashua, Concord, Blackstone, and Taunton Basins that receive relatively large discharges of treated wastewater effluent (figs. 6A and 6B). Within each of these Planning Basins, the most surcharged subbasins are found near the headwaters of the main-stem river or in tributary streams where discharge volumes of treated wastewater effluent are large relative to natural outflows from the subbasin. Geographic patterns of potential alteration are unique to each Planning Basin;

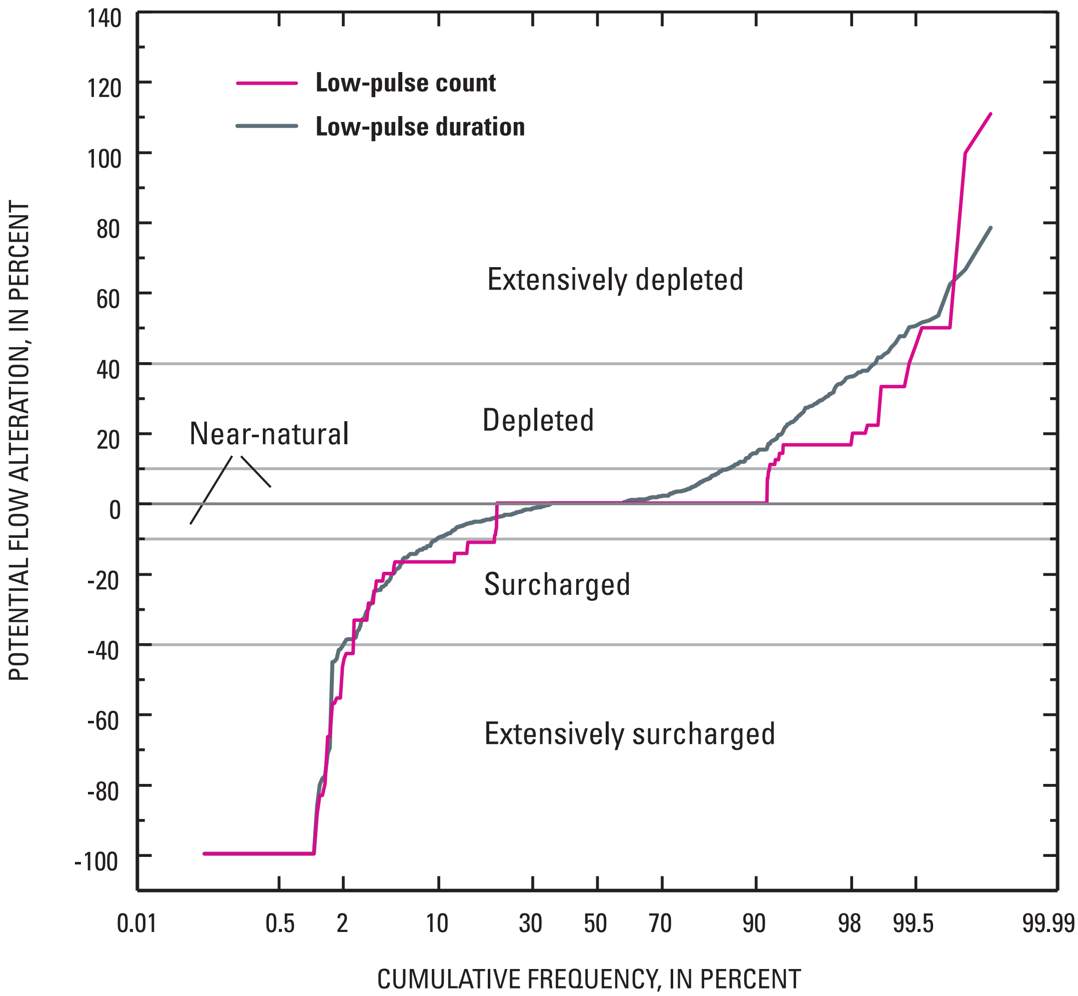

Figure 5. Cumulative frequency distribution of the potential alterations of low-pulse count and duration statistics in Massachusetts subbasins, water-use scenario 1.

however, net depletion at both the subbasin and HUC-12 scales was generally indicated to be greatest in headwater and small tributary subbasins, and extensive surcharging, with some exceptions, is more typical of main-stem subbasins.

Because of the comparatively high natural streamflows and low withdrawal rates in January (fig. 2), net streamflow depletion was indicated to be modest statewide during this month. In April, when natural streamflows typically reach their highest levels of the year (Armstrong and others, 2008), even less alteration can be attributed to water use (fig. 7). Only a small number of subbasins are indicated to be extensively surcharged in April, and no subbasins are extensively depleted. At the HUC-12 scale, January and April flow alterations are indicated to be relatively small, with only one HUC-12 (in the Blackstone Basin) showing extensive surcharging in January, and two HUC-12s (in the French and Blackstone Basins, respectively) showing extensive surcharging in April. No basins show extensive depletion at the HUC-12 spatial scale during these high-flow months.

The geographic pattern of potential streamflow alteration differs markedly in the lower flow months of August and October and during the annual 7-day minimum-flow period. Natural streamflows statewide, under August median-flow conditions, are typically about 80 percent lower than their annual medians (Armstrong and others, 2008); however, groundwater withdrawal rates in June, July, and August are typically about 20 to 30 percent higher than their annual medians (fig. 2). As a result, net water use under water-use scenario 1 is large relative to unaffected flow in the summer months, and streamflows are therefore estimated to be more extensively altered (greater than 40-percent alteration as either depletion or surcharging) during these months. This is most evident, although not limited to, subbasins immediately to the north, west, and south of the inner metropolitan Boston region in the Ipswich, Merrimack, North Coastal, Shawsheen, Mystic, Concord, Blackstone, Nashua, Charles, South Coastal, Neponset, and Taunton state planning basins (figs. 8 and 10; fig. 9 shows October).

Main-stem subbasins with some degree of surcharging in January and April show more extensive surcharging in August. August flow depletion is also indicated for isolated subbasins in the Deerfield, Westfield, and Connecticut Basins of western Massachusetts, in addition to surcharging of flow in the main-stem subbasins of the Housatonic Basin. October patterns of potential streamflow alteration (fig. 9) are similar to those for August, though less widespread geographically, and are consistent with generally reduced groundwater-withdrawal rates and increased natural streamflows in October (fig. 2). At the HUC-12 scale, August and October flows are also substantially altered, as expected during these lower flow months. Some degree of streamflow surcharging (greater than 10 percent of unaffected flow) is indicated for multiple HUC-12s in the Housatonic state planning basin and several basins in central and eastern Massachusetts (Nashua, Blackstone, Assabet, and Taunton Basins). Depletion of flow at the HUC-12 scale is also widespread in this part of the state, in the Blackstone, Sudbury, Charles, Neponset, Ipswich, Shawsheen, Mystic, and in some areas in the Merrimack state planning basin.

The most widespread areas of extensive flow alteration are indicated for the annual 7-day minimum-flow period (fig. 10). Most of the state planning basins with extensive depletion in August show an increased number of extensively depleted subbasins during the 7-day minimum-flow period. As previously noted, a total of 121, or 8 percent, of Massachusetts subbasins were indicated to have 100-percent net depletion of streamflow during this annual low-flow period under water-use scenario 1. The subbasins with estimated zero flow ranged in area from 1.8 to 58 mi^2 and were widely distributed geographically, occupying 20 of the 27 state planning basins. A total of 44, or 3 percent, of the subbasins were indicated to have net surcharging greater than 100 percent of natural flow (more than double the natural flow) during the 7-day minimum-flow period (table 4). The areas of these 44 subbasins ranged from 2 to 205 mi^2 and occupied 14 of the 27 state planning basins. Finally, it is important to note that modest surcharging (10 to 20 percent above unaffected flow) was indicated for some of the smaller subbasins of the outer metropolitan Boston region, under the low-flow conditions of August, October, and the annual 7-day minimum period (figs. 8A, 9A, and 10A). This modest surcharging is likely to be most common in subbasins served by imported, publicly supplied water and private septic systems.

At the HUC-12 scale, potential streamflow alterations during the 7-day minimum-flow period were lower than the alterations indicated for the subbasins, which are smaller than the HUC-12s. For example, the entire Sudbury Basin was estimated to be 30 to 40 percent depleted at the HUC-12 scale. At the subbasin scale, in contrast, some areas of the Sudbury Basin were indicated to be surcharged, others to be extensively depleted (greater than 40 percent), and still others to have near-natural streamflows.

The low-pulse count and duration statistics (figs. 11, 12) show a geographic pattern opposite to that of the median monthly and 7-day minimum streamflows. As noted previously, the low-pulse count and duration become smaller in surcharged subbasins and larger in depleted basins. As a result, major decreases in these statistics were indicated for portions of the Housatonic, Nashua, Assabet, Blackstone, Ten Mile, and Taunton Basins with relatively high discharges of treated wastewater. Conversely, the low-pulse count and duration increased modestly in areas with net depletion of flow. Relatively few subbasins underwent extensive (greater than 40 percent) increases or decreases in the low-pulse statistics in response to water-use scenario 1 (table 4).

The spatial distributions of the low-pulse count and duration indicators at the HUC-12 scale were similar to their respective distributions at the subbasin scale. At both scales, the number of surcharged areas was less than the number of depleted basins (as indicated by these two statistics), but the relative degree of alteration in the surcharged basins was greater than in the depleted basins.

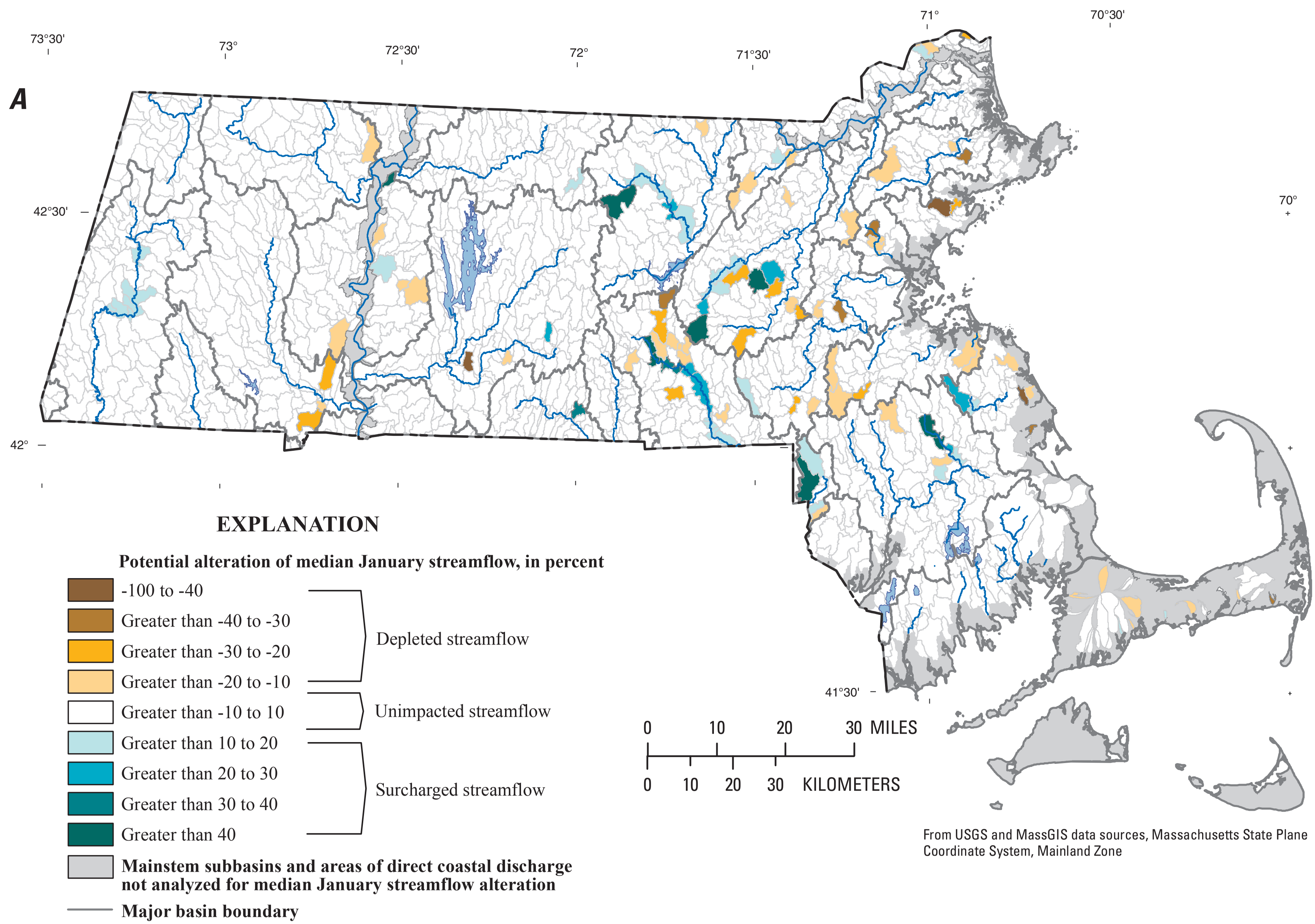

Figure 6. *(A)* Potential alteration of median January streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median January streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

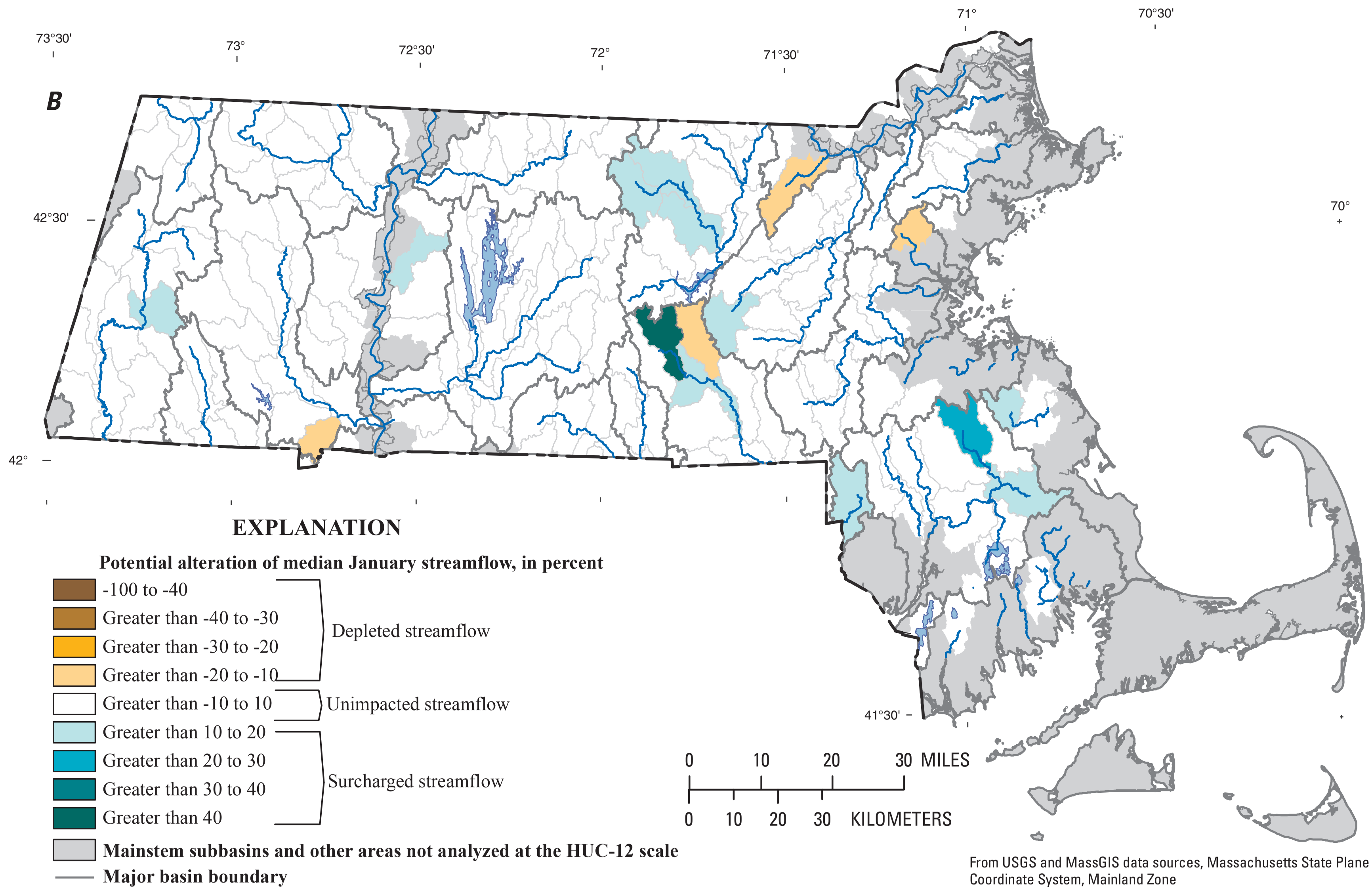

Figure 6. *(A)* Potential alteration of median January streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median January streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

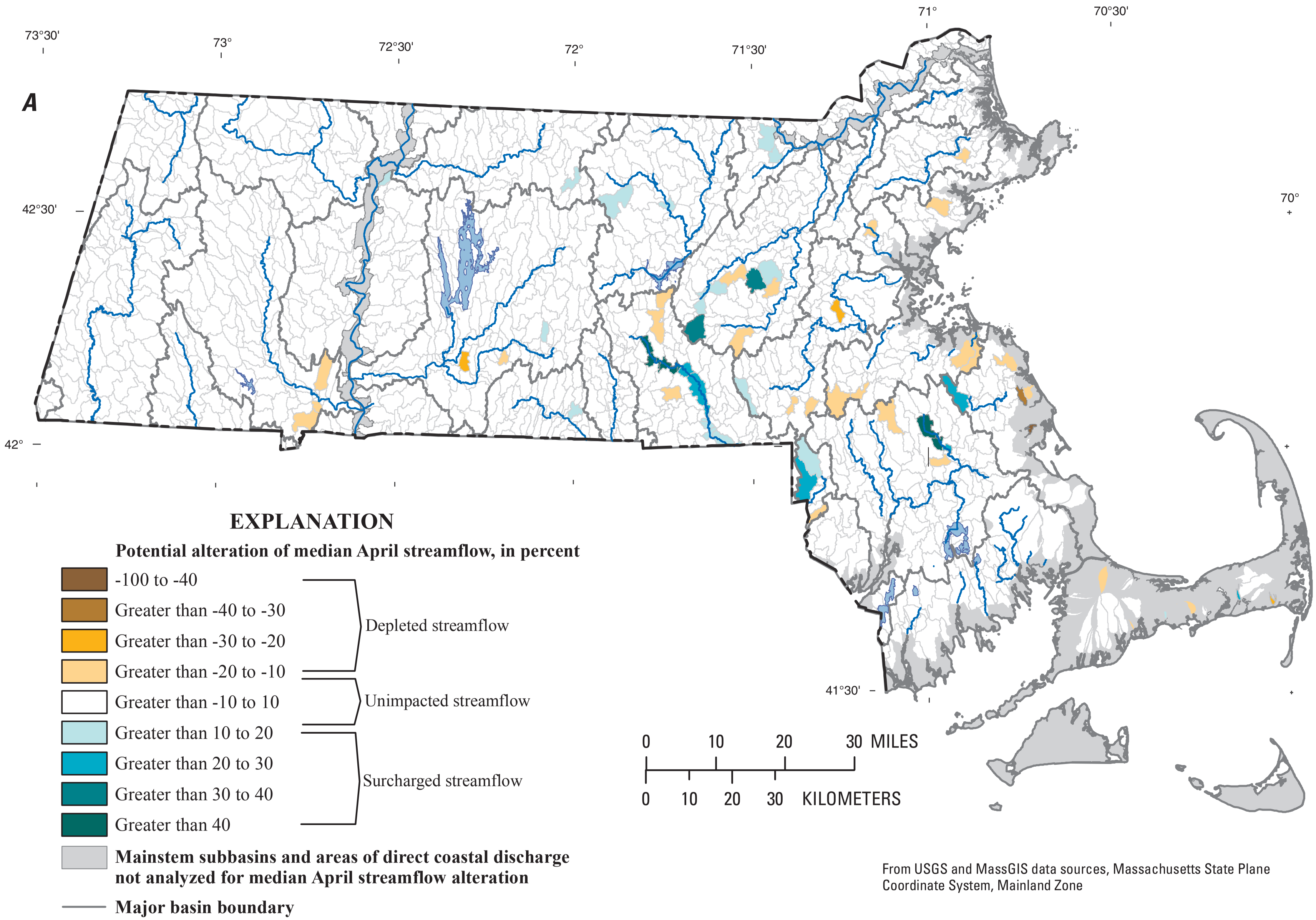

Figure 7. *(A)* Potential alteration of median April streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median April streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

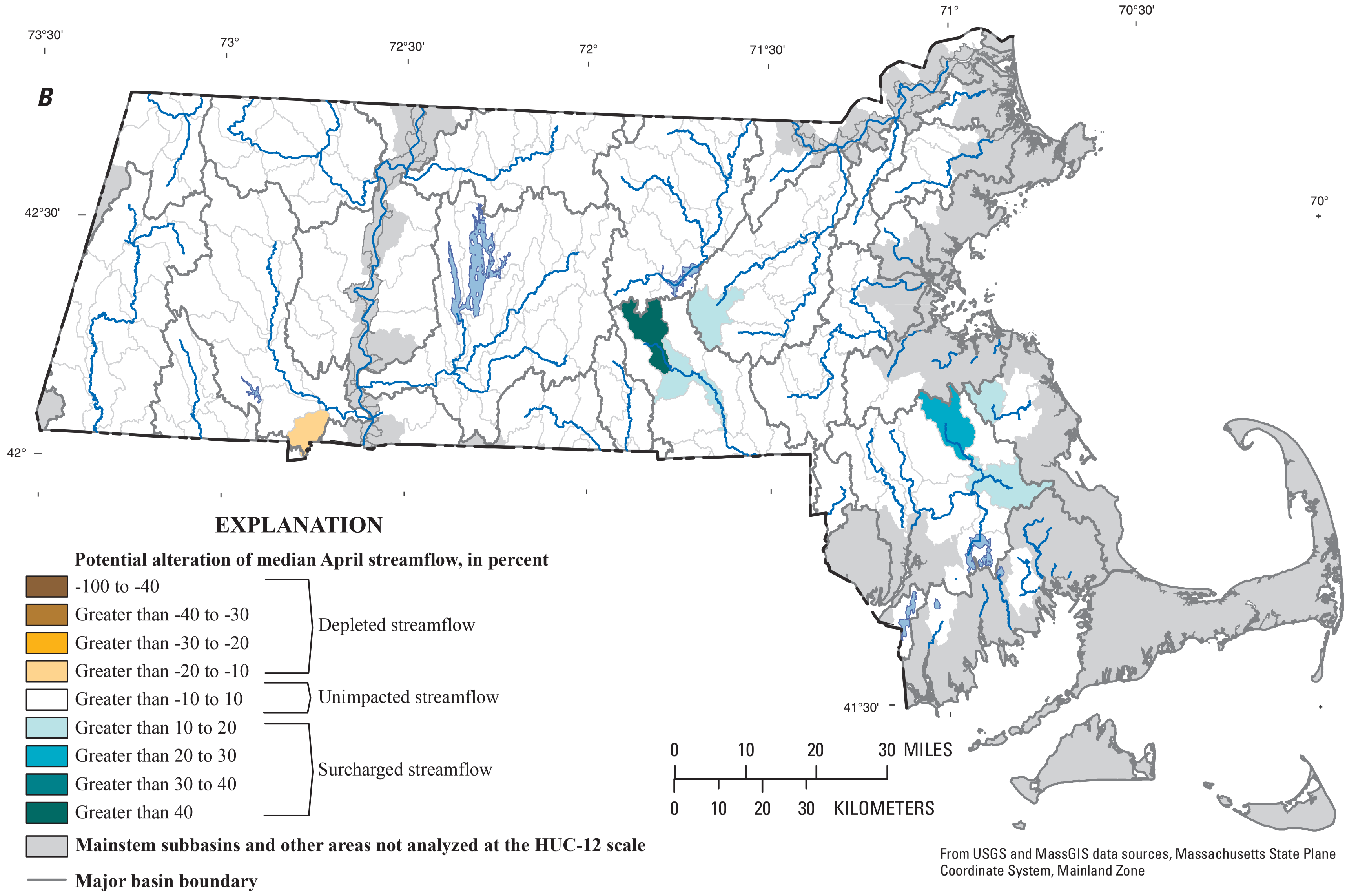

Figure 7. *(A)* Potential alteration of median April streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median April streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

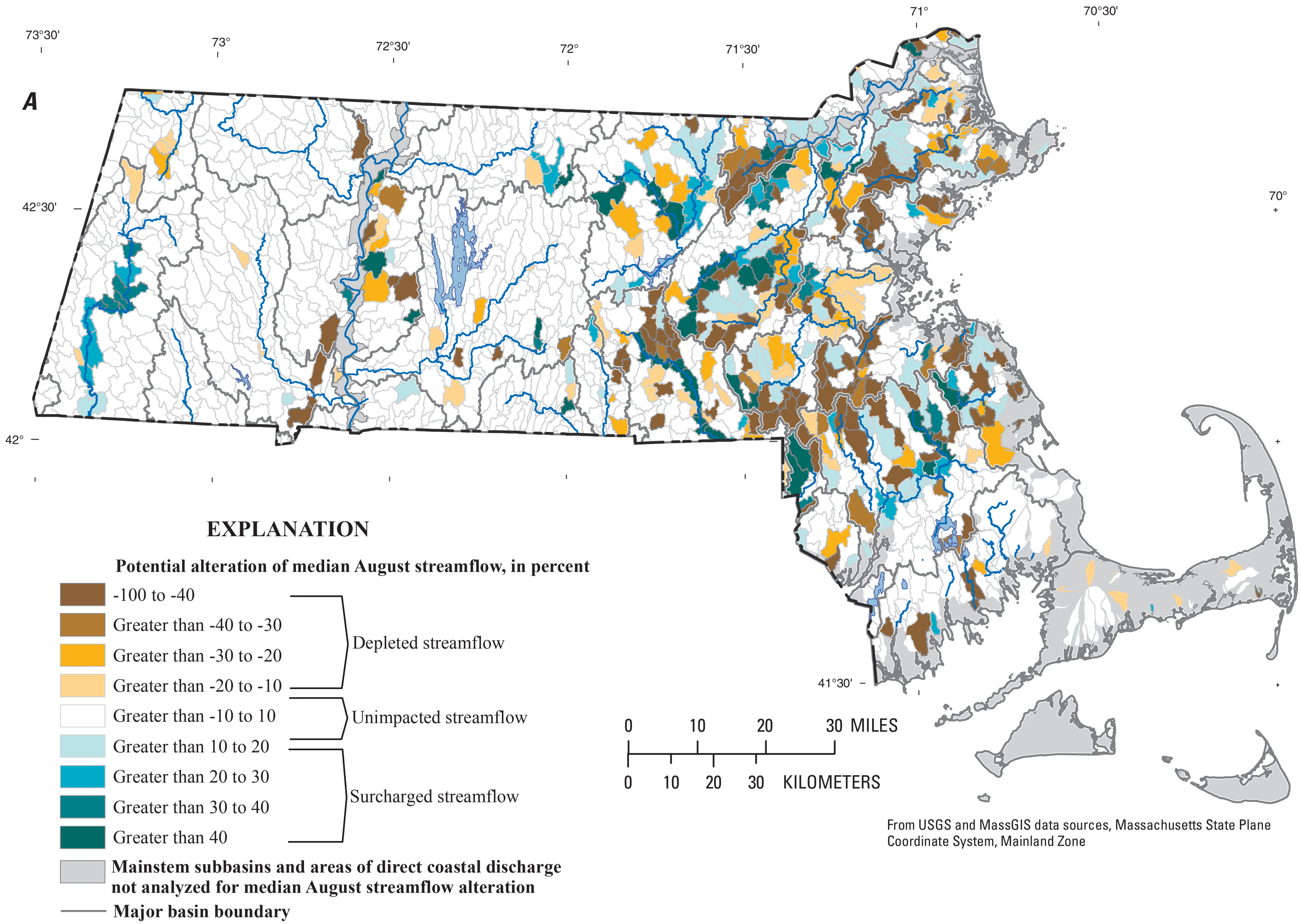

Figure 8. *(A)* Potential alteration of median August streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median August streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

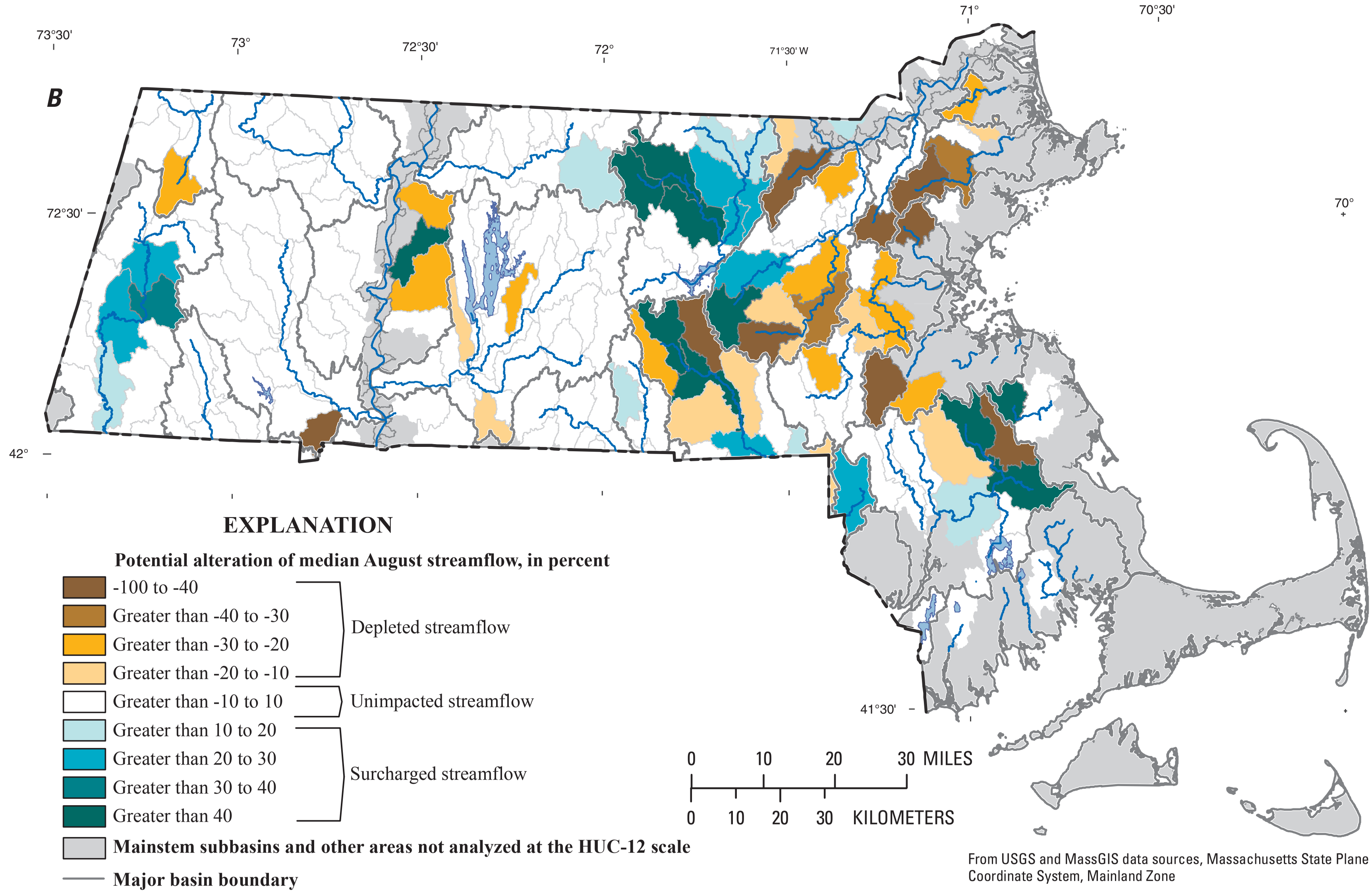

Figure 8. *(A)* Potential alteration of median August streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median August streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

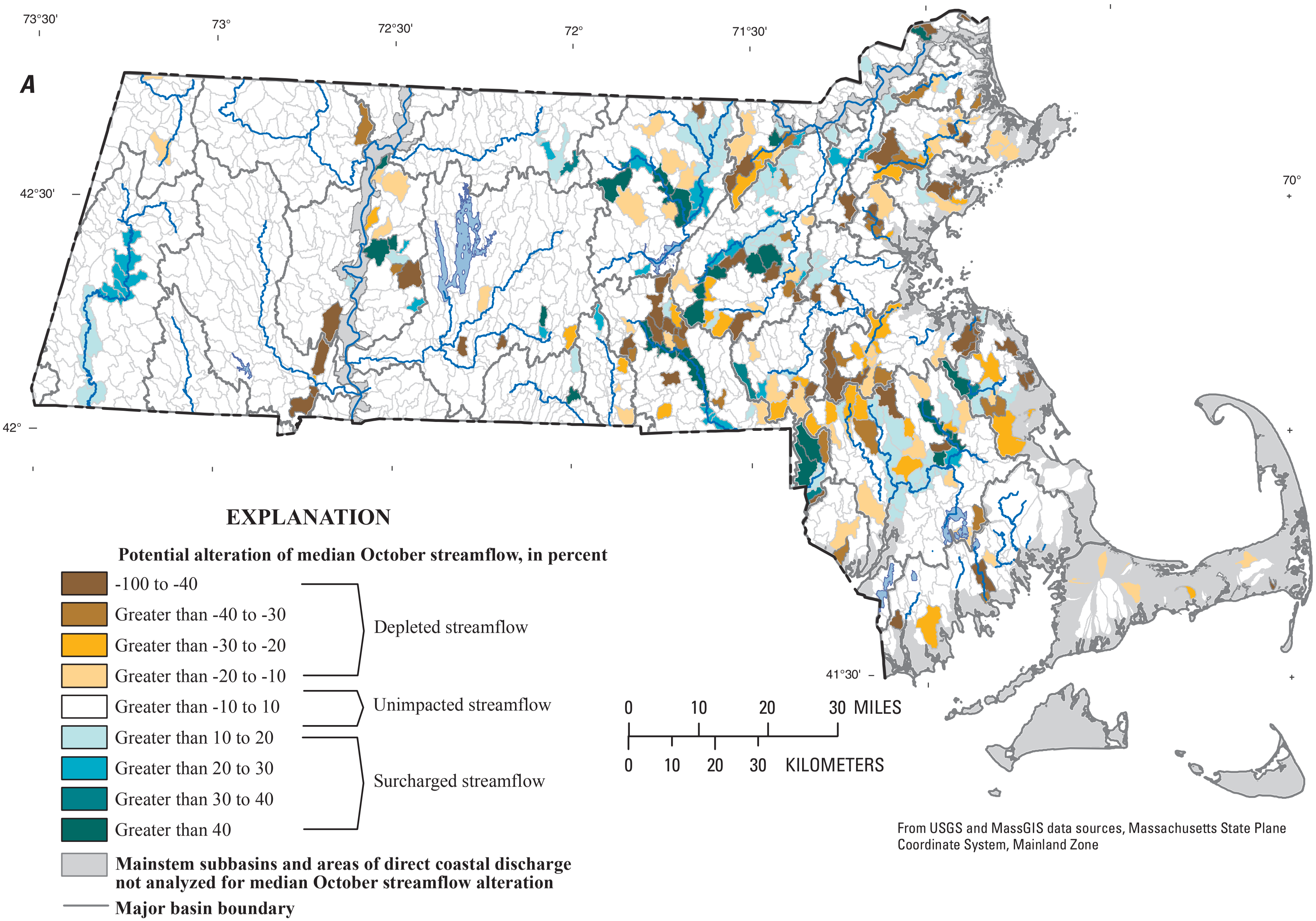

Figure 9. *(A)* Potential alteration of median October streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median October streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

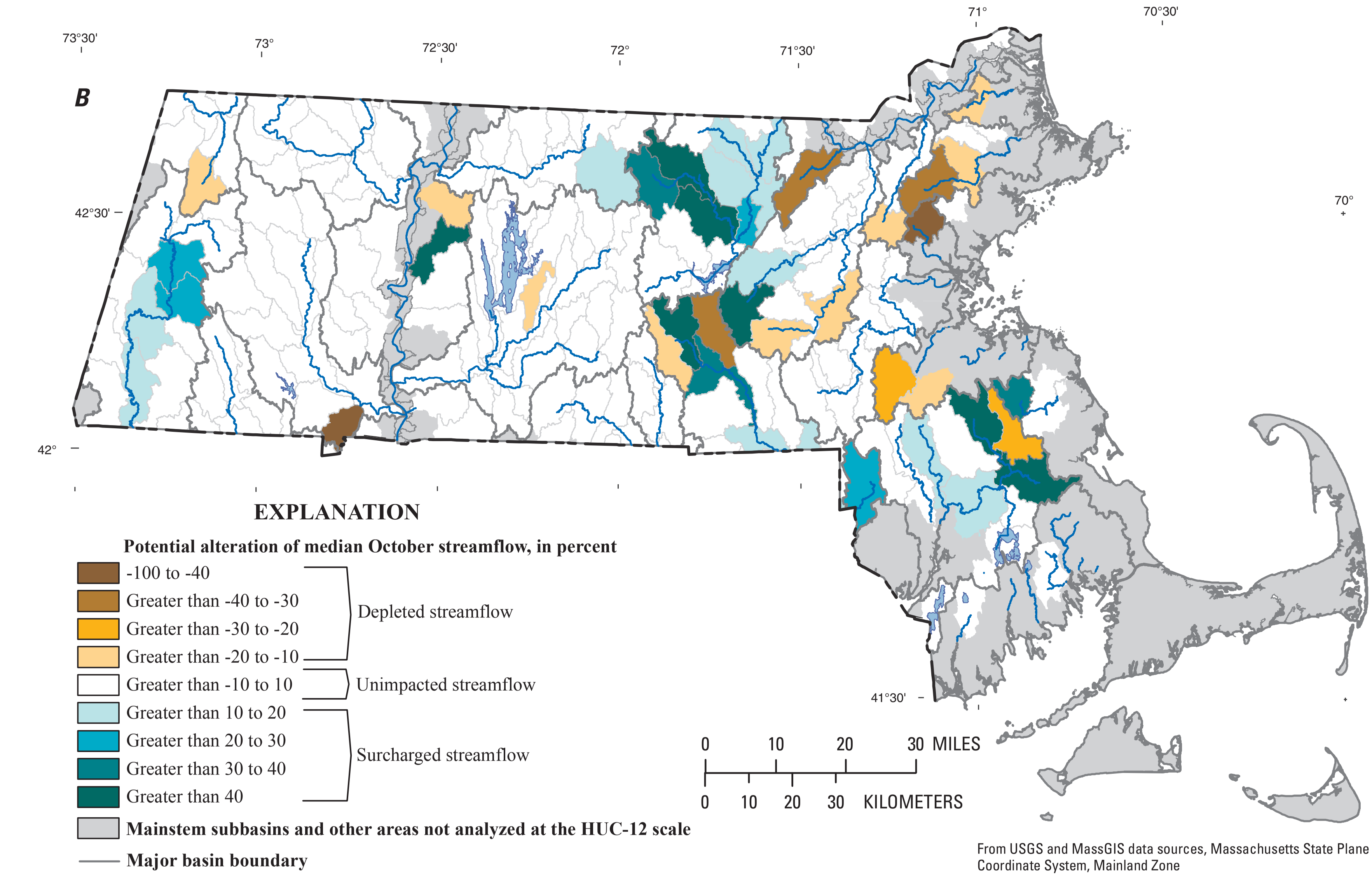

Figure 9. *(A)* Potential alteration of median October streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median October streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

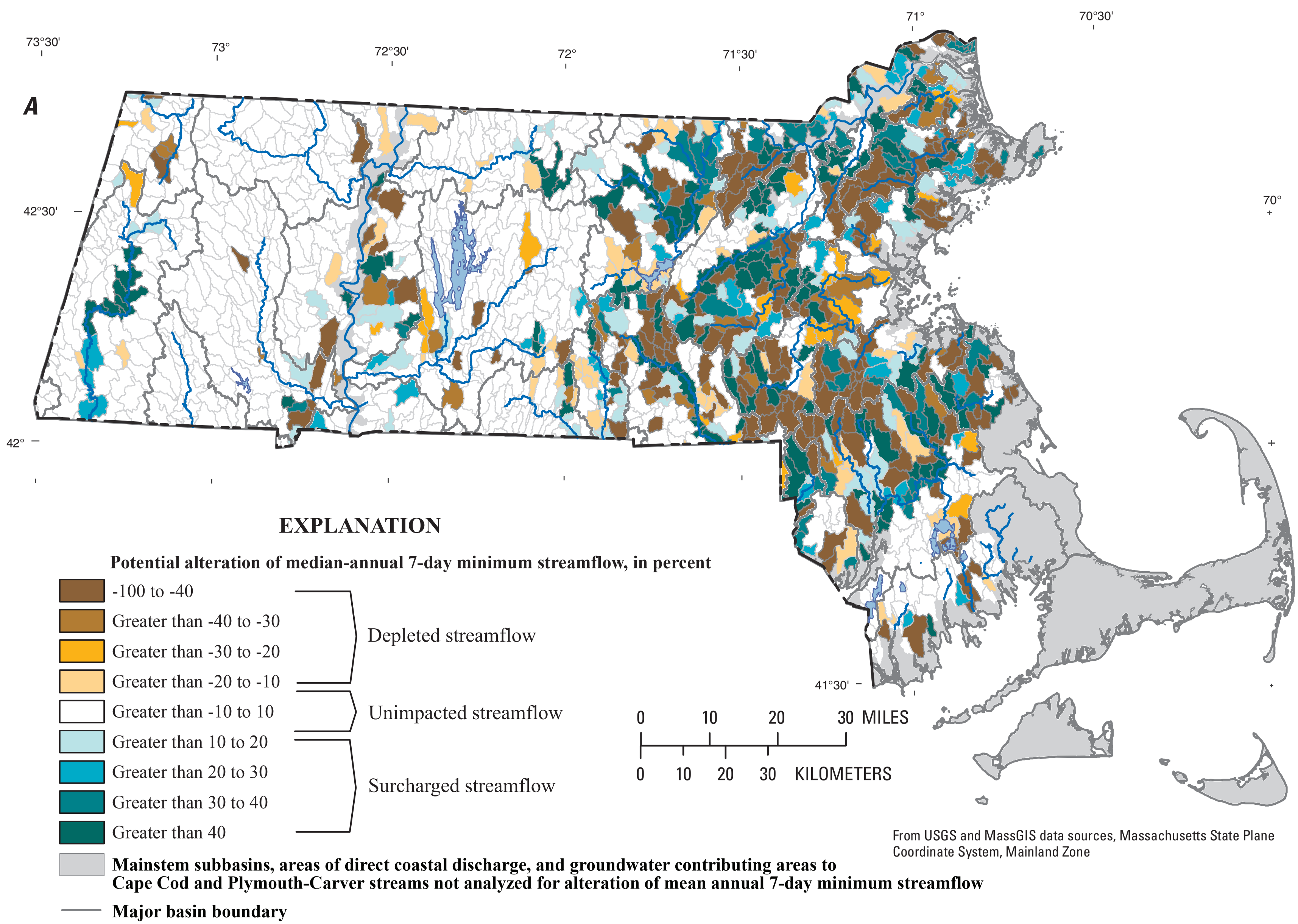

Figure 10. *(A)* Potential alteration of median annual 7-day minimum streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median annual 7-day minimum streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

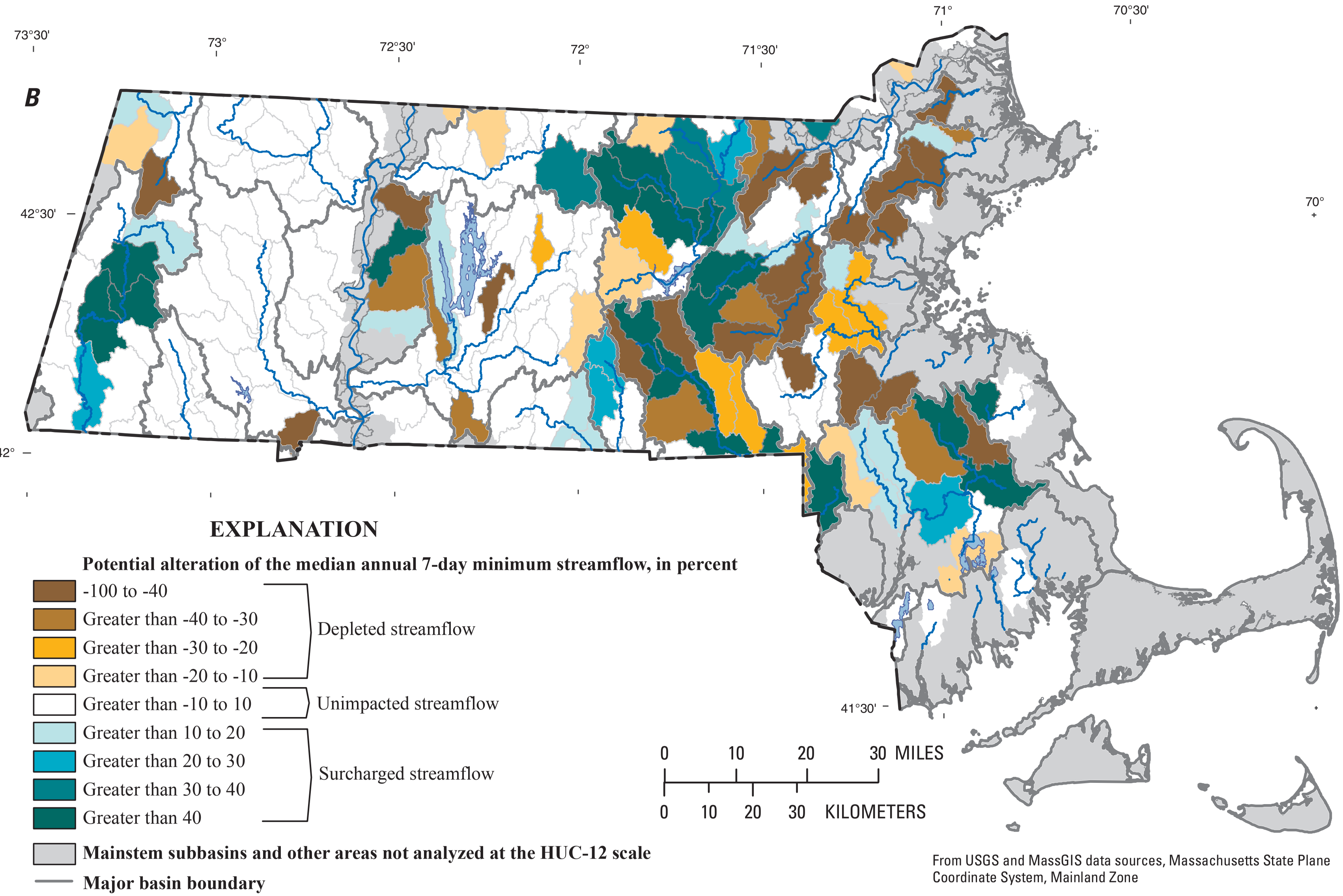

Figure 10. *(A)* Potential alteration of median annual 7-day minimum streamflow in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration of median annual 7-day minimum streamflow in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

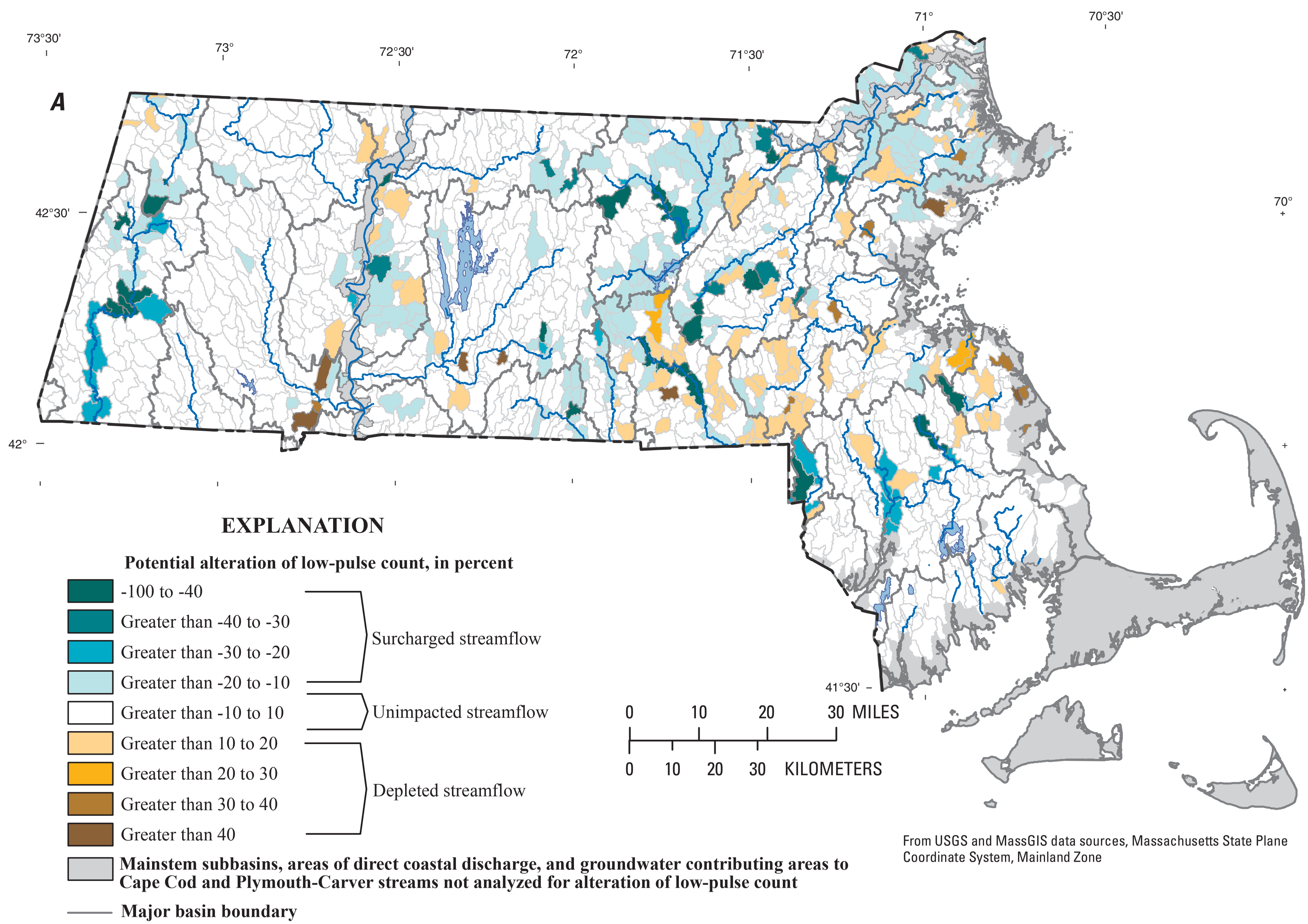

Figure 11. *(A)* Potential alteration in low-pulse count in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration in low-pulse count in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

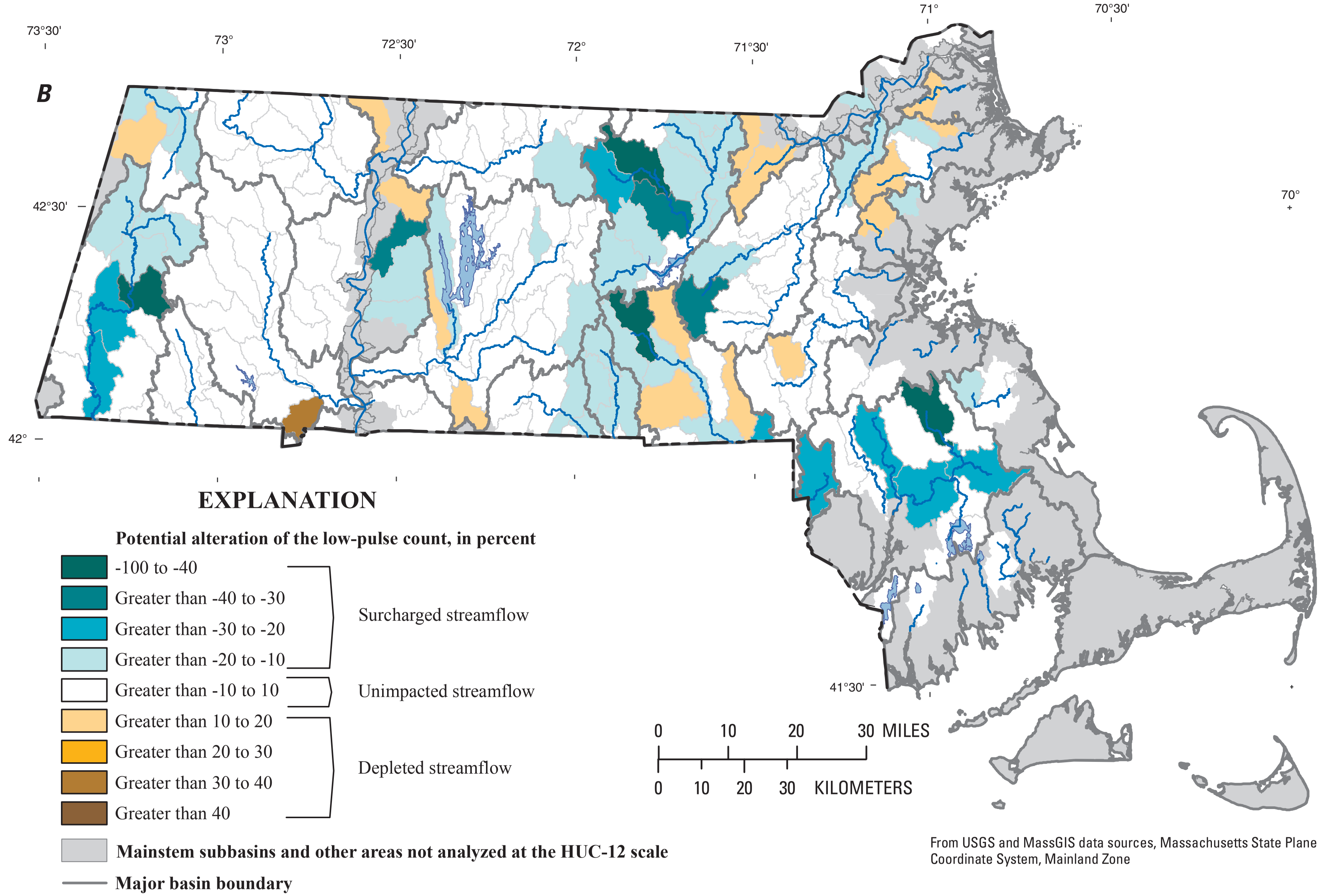

Figure 11. *(A)* Potential alteration in low-pulse count in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration in low-pulse count in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

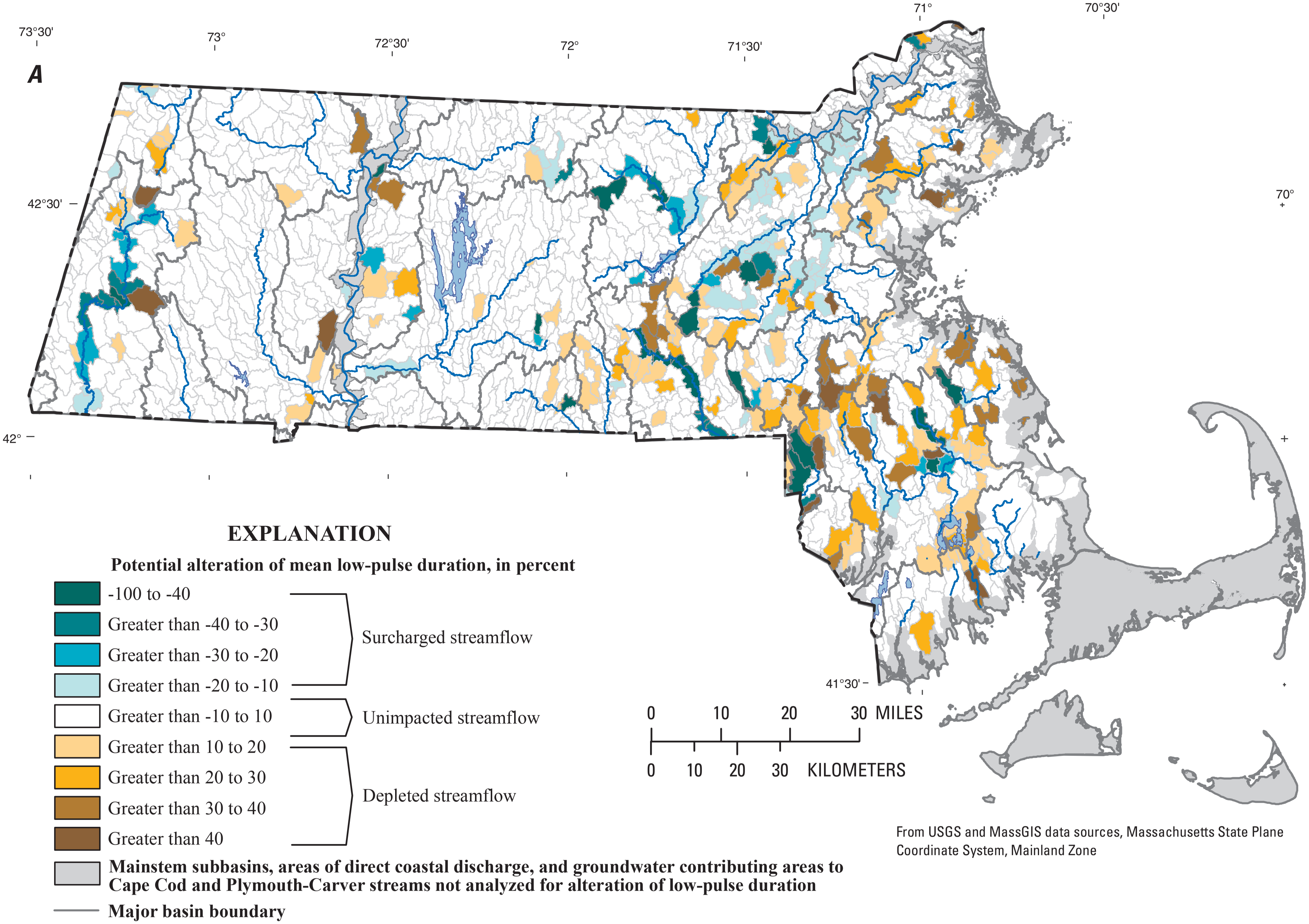

Figure 12. *(A)* Potential alteration in low-pulse duration in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration in low-pulse duration in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).

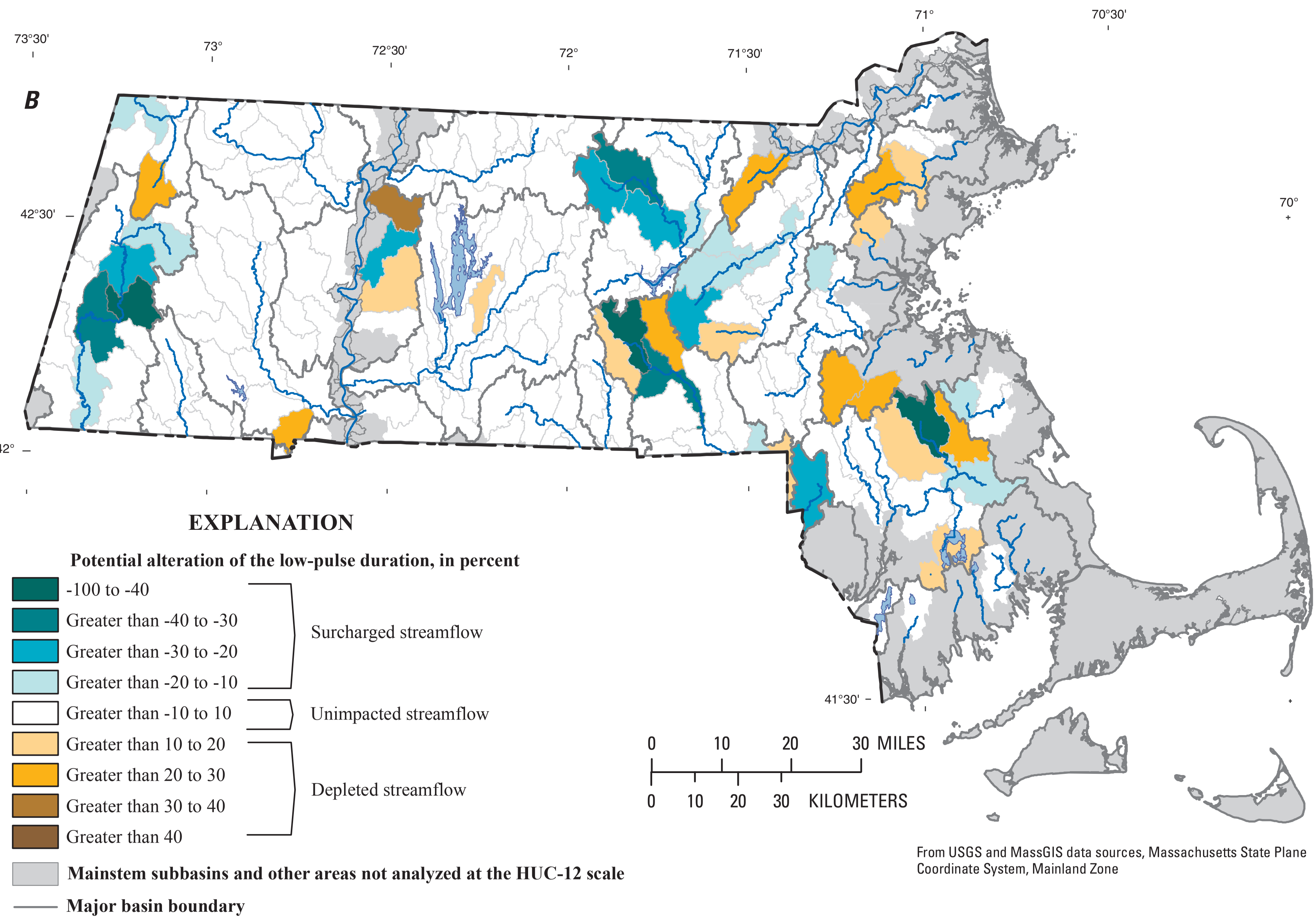

Figure 12. *(A)* Potential alteration in low-pulse duration in Massachusetts, water-use scenario 1 (no surface-water reservoir withdrawals). *(B)* Potential alteration in low-pulse duration in Massachusetts, water-use scenario 1, at the 12-digit Hydrologic Unit (HUC-12) scale (no surface-water reservoir withdrawals).—Continued

Water-Use Scenario 2—Including Surface-Water-Reservoir Withdrawals

Water-use scenario 2 incorporated reported surface-water-reservoir withdrawals in addition to all of the water-use categories of scenario 1. The water-use scenario 2 flow-alteration indicators, relative net demand (RND) and water-use intensity (modified from Weiskel and others, 2007), were both calculated for long-term, mean annual streamflow and water-use conditions. As previously discussed, these are the only conditions under which the effects of surface-water-reservoir withdrawals on subbasin outflows can be accurately characterized without site-specific information concerning the hydraulic and operational characteristics of each supply reservoir in the subbasin (Waldron and Archfield, 2006).

Long-term RND is defined as the potential alteration of the long-term, mean annual subbasin outflow, in percent:

$$RND = \left(A / U - 1\right) * 100 , \qquad (3)$$

where

U is the long-term, mean annual unaffected outflow from any subbasin of interest for the period 1961 to 2004; and

A is the mean annual affected outflow, incorporating the effects of groundwater withdrawals, direct surface-water withdrawals from streams, surface-water-reservoir withdrawals, and wastewater discharges averaged over the 2000–2004 period (water-use scenario 2).

Because summer low flows in Massachusetts are substantially lower than mean annual flows per unit basin area (Armstrong and others, 2008), and because summer withdrawals are generally somewhat higher than mean annual withdrawals (fig. 2; table 2), a given value of long-term RND for a particular subbasin can be expected to be associated with a substantially higher percentage of alteration for that subbasin's median August flow, 7-day minimum flow, or other low flows. Therefore, for the purposes of this study, the flow-alteration thresholds designated "near-natural" and "extensive" were set more conservatively for the long-term RND indicator than for the seasonal indicators previously described. Long-term RND values of -5 to +5 percent were chosen to indicate near-natural long-term average conditions, and long-term RND values less than -20 percent or greater than +20 percent were chosen to indicate extensive potential flow alteration by water use.

Long-term RND was indicated to be near-natural (-5 to +5 percent) in 77 percent of the state's subbasins and groundwater contributing areas (table 5; fig. 13), and extensively altered (more negative than -20 percent or more positive than +20 percent) in 5.7 percent, or 81, of the state's subbasins. A total of 66 of these 81 subbasins were indicated to be extensively depleted, and 15 were indicated to be extensively surcharged on a long-term basis. This asymmetry with respect to the number of extensively depleted and surcharged subbasins is evident under both water-use scenarios 1 and 2 (for example, figs. 8 and 13) and likely resulted from the large number and wide distribution of withdrawals as compared to wastewater discharges, which are fewer in number and generally confined to main-stem rivers.

Table 5. Frequency table of annual relative net demand in percent of unaffected streamflow, for 1,429 Massachusetts subbasins and groundwater contributing areas, water-use scenario 2 (including surface-water reservoir withdrawals).

[For each range of relative net demand, the number of subbasins and groundwater contributing areas in the range, and the percentage of the total is given. Negative values of annual relative net demand indicate potential streamflow depletion by net water use; positive values indicate potential net surcharging from water use. Water-use scenario 2 includes surface-water reservoir withdrawals; <, less than]

Ranges of long-term annual relative net demand (percent of unaffected flow)	Number of subbasins and groundwater contributing areas in each range	Percentage of total
-100 to <-80	0	0.00
-80 to <-70	1	0.07
-70 to <-60	3	0.21
-60 to <-50	6	0.42
-50 to <-40	11	0.77
-40 to <-30	14	0.98
-30 to <-20	31	2.17
-20 to <-15	42	2.94
-15 to <-10	51	3.57
-10 to <-5	111	7.77
-5 to <0	690	48.29
0 to <5	414	28.97
5 to <10	26	1.82
10 to <15	11	0.77
15 to <20	3	0.21
20 to <30	8	0.56
30 to <40	5	0.35
40 to <50	1	0.07
50 to <60	0	0.00
60 to <70	0	0.00
70 to <80	1	0.07
80 to <100	0	0.00

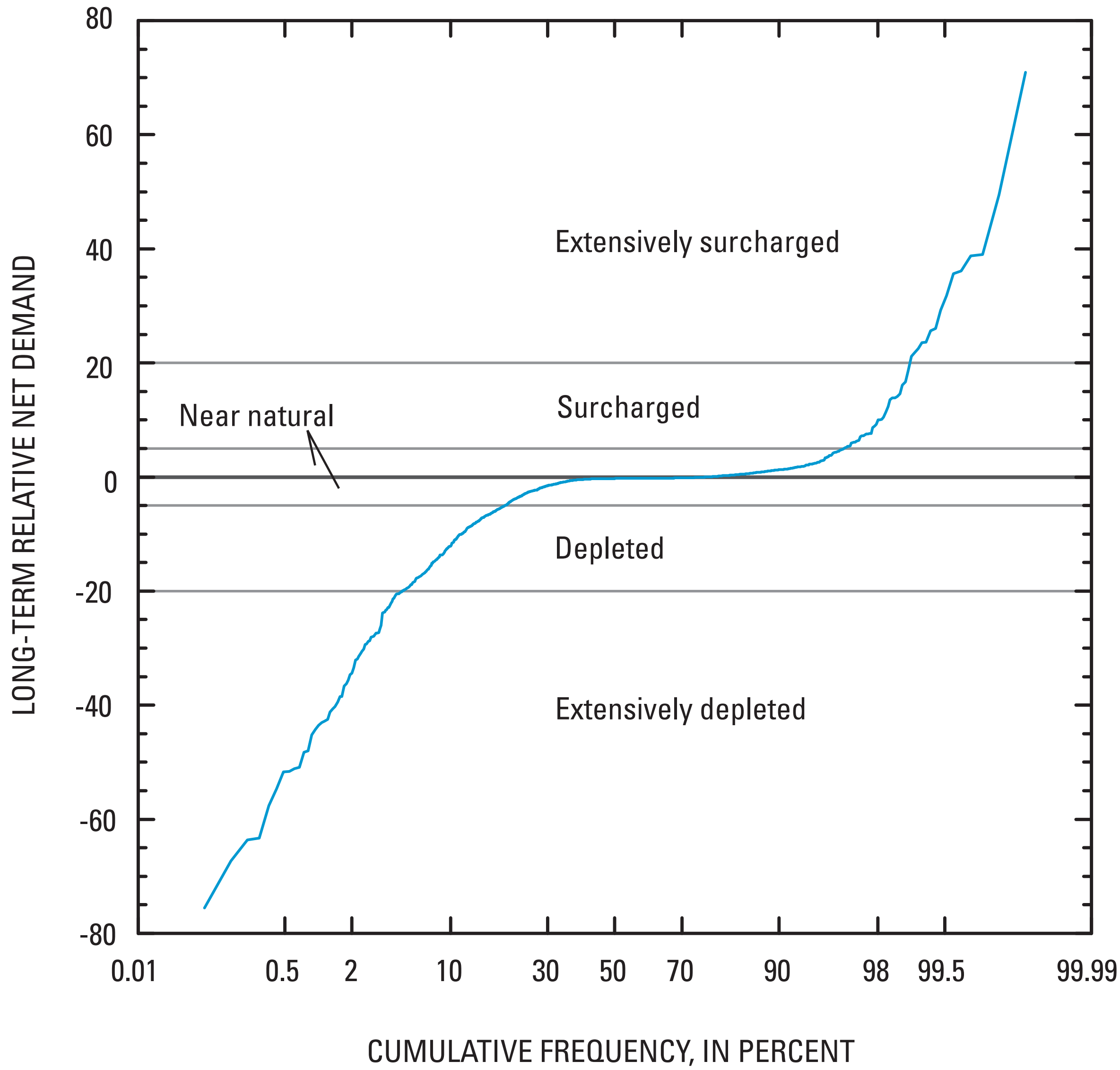

Figure 13. Cumulative frequency distribution of the potential alterations of long-term relative net demand, water-use scenario 2 (with surface-water reservoir withdrawals).

The geographic distribution of long-term RND (fig. 14; figs. 1–8) indicates the effects of all types of reported—as well as estimated domestic—withdrawals and discharges on the long-term-average water balance of Massachusetts subbasins. The potential effects of surface-water-reservoir withdrawals on subbasin water balances (for example, in the Westfield, Chicopee, Nashua, Blackstone, Charles, Ipswich, Weymouth-Weir, Taunton, Merrimack, and Buzzards Bay Basins) are particularly evident in maps of the long-term RND indicator. These effects are to be expected, because large areas of numerous Massachusetts subbasins were acquired and protected over the past 160 years specifically for the purpose of supplying drinking water to cities (Weiskel and others, 2005). As previously noted, the seasonal effects of surface-water withdrawals on downstream flows were not estimated by the present study because the information required to assess these effects was not available statewide. Depending upon how a water-supply reservoir is operated, the seasonal effects of reservoir withdrawals on downstream flow regimes may be greater than, similar to, or less than the seasonal effects of the groundwater withdrawals and the surface-water and groundwater discharges under water-use scenario 1 (for example, see fig. 8). Given the current state of knowledge, long-term RND is best viewed as an indicator of the potential long-term effects of all types of water use, including withdrawals from surface-water reservoirs, on streamflow and aquatic habitat. Strongly negative RND values for a particular subbasin with water-supply reservoirs indicate that reservoir-specific data collection and simulation modeling may be needed in order to fully assess streamflow impacts and evaluate optimal management strategies for meeting both water-supply needs and instream flow targets in downstream ecosystems. Conversely, strongly positive long-term RND values indicate reaches where site-specific studies may be needed to assess the degree of disturbance to the natural flow regime by treated wastewater discharges and the overall assimilative capacity of downstream reaches in relation to the wastewater-discharge regime.

RND indicates the long-term net alteration of subbasin outflow by withdrawals and discharges under water-use scenario 2. However, if subbasin withdrawals (H_{out}) and return flows (H_{in}) are similar in magnitude, they may have little net effect on the long-term outflow from a subbasin, but nonetheless represent a substantial fraction of the subbasin water budget and a potential source of water-quality and habitat impairment. The water-use-intensity indicator, when applied in combination with RND under water-use scenario 2, can be used to identify human-flow-dominated, or churned, water-use regimes (Weiskel and others, 2007). Long-term water-use intensity is defined, for the purposes of this report, as the total magnitude of human flows to and from a subbasin ($H_{out} + H_{in}$) relative to the long-term average unaffected outflow from the subbasin (U) and is expressed as a percentage of the unaffected annual outflow (modified from Weiskel and others, 2007):

$$\mathit{Water\text{-}Use\ Intensity} = \left[\left(H_{out} + H_{in}\right) / U\right] * 100 , \qquad (4)$$

Table 6. Frequency table of annual water-use intensity in percent of unaffected flow, for 1,395 Massachusetts subbasins, water-use scenario 2 (including surface-water reservoir withdrawals).

[Water-use scenario 2 includes surface-water reservoir withdrawals; <, less than]

Ranges of annual water-use intensity (percent of unaffected flow)	Number of subbasins in each range	Percentage of total
Less than 0.0001	0	0.00
0.0001 to <0.001	2	0.14
0.001 to <0.01	25	1.79
0.01 to <0.1	396	28.39
0.1 to <1	464	33.26
1 to <5	155	11.11
5 to <10	186	13.33
10 to <20	84	6.02
20 to <30	26	1.86
30 to <40	20	1.43
40 to <50	32	2.29
50 to <100	3	0.22
100 to <200	2	0.14
200 to <300	0	0.00
Greater than 300	0	0.00

Subbasin water-use intensities may range from zero (no withdrawals or discharges in a subbasin) to arbitrarily large positive values (withdrawals plus discharges that are large relative to natural outflows from a subbasin).

Water-use intensity was found to be a highly sensitive indicator of water-use conditions in Massachusetts subbasins, varying by over four orders of magnitude (10,000-fold) across the state (from 0.0044 to 230 percent of unaffected flows; table 6). Under long-term average conditions, 64 percent of the state's subbasins were indicated to have near-natural water-use intensities (defined, for the purposes of this study, as a water-use intensity of less than 5 percent), whereas 12 percent of the state's subbasins were indicated to have extensive potential alteration by water use (intensities greater than 20 percent). The geographic distribution of water-use intensity was similar to that of RND (figs. 15A and 15B). As with RND, low water-use intensities were associated with relatively undeveloped subbasins of low population density served by private domestic wells and septic systems. High water-use intensities were in subbasins across the state with high rates of withdrawal, discharge, or both.

Figure 16 shows the relation between long-term average RND and water-use intensity for Massachusetts subbasins and also indicates the long-term average distribution of churned, surcharged, depleted, and near-natural water-use regimes in Massachusetts based on the indicator threshold values defined above for RND and water-use intensity. The majority of subbasins (887, or 64 percent statewide) were indicated to have near-natural water-use regimes, with intensities less than 5 percent and RND between -5 and 5 percent. Depleted regimes were indicated for 255, or 18 percent, of the subbasins (RND less than -5 percent). Churned regimes were indicated for 199, or 14 percent of the subbasins (intensities greater than 5 percent, and RND between -5 and 5 percent), and surcharged regimes were indicated for 54, or 4 percent, of the subbasins (RND greater than 5 percent). Subbasins with similar degrees of potential flow alteration, as indicated by long-term RND, can have substantially different water-use intensities (fig. 16).

Long-term RND and water-use intensity were also determined at the HUC-12 scale under water-use scenario 2 (including reservoir withdrawals; figs. 14B, 15B). At this scale, potential alteration of streamflow by large reservoirs serving metropolitan Boston, and cities such as Springfield, Cambridge, New Bedford, and Fall River are apparent. However, the potential effects of smaller reservoirs on streamflows, which are apparent at the subbasin scale (fig. 14A), may be masked at the HUC-12 scale. Water-use intensity at the HUC-12 scale (fig. 15B) indicates the effects of both large reservoir withdrawals and large discharges of treated wastewater.

A total of 45 HUC-12s, or 24 percent of the statewide total, were found to have churned water-use regimes (defined, for the purposes of this study, as a condition where RND is between -5 and 5 percent and water-use intensity is greater than 5 percent). A greater percentage of basins are churned at the HUC-12 scale (24 percent) than at the subbasin scale (12 percent) because of the larger spatial scale of aggregation for withdrawals and discharges. A total of 97 HUC-12s (53 percent) had near-natural water-use regimes (water-use intensities less than 5 percent, and RND between -5 and 5 percent). Depleted regimes (RND less than -5 percent) were indicated in 18 percent of the subbasins, and surcharged regimes (RND greater than 5 percent) in 5 percent of the subbasins.

The relative proportions of the four respective basin water-use regimes (near-natural, churned, depleted, and surcharged) are generally similar at the subbasin and HUC-12 scales of analysis. However, the differences in regime distribution between the two scales merit further consideration. First, as previously noted, the larger scale of aggregation results in a greater prevalence of churned conditions at the HUC-12 scale than at the subbasin scale (24 percent compared to 14 percent of basins). Second, surcharged conditions were more common at the HUC-12 scale (5 percent compared to 4 percent of basins). Third, the higher percentage of churned and surcharged basins results in a smaller number of near-natural basins and basin area at the HUC-12 scale (53 compared to 64 percent of the subbasins statewide. Finally, the percentage of depleted basins is about the same at both scales (18 percent), consistent with the more even spatial distribution of reported withdrawals (especially groundwater withdrawals) across the state compared to reported discharges, which are generally concentrated along the larger main-stem rivers. These scale-related effects are important to consider in the interpretation of the flow-alteration indicators of this study at the subbasin and HUC-12 scales.

Indicators of Potential Streamflow Alteration and Habitat Fragmentation by Dams

Massachusetts has one of the highest concentrations of dams of any state in the Nation (U.S. Army Corps of Engineers, 1996); Worcester County in central Massachusetts ranks first among the 3,043 U.S. counties in the number of dams listed in the National Inventory of Dams (425; Graf, 1999). This high concentration of dams reflects the state's long industrial history, which began in the 1630s when North America's first grist mills were built on the Charles and Neponset Rivers. Because of the high concentration of dams in Massachusetts, it is important to consider the potential ecological effects of dams in any statewide set of basin-alteration indicators.

Evaluation of the effects of dams on the stream ecosystems of New England has only recently begun (for example, Nislow and others, 2002; Zimmerman and Lester, 2006; Gephard, 2008). In general, dams and their impoundments, whether constructed for flood control, hydropower, recreation, or water supply, have the potential to affect stream ecosystems in three principal ways. First, dams alter streamflow regimes, sediment transport, and the associated physical habitats in both impounded and downstream river reaches. Second, dams alter temperature and dissolved oxygen regimes in both impounded and downstream waters, affecting the physiology and species composition of fish communities and other biota. Finally, dams are one of the most important factors affecting the connectivity of stream ecosystems, restricting the free passage of nutrients, fish, and other biota, and thus the availability of critical habitats for migratory species such as herring and salmon (Bednarek, 2001; Poff and Hart, 2002; Gephard, 2008). These potential effects apply to all types of dams and impoundments, not just to those associated with public-supply reservoirs. The actual degree of ecological impact from a given dam and impoundment depends upon a variety of factors, including the stream type, the drainage area and storage-discharge relation for the impoundment, the dam size and control structure(s), and specific management practices at the site. Riverine habitat is also fragmented by road crossings and culverts; however, this type of fragmentation could not be quantified for this project due to the lack of statewide, georeferenced data in electronic form.

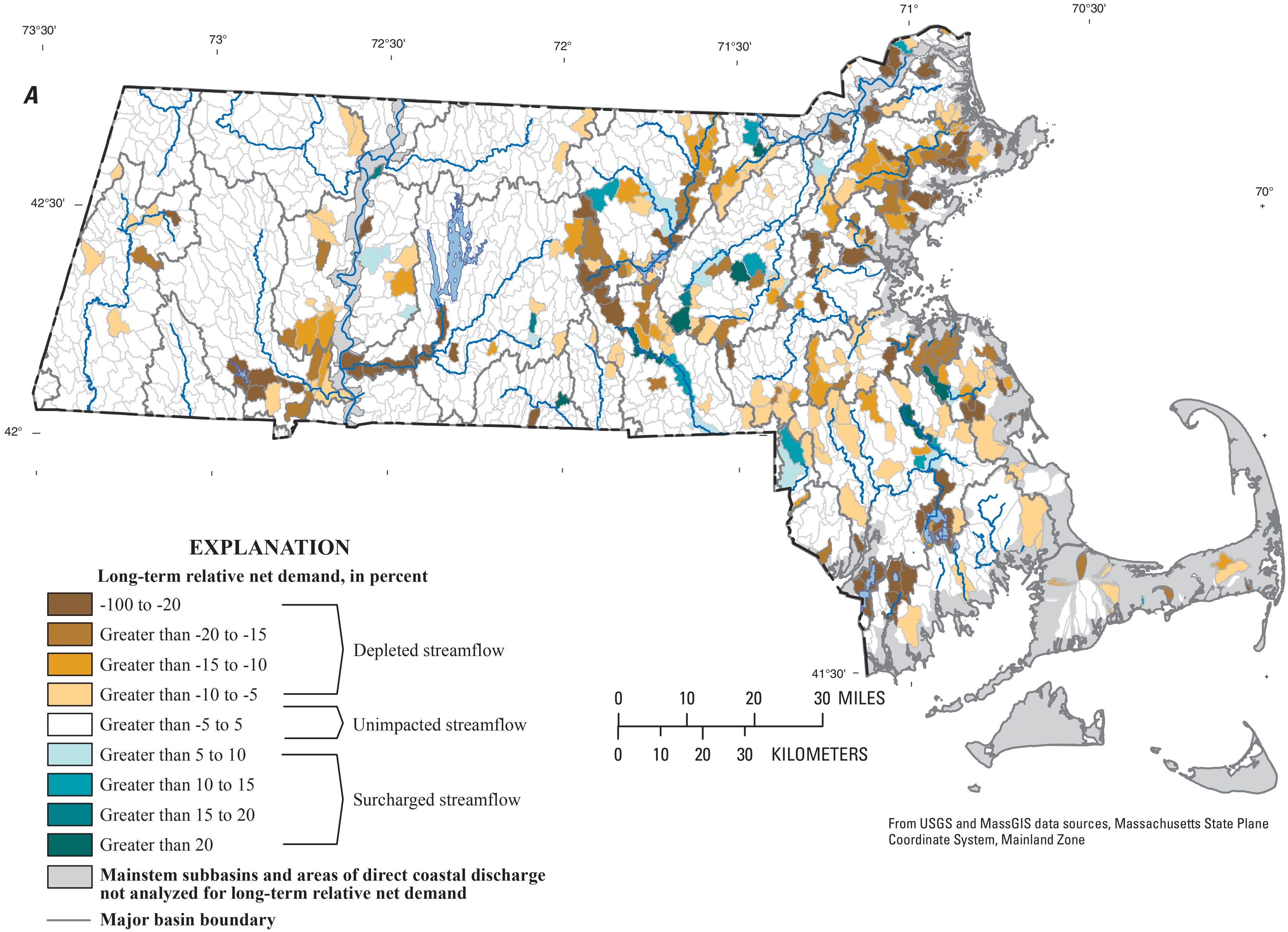

Figure 14. *(A)* Long-term relative net demand, water-use scenario 2 (with surface-water reservoir withdrawals). *(B)* Long-term relative net demand, water-use scenario 2, at the 12-digit Hydrologic Unit (HUC-12) scale (with surface-water reservoir withdrawals).

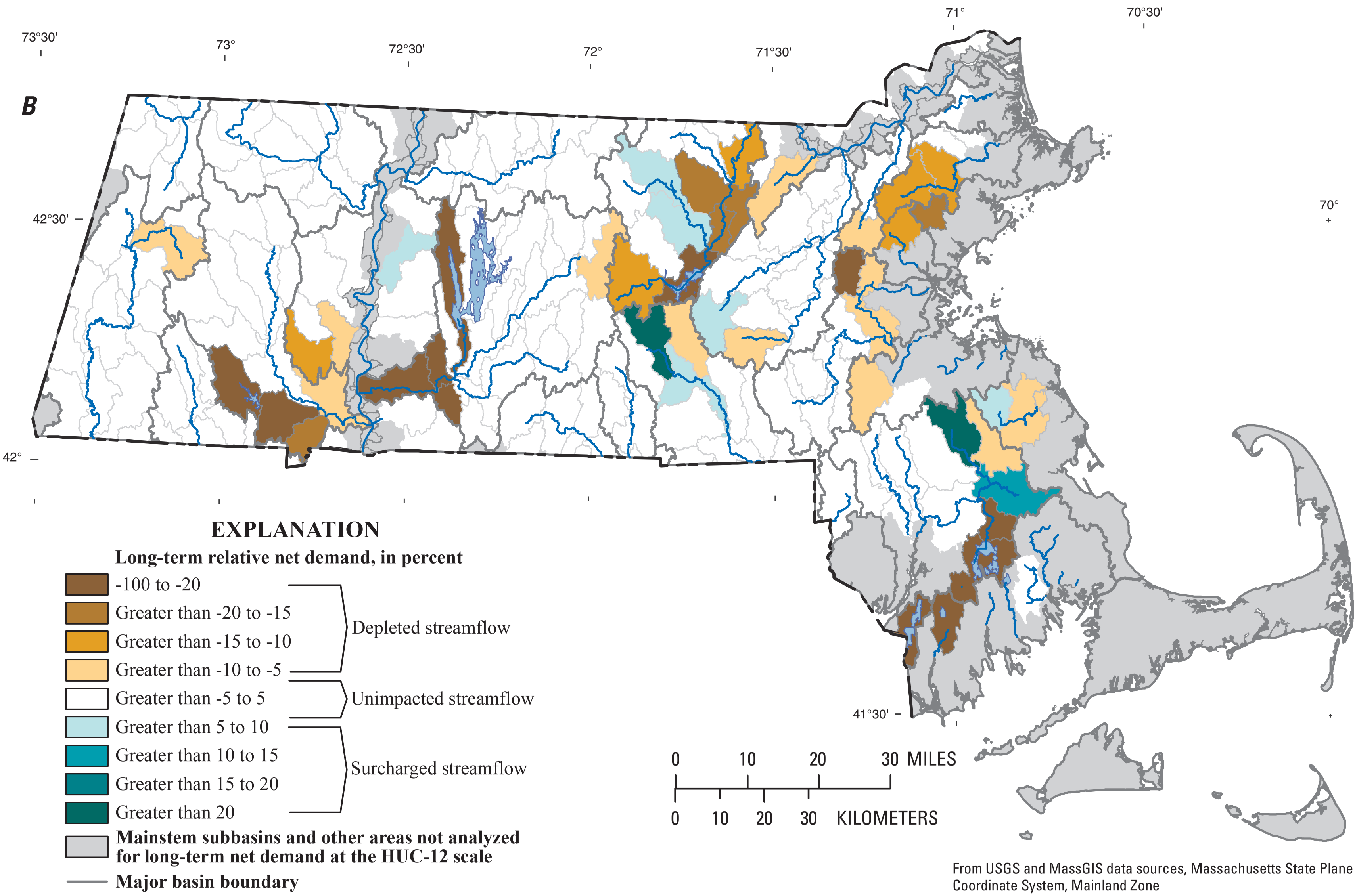

Figure 14. *(A)* Long-term relative net demand, water-use scenario 2 (with surface-water reservoir withdrawals). *(B)* Long-term relative net demand, water-use scenario 2, at the 12-digit Hydrologic Unit (HUC-12) scale (with surface-water reservoir withdrawals).—Continued

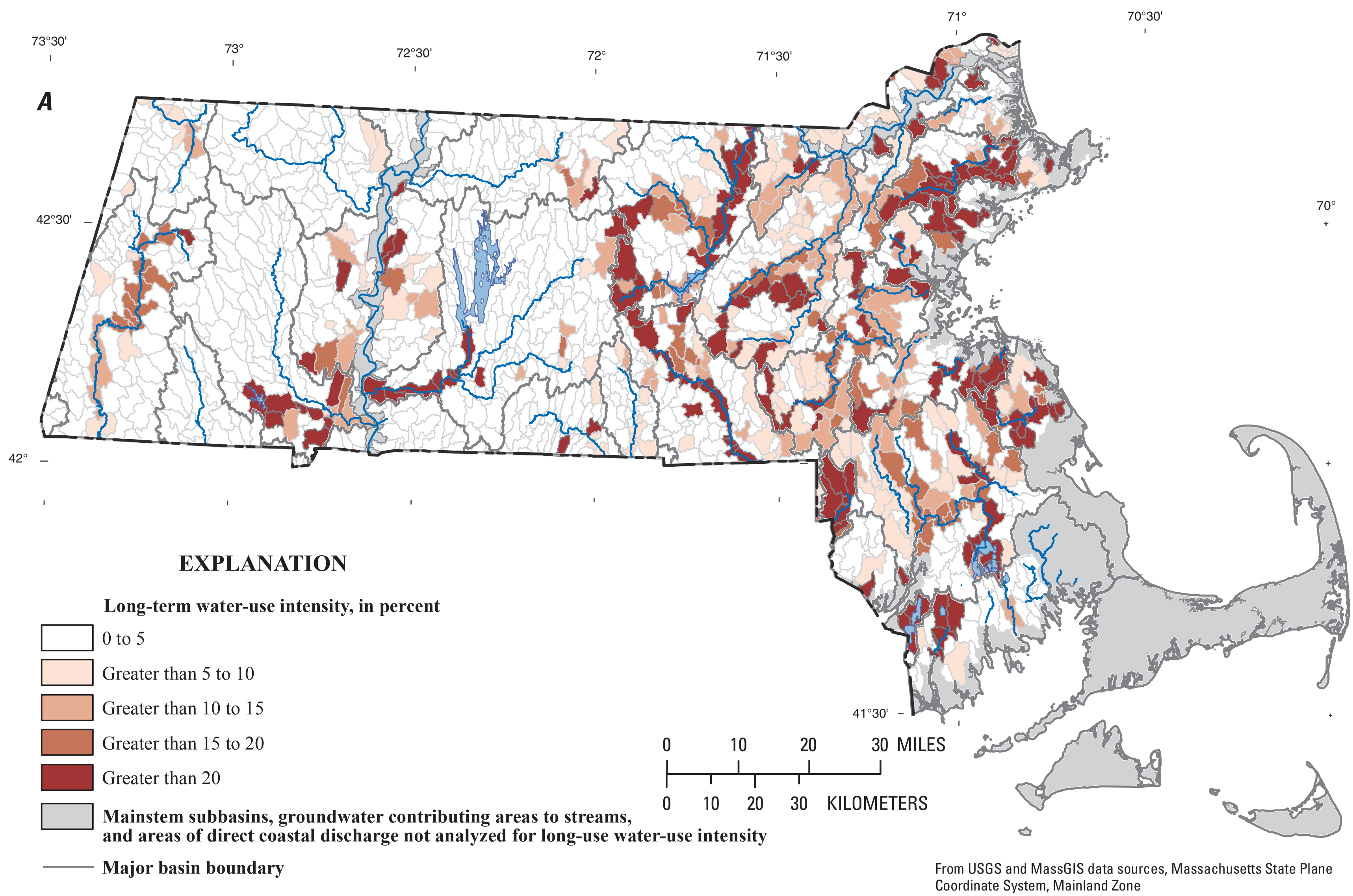

Figure 15. *(A)* Long-term water-use intensity, water-use scenario 2 (with surface-water reservoir withdrawals). *(B)* Long-term water-use intensity, water-use scenario 2, at the 12-digit Hydrologic Unit (HUC-12) scale (with surface-water reservoir withdrawals).

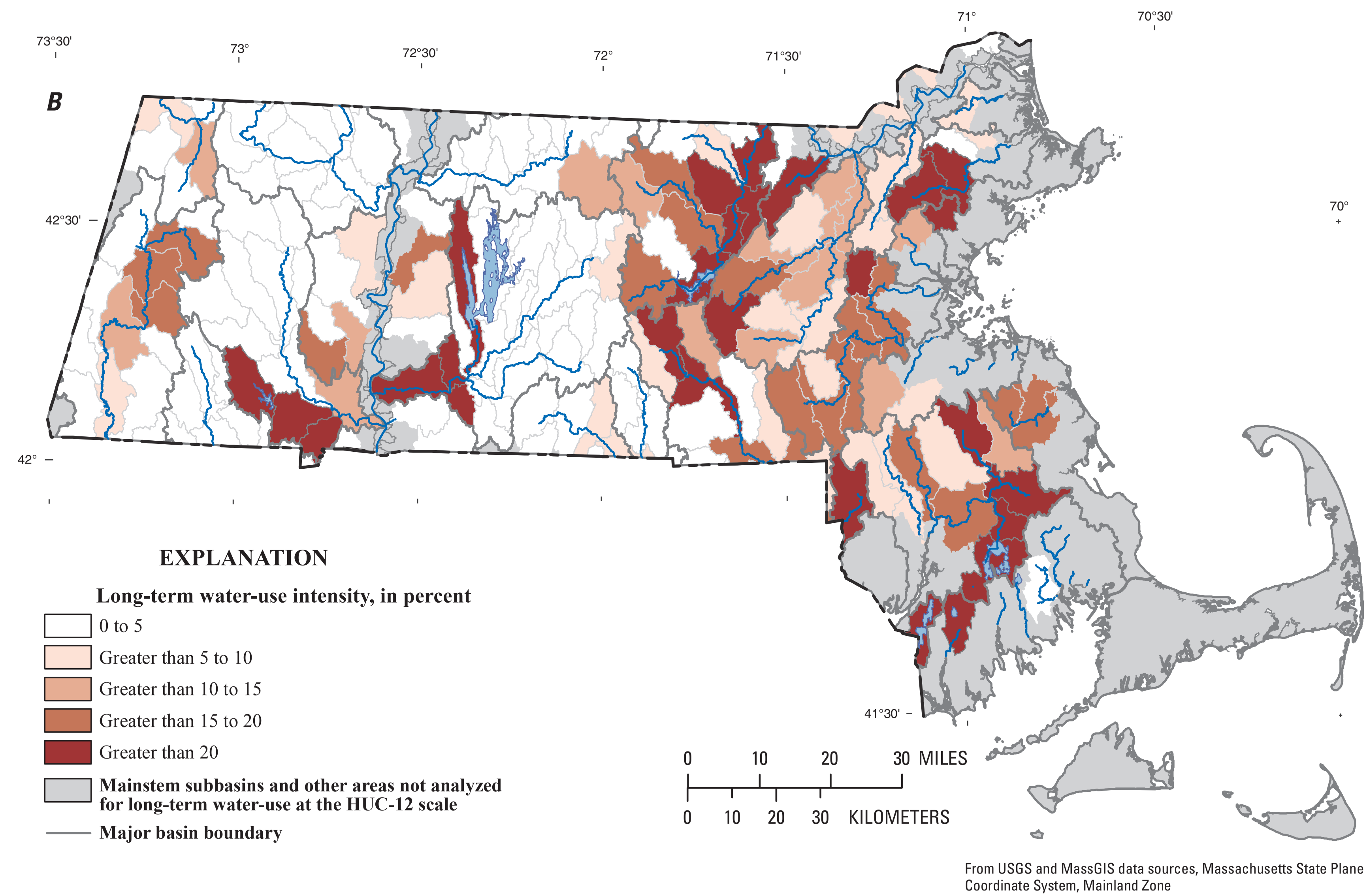

Figure 15. *(A)* Long-term water-use intensity, water-use scenario 2 (with surface-water reservoir withdrawals). *(B)* Long-term water-use intensity, water-use scenario 2, at the 12-digit Hydrologic Unit (HUC-12) scale (with surface-water reservoir withdrawals).—Continued

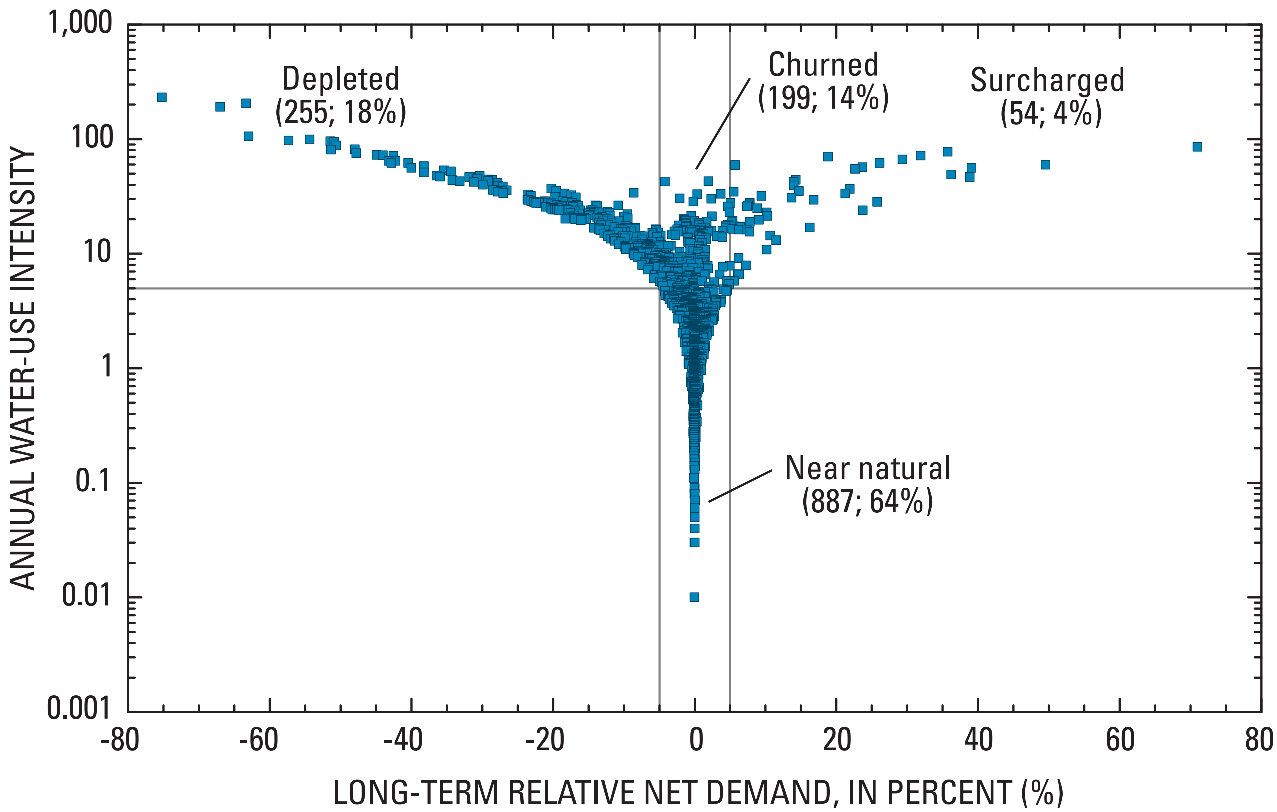

Figure 16. Relation of long-term relative net demand to water-use intensity, water-use scenario 2. Number of subbasins and groundwater contributing areas in each water-use-regime class, and percentage of the total in each class, are given in parentheses.

Quantifying Potential Dam Effects

At a screening level of analysis, two indicators are commonly used in the literature to represent the potential impacts of dams. The first is the reservoir storage ratio (SR), in units of days:

$$SR = (V_{max}) / U_{dam} , \quad (5)$$

where

V_{max} is the maximum impounded storage behind the reservoir dam, in units of volume; and

U_{dam} is the predevelopment, long-term mean annual streamflow at the dam location, in units of volume per time.

This indicator is used to assess the first class of potential impacts described above—the effects of dams on streamflow and sediment-transport regimes (see, for example, Graf, 1999; Poff and Hart, 2002; Zimmerman and Lester, 2006; Vogel and others, 2007).

The second indicator of potential dam impacts is the dam density (DD), in units of number of dams per stream mile:

$$DD = N_{dams} / SL , \quad (6)$$

where

N_{dams} is the number of dams in a subbasin, and

SL is the total length of streams in a basin, in miles.

This indicator is used to represent the third class of potential dam impacts described above—stream-habitat fragmentation (Graf, 1999; Poff and others, 2007). In this section, methods and findings concerning storage ratio and dam density are presented at the subbasin scale. Both indicators are used in this study to denote potential, rather than actual, ecosystem effects of dams and artificial impoundments. Actual ecosystem impacts depend upon dam-management practices and other site-specific factors that were not addressed in this study.

In order to obtain the SR at the subbasin scale (rather than for individual reservoirs), the Maximum Storage (V_{max}) was determined for 1,678 dams in the National Inventory of Dams (NID; U.S. Army Corps of Engineers, 1996), and the individual values were then added for each subbasin. The sum for each subbasin was then divided by the estimated mean annual unaffected streamflow at the outlet of each subbasin. (A total of 1,497 of the 1,678 dams in the present analysis are in Massachusetts; the remainder are in parts of the study subbasins in adjoining states that contribute streamflow to Massachusetts subbasins.)

To assess dam density, a more extensive data set of 4,025 dam locations was used. This data set was compiled by the Massachusetts Riverways Program (C. Leuchtenburg, Massachusetts Riverways Program, written commun., 2009) and was largely derived from the MDCR Office of Dam Safety database. The number of dams in each subbasin was determined, and then divided by the total stream length in each subbasin. The state data set includes many smaller dams not included in the NID. Although storage information is lacking for these smaller dams, they were included in the dam-density indicator analysis because they have the potential to fragment stream ecosystems.

Storage Ratio and Dam Density

Subbasin SRs were found to vary widely across Massachusetts (table 7; fig. 17). One-third (33 percent) of Massachusetts subbasins have either no impounded storage, or less than 1 day of impounded storage, according to the National Inventory of Dams. These subbasins can be reasonably assumed to have mainly small, run-of-the-river dams with relatively low impact on the overall streamflow regime. By contrast, a total of 45 (or 3 percent of) Massachusetts subbasins have very large storage ratios, with over 1 year of impounded storage (table 7). The potential for extensive alteration of all portions of the streamflow regime is indicated for these subbasins. Our findings are consistent with national analyses (Graf, 1999), which indicate relatively low storage ratios, on average, for New England—in contrast to the western states, where high storage ratios are common. Of the remaining dams in Massachusetts, 64 percent have 1 day to 1 year of impounded storage (table 7; fig. 17).

Table 7. Frequency tables of storage ratio and dam density for Massachusetts subbasins with the number of subbasins and the percentage of the statewide total in each range.

[See text for explanation of indicators; <, less than]

Storage ratio			Dam density		
Days of storage	**Frequency**	**Percentage**	**Dams per stream mile**	**Frequency**	**Percentage**
0	437	30.6	0	250	17.5
0.18 to <0.1	6	0.4	0 to <0.1	252	17.6
0.1 to <1	22	1.5	0.1 to <0.2	422	29.6
1 to <7	131	9.2	0.2 to <0.3	245	17.2
7 to <14	98	6.9	0.3 to <0.4	133	9.3
14 to <30	172	12.0	0.4 to <0.5	59	4.1
30 to <60	156	10.9	0.5 to <0.6	26	1.8
60 to <120	182	12.7	0.6 to <0.8	26	1.8
120 to <365	179	12.5	0.8 to <1.0	6	0.4
>365	45	3.2	1.0 to <1.2	4	0.3
			1.2 to <1.4	4	0.3
			1.4 to <1.6	0	0.0
			1.6 to <1.8	1	0.1
			>1.8	0	0.0

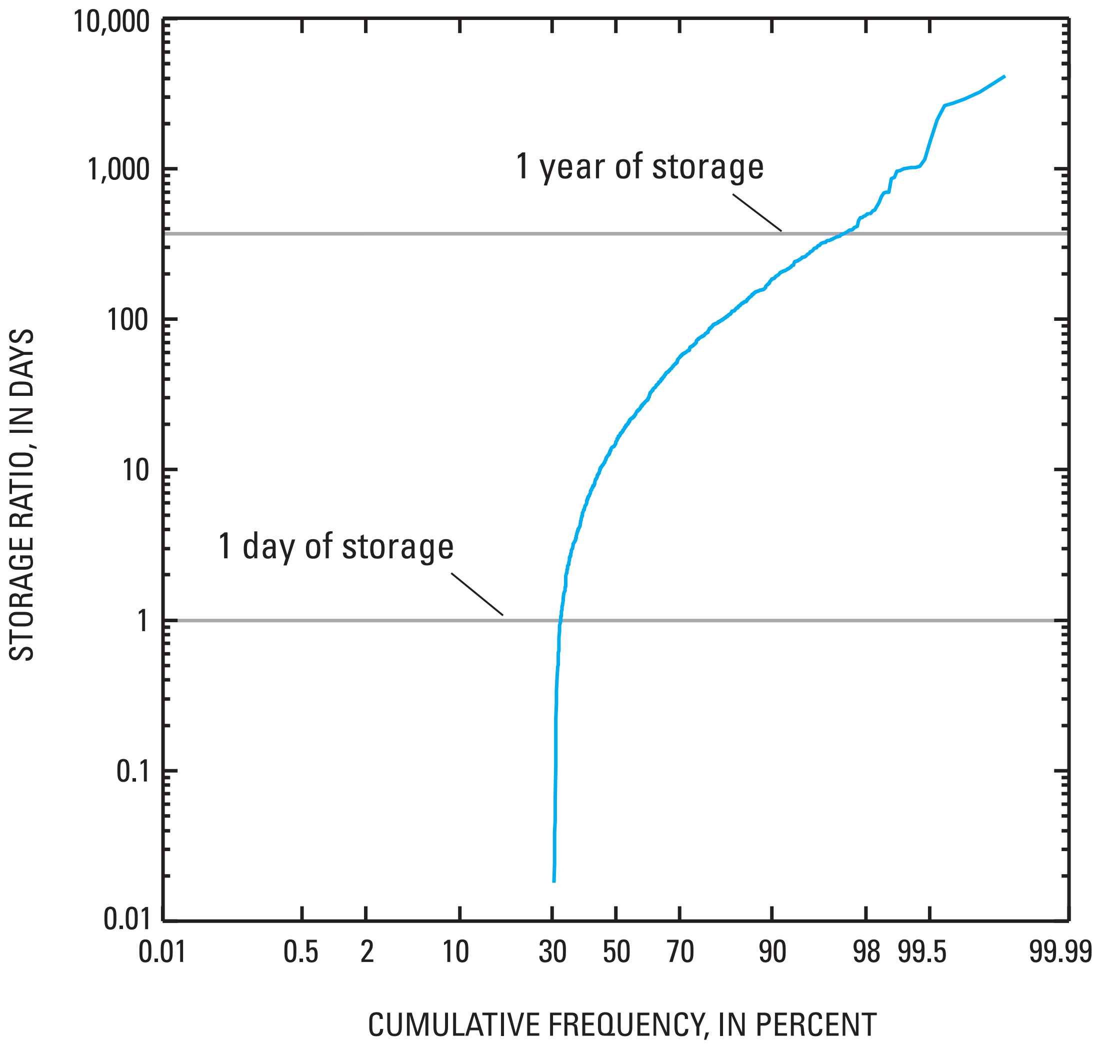

Figure 17. Cumulative frequency distribution of subbasin storage ratios.

Statewide, subbasin storage ratios are greatest in the Deerfield, Westfield, Chicopee, and Nashua River Basins in central and western Massachusetts (fig. 18). In the Deerfield Basin, high storage ratios are especially associated with hydropower operations; the latter three basins reflect the additional effects of large public-supply reservoirs. In eastern Massachusetts, the Charles, North Coastal, Taunton, and Ten Mile Basins all have individual subbasins with high storage ratios. In most cases, these subbasins are actively managed for urban public water supply.

At the HUC-12 scale (fig. 18B), the geographic distribution of storage ratio is generally similar to the distribution at the subbasin scale (fig. 18A). The potential effects of large water-supply and hydropower dams are evident at the HUC-12 scale, but the potential effects of small dams are less evident. In particular, it is more difficult to detect the effects of dams on smaller tributaries, as compared to main-stem rivers, in contributing to the storage ratio at the HUC-12 scale.

Dam density also differs widely among subbasins across the state (table 7, fig. 19). A total of 250 subbasins (18 percent of the statewide total) have no dams recorded in the MassRiverways database. These 250 undammed subbasins differ in drainage area from less than 0.5 mi^2, in the Plymouth-Carver Region, to about 40 mi^2, in the Westfield River Basin, and have a median area of 3.8 mi^2. Eight of the 10 largest undammed subbasins, by area, are in western Massachusetts, with two each in the Westfield, Hudson, and Housatonic Basins, and one in the Chicopee Basin (fig. 20A). Statewide, the median dam density among the 1,429 subbasins was 0.15 dams per stream mile, or about 1 dam per 6.7 miles of stream. Fewer than 1 percent of the subbasins have more than 1 dam per stream mile (table 7). The highest densities are in Worcester County in the Nashua, Blackstone, Millers, and Upper Chicopee Basins (fig. 20A), consistent with an analysis of U.S. counties by Graf (1999). High dam densities, likely associated with cranberry cultivation, are also in the Buzzards Bay state planning basin in the Plymouth-Carver region and in western Cape Cod. As previously noted, dams are one of the main types of human infrastructure that reduces the connectivity of stream ecosystems. The impact of dams on these ecoystems can be expected to be greatest in central Massachusetts and parts of southeastern Massachusetts where the dam densities are highest; however, the nature and extent of these potential ecological effects have not been characterized statewide.

Because dams are so widespread geographically in Massachusetts, dam density is clearly displayed at the HUC-12 scale (fig. 20B). However, the HUC-12 scale of aggregation masks the presence of smaller subbasins with few or no dams in basins with a large total number of dams, such as the Nashua and Blackstone planning basins in central Massachusetts. Conversely, subbasins with dam densities higher than the basin average are generally not apparent.

Indicators of Impervious Cover

Impervious cover (IC) is widely recognized as both a surrogate for urban land use (Coles and others, 2004; Schueler and others, 2009) and an important landscape property in its own right. Many components of stream ecosystems, including algal assemblages, macroinvertebrates, fish communities, and individual fish species have been shown to respond negatively to increases in basin IC. These negative effects are manifested largely by the effects of IC on water quality, and to some degree on streamflow regimes and aquatic habitat (Wang and others, 2000; Walsh and others, 2005; Wenger and others, 2008; Coles and others, 2009). In recent years, georeferenced datalayers of IC (paved roads, streets, driveways, parking lots, and building roofs) have also become widely available, some at resolutions of 1 m or less (Massachusetts Office of Geographic and Environmental Information, 2007).

Not all impervious cover (total IC) is hydrologically effective, that is, directly connected to surface-water bodies through storm drains or other drainage infrastructure. The degree to which IC will immediately affect streamflow, water quality, and aquatic ecosystems in a given basin depends upon the fraction of IC that is hydrologically effective. The development of functional relations between total IC and hydrologically effective IC is a topic of active research; such relations have not been established statewide for Massachusetts and are not presently incorporated into the SYE (Archfield and others, 2010). Therefore, total IC (referred to henceforth as IC) is used in this study to indicate urban land use and its potential water-quality effects on aquatic ecosystems.

Quantifying Subbasin Impervious Cover

The spatially averaged IC (in percent of total area) was calculated for each subbasin on both a cumulative and local basis. Cumulative IC was calculated as the average IC for the entire area upstream of a given subbasin outlet. Local IC was calculated as the average IC in the local area (or hydrologic unit) between a given subbasin outlet and the next upstream subbasin outlet. Two gridded IC data sets are available for Massachusetts. The National Land Cover Dataset (NLCD) is derived from 2001 Landsat satellite imagery and provides the percent IC for 30-m grid cells for the entire Nation (Multi-Resolution Land Characteristics Consortium, 2005). A more detailed datalayer is available for Massachusetts, consisting of a 1-m binary grid derived from 2005 infrared orthoimagery by the MassGIS office (Massachusetts Office of Geographic and Environmental Information, 2007).

For purposes of comparison, both the MassGIS and the NLCD grids were laid over the subbasin polygons and the percent IC was calculated. Although the data from the two sources are comparable, significant differences are evident between the data sets at the subbasin scale of aggregation used for this study, particularly at the high and low ends of the percent IC range (fig. 21). In general, the NLCD underestimates

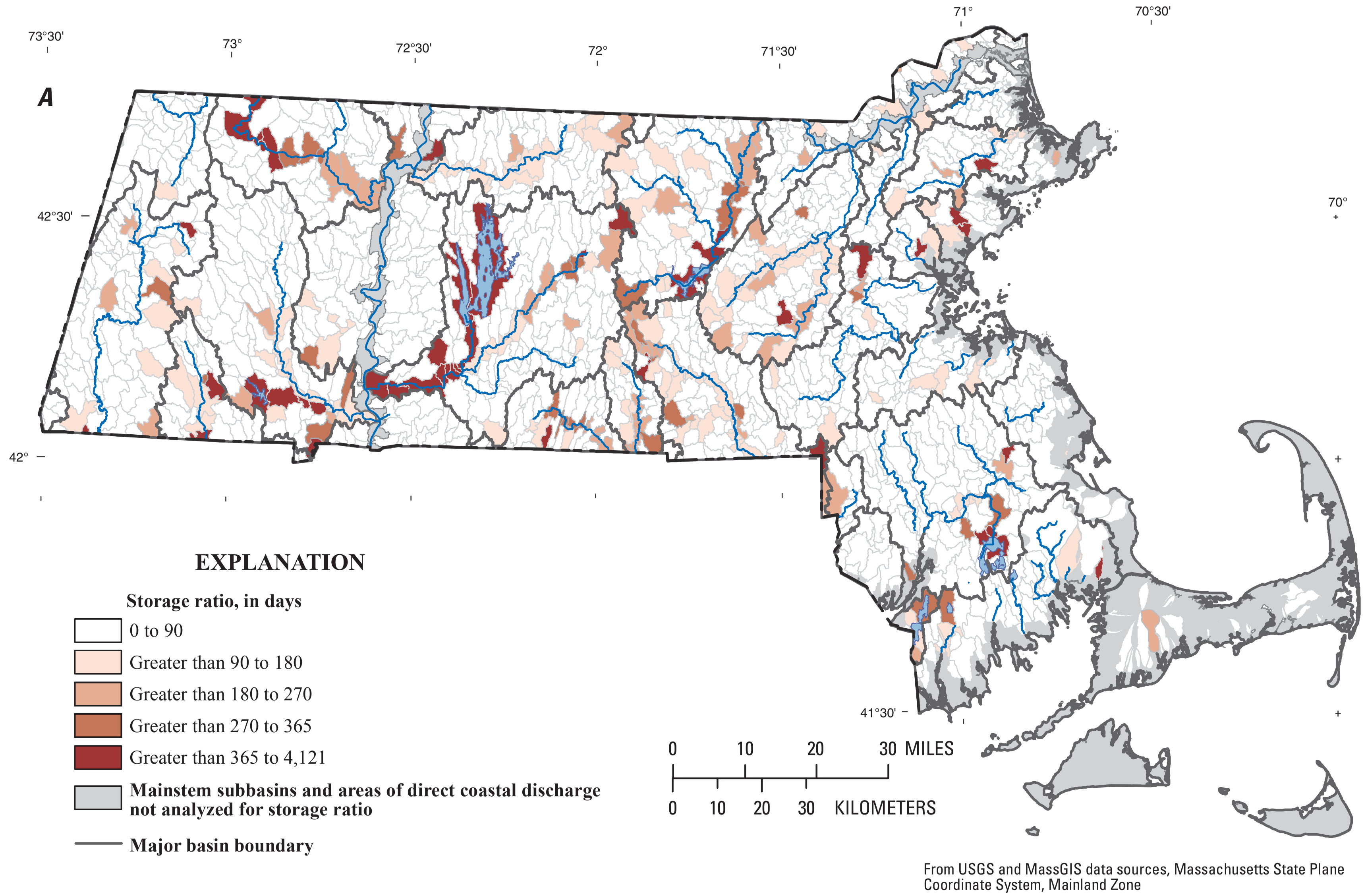

Figure 18. *(A)* Subbasin storage ratios in Massachusetts. *(B)* Subbasin storage ratios in Massachusetts, at the 12-digit Hydrologic Unit (HUC-12) scale.

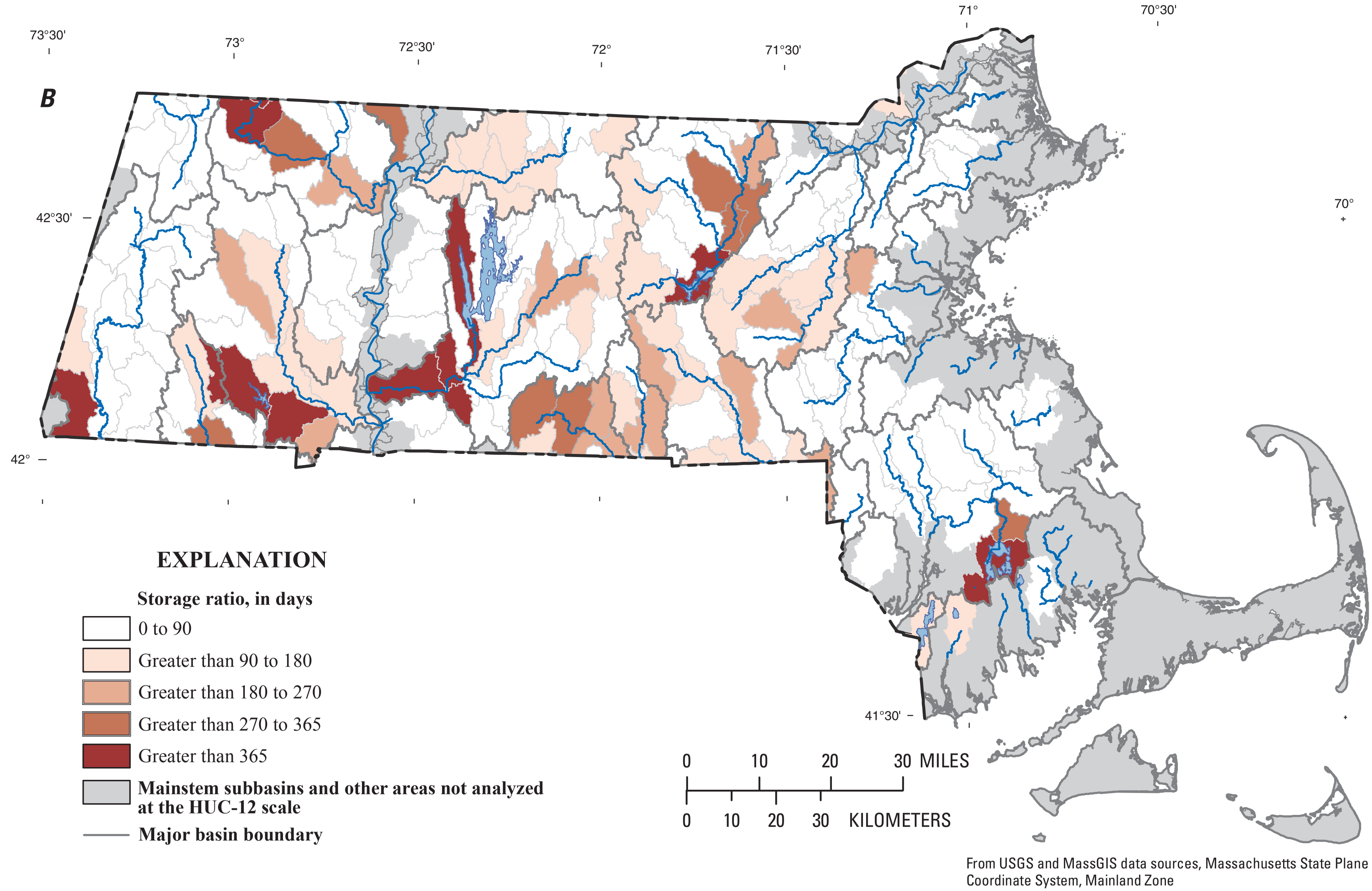

Figure 18. *(A)* Subbasin storage ratios in Massachusetts. *(B)* Subbasin storage ratios in Massachusetts, at the 12-digit Hydrologic Unit (HUC-12) scale.—Continued

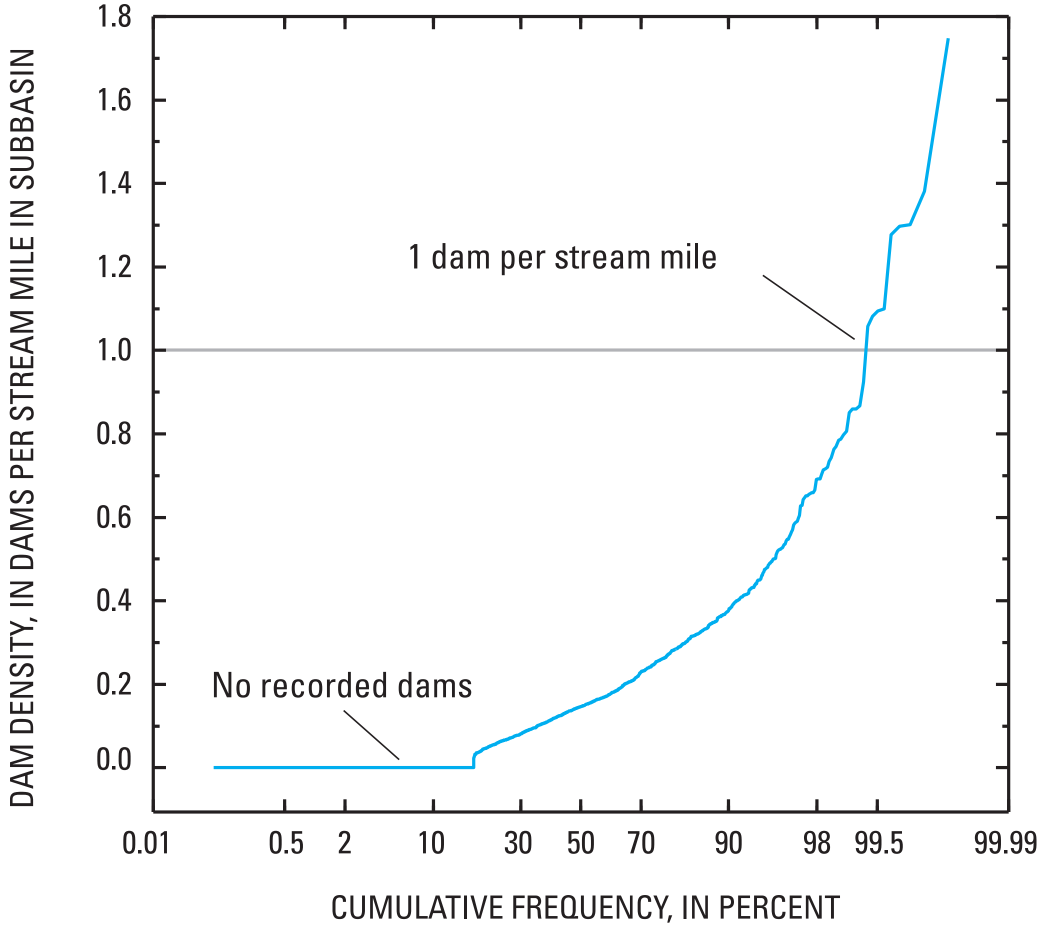

Figure 19. Cumulative frequency distribution of dam density in Massachusetts subbasins.

IC (relative to the MassGIS datalayer) in rural areas and overestimates IC in highly urbanized areas. For this reason, MassGIS data were used in preference to NLCD data for basins completely within Massachusetts.

For basins with some area outside of Massachusetts, the percent IC was estimated using linear-regression relations between the two datalayers to correct the bias in the NLCD data. Separate linear-regression relations were developed from the log-transformed data for local and cumulative IC, respectively (table 8), using data from basins entirely within Massachusetts, as follows:

$$\ln(\text{MassGIS}) = \beta_o + \beta_1 * \ln(\text{NLCD}) , \quad (7)$$

where

ln(MassGIS) is the natural logarithm of the percent IC as calculated with the 1-m MassGIS grid,
β_o is the intercept of the equation,
β_1 is the slope of the equation, and
ln(NLCD) is the natural logarithm of the percent total IC calculated with the 30-m NLCD.

Finally, it should be noted that the percent total IC classes used in the present study (table 9, fig. 22) differ from those of the NLCD. The total IC classes chosen for the present study range from less than 4 percent (relatively undeveloped) to greater than 16 percent (high-intensity development), consistent with the most recent literature concerning relations between total percent IC, extent of development, and stream habitat quality (Wenger and others, 2008; Schueler and others, 2009).

Local and Cumulative Impervious Cover

Local percent IC cover ranged from 0 to 74 percent at the scale of the subbasins created for this study (table 9; fig. 22). Whereas completely undeveloped subbasins were rare in Massachusetts (with only two subbasins identified as 0-percent IC locally), about one-third of the state's subbasins could be considered relatively undeveloped for the purposes of this study, with less than 4-percent local IC. About one-quarter of the subbasins could be considered to have had low-intensity development, with local IC values of 4 to 8 percent, and another 17 percent, or one-sixth, of the subbasins to have had low-to-medium intensity development, with local IC values of 8 to 12 percent. Among the more highly developed subbasins, 148 (or 11 percent of the statewide total) could be considered to have had medium-intensity development (12 to 16 percent local IC), and 253 (or 18 percent of the statewide total) to have had high-intensity development, with percent local IC values greater than 16 percent.

Cumulative percent IC ranged from 0.34 to 54 percent across the subbasins of the state. Because cumulative percent IC for a given subbasin is averaged over a larger area than local IC, values of cumulative IC generally are somewhat smoothed in comparison to local IC, with higher values at the low end of the IC frequency distribution and lower values at the high end of the IC frequency distribution. Examination of figure 22 indicates that this was the case for Massachusetts, although local IC exceeded cumulative IC over the upper 85 percent of the distribution, and local and cumulative IC were very close to each other over the lower 15 percent of the frequency distribution.

The geographic distribution of local and cumulative percent IC in Massachusetts was generally correlated with the locations of large and medium-sized cities, their surrounding suburbs, and the highway corridors that link major urban centers (figs. 23 and 24). The metropolitan Boston area had the highest number of high-IC subbasins (that is, IC greater than 16 percent), followed by the Springfield-Holyoke-Chicopee area, Greater Worcester, and several smaller urban centers. Certain highway corridors were associated with relatively high degrees of IC in their underlying subbasins, for example, the corridors linking Boston to Lowell and Lawrence, the corridor between Boston and Worcester, and the corridor between Boston and northeastern Rhode Island. The state planning basins with the highest percentages of IC included the Boston Harbor (Mystic, Neponset, and Weymouth/Weir), Shawsheen, and parts of the North Coastal and Charles River Basins.

In specific areas of the state, local and cumulative IC differed substantially. For example, local IC for the subbasin at the mouth of the Chicopee River Basin was 38 percent, reflecting urban development in the City of Chicopee. Cumulative IC for this subbasin, by contrast, was only 4.7 percent, because of the large fraction of upstream undeveloped area in this 723-mi^2 planning basin. A similar pattern was indicated for the main-stem subbasins of the North Nashua River occupied by the cities of Fitchburg and Leominster. In these two subbasins, cumulative IC (8.7 and 11 percent, respectively) was also substantially lower than local IC (28 and 24 percent, respectively), reflecting the influence of undeveloped areas in the North Nashua River headwaters. The opposite pattern was found in certain parts of eastern Massachusetts—for example, in the main-stem subbasins of the lower Sudbury and middle Charles River Basins. In both of these cases, cumulative IC (15 and 14 percent, respectively) was greater than local IC (6.4 and 7.6 percent, respectively) because of the influence of upstream urban areas.

At the HUC-12 scale, statewide patterns of local impervious cover can also be discerned in the areas analyzed (fig. 23B). In particular, the urban areas of metropolitan Boston, Springfield-Holyoke-Chicopee, Worcester, and the Merrimack River valley are evident at this scale, as is the urban corridor between Boston and the Merrimack Valley. Cumulative IC (fig. 24B) was also reasonably represented in portions of the state at the HUC-12 scale. For example, the relatively undeveloped upstream areas in the Chicopee planning basin strongly affected cumulative IC in the City of Chicopee at the HUC-12 scale as well as at the subbasin scale, as can be seen from a comparison of figures 24B and 24A, respectively. The main limitation of the HUC-12 impervious cover maps is their lack of detail. Medium- and small-sized cities are not as effectively represented at the HUC-12 scale as at the subbasin scale. In addition, relatively undeveloped subbasins and natural corridors in otherwise developed areas, such as the large riparian corridors along portions of the main-stem Sudbury and Charles River subbasins (figs. 23 and 24), cannot be discerned at the HUC-12 scale.

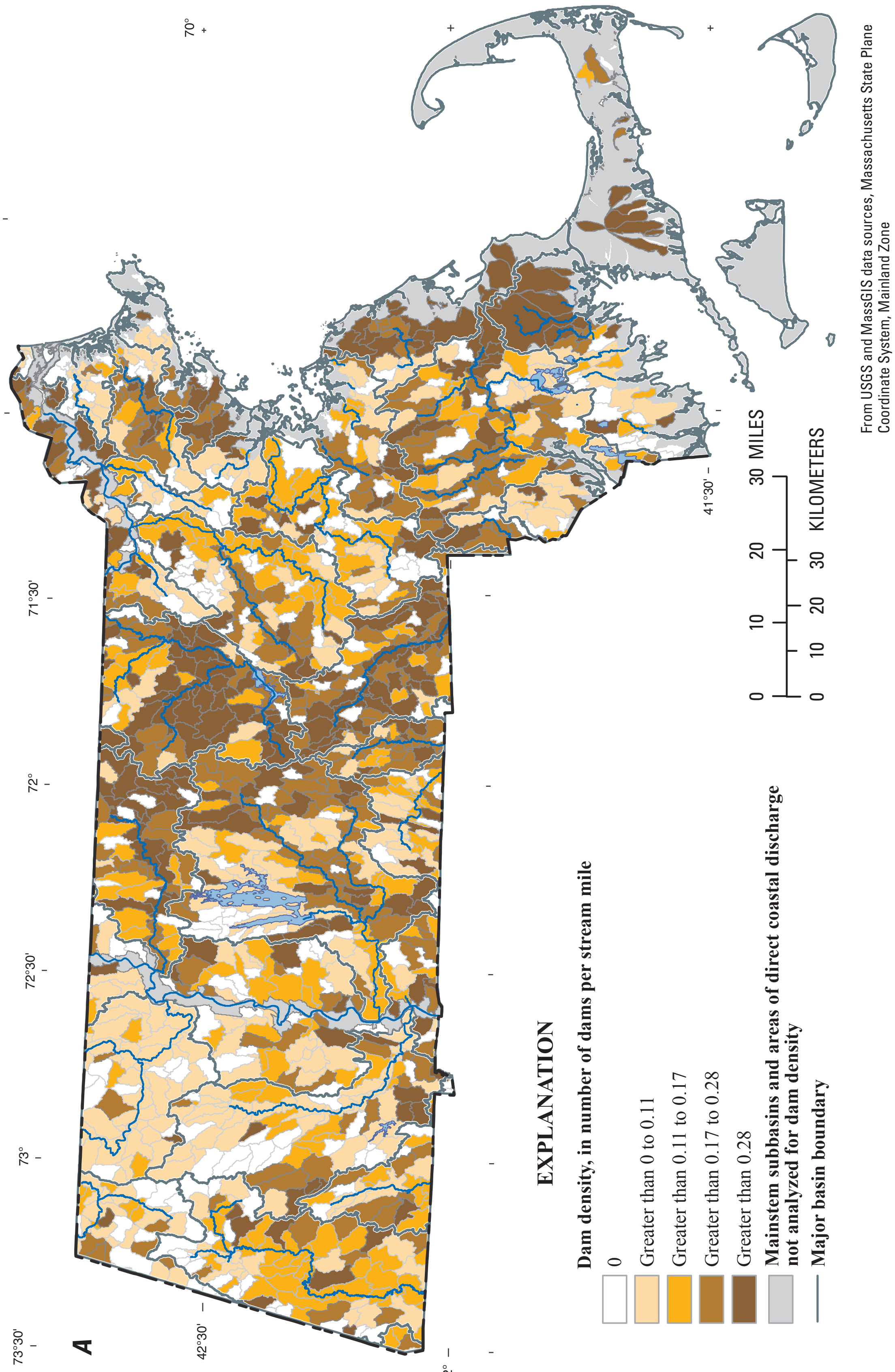

Figure 20. *(A)* Subbasin dam density in Massachusetts. *(B)* Subbasin dam density in Massachusetts, at the 12-digit Hydrologic Unit (HUC-12) scale.

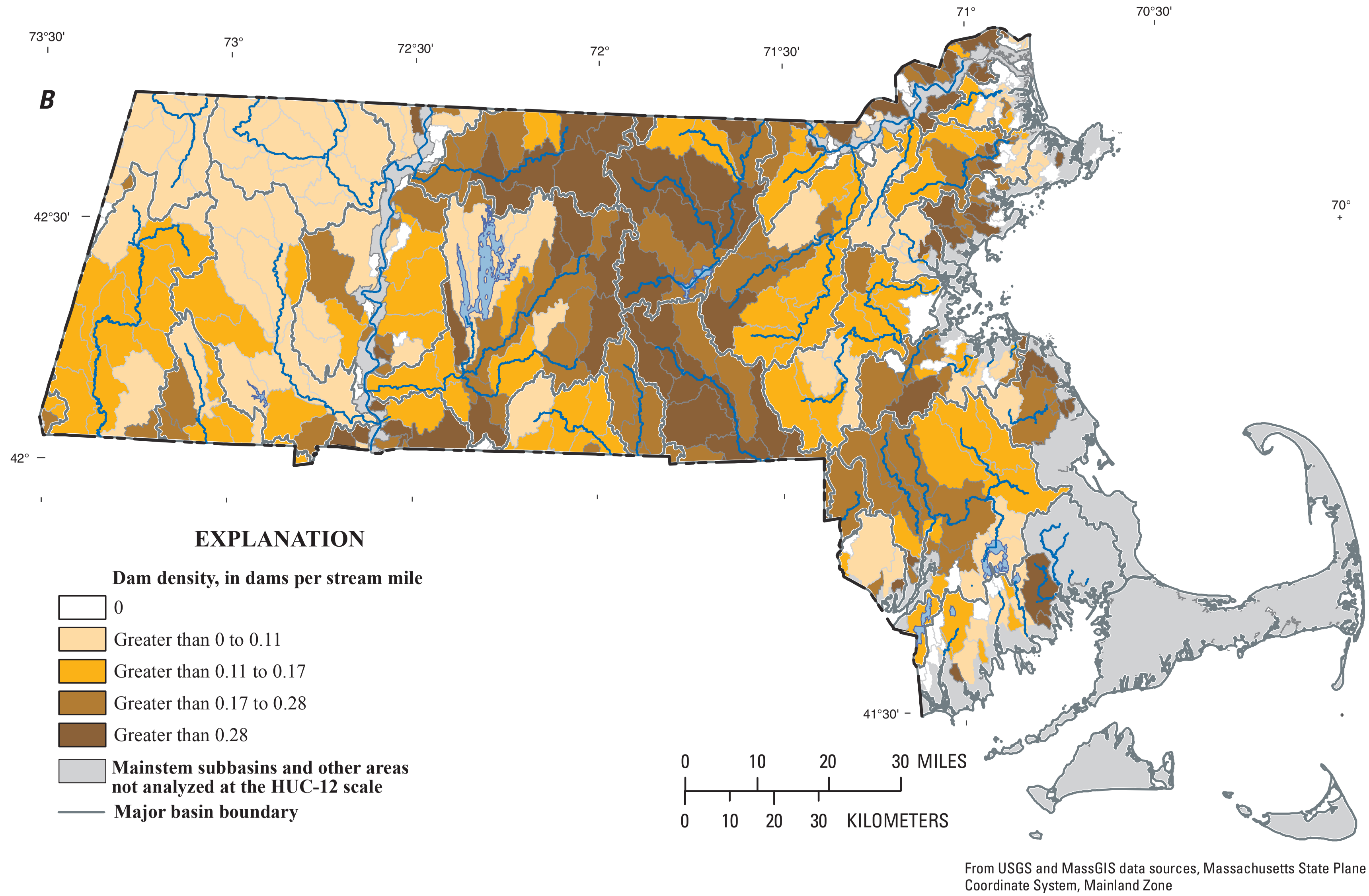

Figure 20. *(A)* Subbasin dam density in Massachusetts. *(B)* Subbasin dam density in Massachusetts, at the 12-digit Hydrologic Unit (HUC-12) scale.—Continued

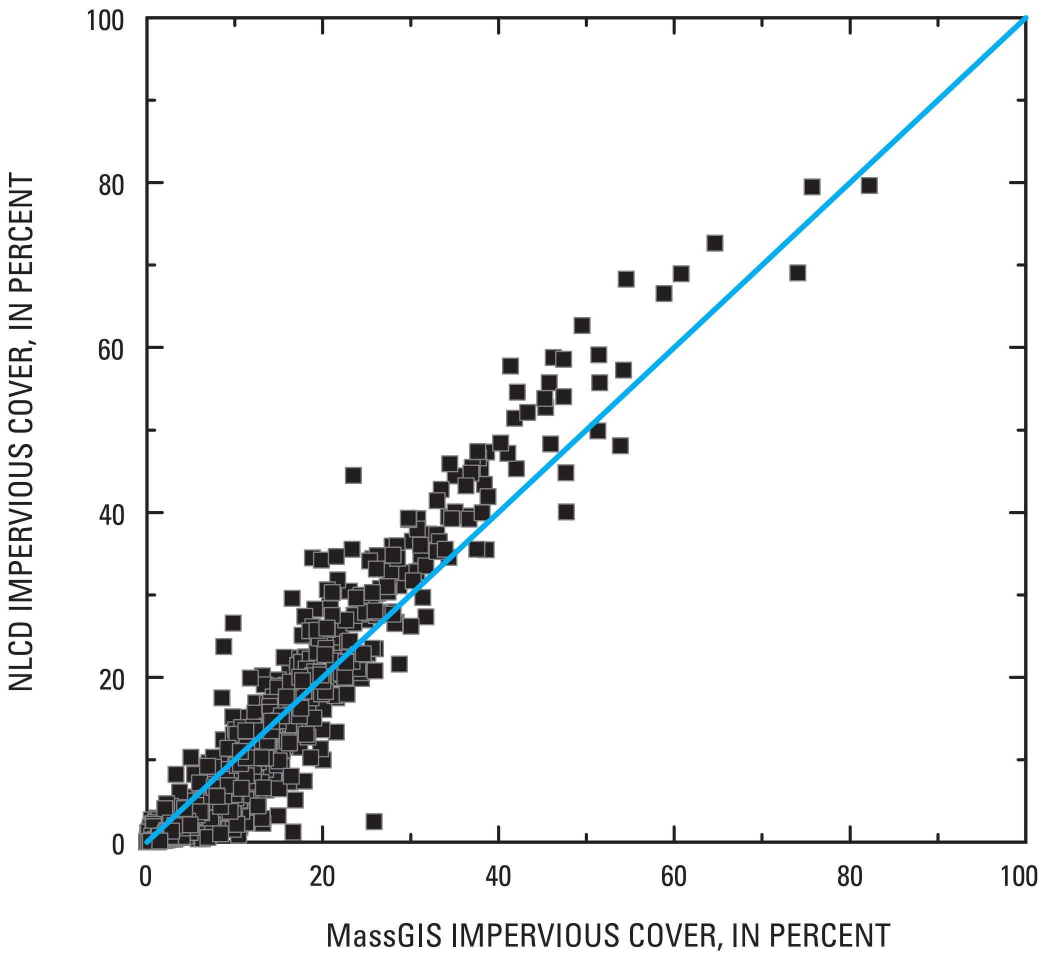

Figure 21. Relation between the National Land Cover Dataset (NLCD) and MassGIS impervious cover datalayers for Massachusetts subbasins.

Table 8. Regression equations developed to estimate an equivalent MassGIS percent impervious cover from NLCD percent impervious cover data at the scale of the subbasins defined for this study.

[NLCD, National Land Cover Dataset impervious cover, in percent; $MASSGIS_{estimated}$, estimated MassGIS impervious cover, in percent; R^2, coefficient of determination. See text for references to data sources and explanation of percent local and cumulative impervious cover.]

Spatial scale	Regression equation	R^2
Cumulative impervious (percent)	$MASSGIS_{estimated} = 3.1582 * NLCD^{0.592}$	93.30 percent
Local impervious (percent)	$MASSGIS_{estimated} = 3.1550 * NLCD^{0.601}$	91.60 percent

Table 9. Frequency tables of local and cumulative percent impervious cover for Massachusetts subbasins, showing the number of subbasins and the percent of the statewide total in each range.

[See text for explanation of indicators and data sources; <, less than]

Local impervious cover			Cumulative impervious cover		
Range, in percent	Frequency	Percentage of total	Range, in percent	Frequency	Percentage of total
0	2	0.1	0	0	0.0
0 to <0.5	10	0.7	0 to <0.5	4	0.3
0.5 to <1	37	2.6	0.5 to <1	29	2.1
1 to <2	163	11.4	1 to <2	173	12.4
2 to <4	241	16.9	2 to <4	273	19.6
4 to <6	169	11.8	4 to <6	214	15.3
6 to <8	167	11.7	6 to <8	142	10.2
8 to <10	118	8.3	8 to <10	106	7.6
10 to <12	121	8.5	10 to <12	102	7.3
12 to <14	96	6.7	12 to <14	104	7.5
14 to <16	52	3.6	14 to <16	63	4.5
16 to <18	53	3.7	16 to <18	51	3.7
18 to <20	31	2.2	18 to <20	26	1.9
20 to <25	67	4.7	20 to <25	56	4.0
25 to <30	41	2.9	25 to <30	21	1.5
30 to <35	27	1.9	30 to <35	18	1.3
35 to <40	12	0.8	35 to <40	6	0.4
40 to <50	14	1.0	40 to <50	5	0.4
50 to <60	7	0.5	50 to <60	2	0.1
60 to <70	0	0.0	60 to <70	0	0.0
70 to <80	1	0.1	70 to <80	0	0.0
80 to <90	0	0.0	80 to <90	0	0.0
90 to <100	0	0.0	90 to <100	0	0.0

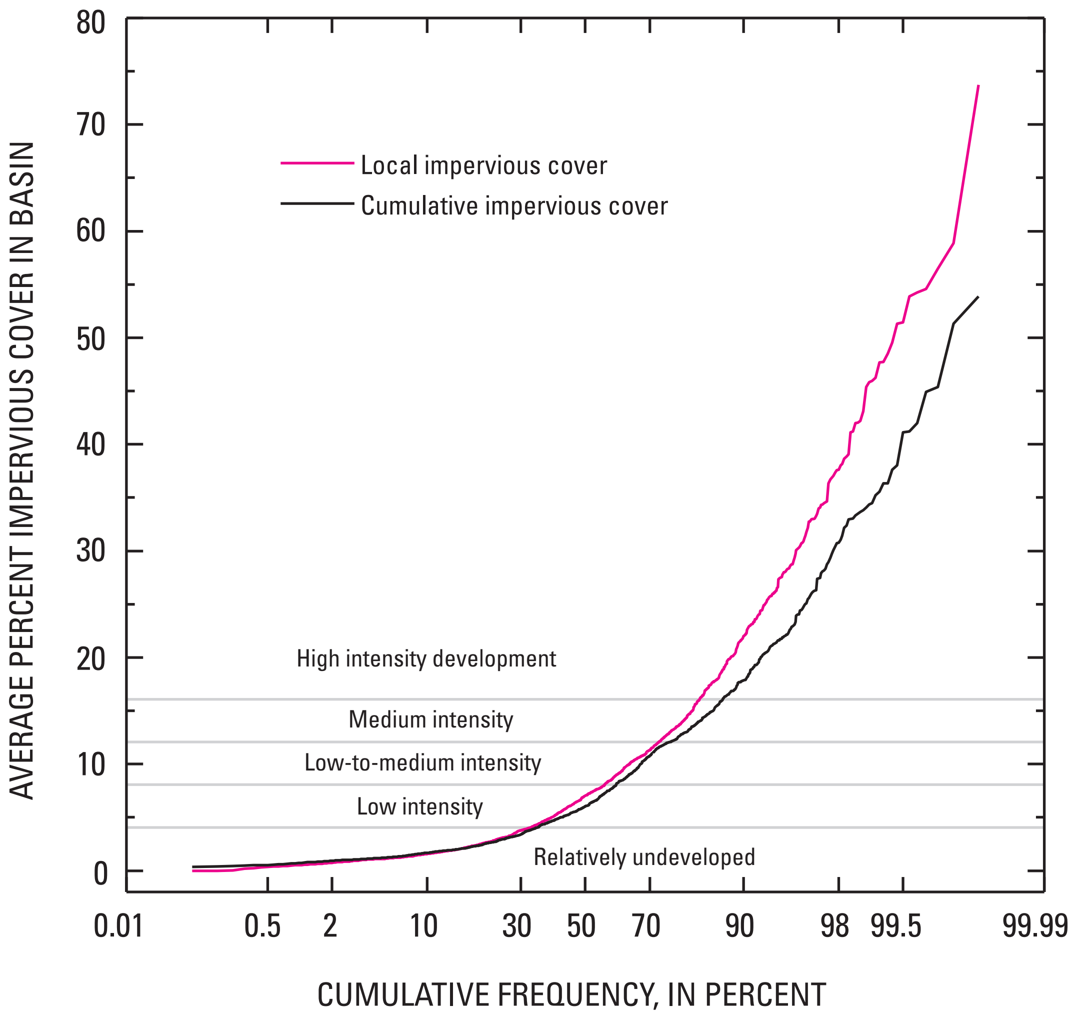

Figure 22. Cumulative frequency distribution of local and cumulative percent impervious cover in Massachusetts subbasins.

Indicators of Water Quality

Stream water quality can be altered by many of the same practices that alter natural streamflows. For example, treated wastewater discharges alter stream water quality directly by introducing water with different physical and chemical characteristics—for example, temperature, specific conductance, and concentrations of nutrients and metals. Stormwater runoff can also carry sediment, bacteria, road-salt contaminants, and organic compounds into a stream. Dams can form impoundments with chemical and biological conditions—for example, dissolved oxygen and chlorophyll concentrations—that are very different than the conditions in the undammed, free-flowing stream. Such alterations of stream water quality may have adverse effects on aquatic life and may result in stream water that is not suitable for some human uses and ecosystem needs.

In the present study, alterations of stream water quality are described using assessments by the MDEP of the capacities of Massachusetts streams to support several beneficial uses. These uses are designated for specific streams and are defined in the Massachusetts Surface Water Quality Standards (SWQS; 314 CMR 4.00). The uses follow the designated uses defined under the Federal Clean Water Act (CWA) for surface water and include aquatic-life support, fish and shellfish consumption, drinking-water supply, and primary (swimming) and secondary (boating) contact recreation (Massachusetts Department of Environmental Protection, Division of Watershed Management, 2007b; not all uses are designated for all streams). The SWQS also define specific water-quality criteria—for example, maximum concentrations of indicator bacteria or minimum concentrations of dissolved oxygen—that must be met for streams to be of sufficient quality to support their designated uses.

Periodically, in accordance with sections 305(b) and 303(d) of the CWA, the MDEP assesses the streams in Massachusetts to determine whether they support their designated aquatic-life and human uses. These assessments are based on available information from many state agencies and other sources (Massachusetts Department of Environmental Protection, Division of Watershed Management, 2007b). First, streams are divided into segments that typically range from about 1 to 10 mi in length. For each stream segment and each of the designated uses that apply to the segment, the MDEP determines whether the use is supported or impaired in the segment. Not all streams are assessed. Stream segments that historically have been assessed for use support in accordance with the CWA typically include the main-stem portions of major rivers and the major tributaries to these rivers. The MDEP maintains a database (Water Body System, [WBS] database) of segments, their designated uses, and the status of their use support for all streams that have historically been included in this assessment process. The MDEP supplements the WBS database with information from the Watershed-Based Plan, which focuses principally on potential nonpoint-source impacts (Massachusetts Department of Environmental Protection, 2009a) and targets segments for assessment based on land uses; however, the indicators of water-quality alteration developed for the present study rely strictly upon the WBS data. Data concerning lake, pond, and reservoir water quality were not used in the present study.

Quantifying Water-Quality Alteration

Two indicators were developed to describe the alteration of water quality in Massachusetts stream reaches within the hydrologic units defined in the present study, based on the information available from MDEP water-quality assessments. (As illustrated in figure 1D, a hydrologic unit is defined as the local part of a subbasin between two subbasin delineation points.) These indicators describe whether the stream was assessed or unassessed for its use support, and, if assessed, whether a stream was found to support its designated uses or to be impaired with respect to those uses. Specifically, the indicators are the percentage of total stream miles in each hydrologic unit that are assessed (WQ Assessed), and the percentage of total assessed stream miles in each hydrologic unit that are impaired for their designated uses (WQ Impaired).

The WQ Assessed and WQ Impaired indicators were determined using the most recent available digital datalayer of stream segments assessed for support of their designated uses under sections 305(b) and 303(d) of the CWA. This datalayer was created from the assessment conducted by MDEP in 2002, a year that is also included in the 2000–2004 period of this study. The 303(d) datalayer was obtained from MassGIS (Datalayer WBS2002; Massachusetts Office of Geographic and Environmental Information, 2005). The MDEP has conducted additional assessments since 2002, but the results of those assessments (which, in a few cases, involved alterations of stream-segment boundaries) were not available in digital form at the time of the present study. The 2002 datalayer includes 589 stream segments totaling 2,675 stream miles and is based on the stream segments defined in the 2002 version of the MDEP WBS database. Information about the water-quality status of the stream segments is included in the datalayer in attributes that describe whether the segment supports or is impaired for one or more of its designated uses and, if impaired, the specific contaminants or other known cause of the impairment in that segment. The stream segments in the datalayer are, in nearly all cases, either the main stems of rivers or major tributaries to rivers. Finally, it should also be noted that all of the water bodies in Massachusetts, together with those in New York and the other New England states, were listed in 2007 as impaired for mercury, which was derived predominantly from atmospheric sources (Massachusetts Department of Environmental Protection, 2009b). However, the distribution of mercury-impaired waters in Massachusetts was not considered in this study.

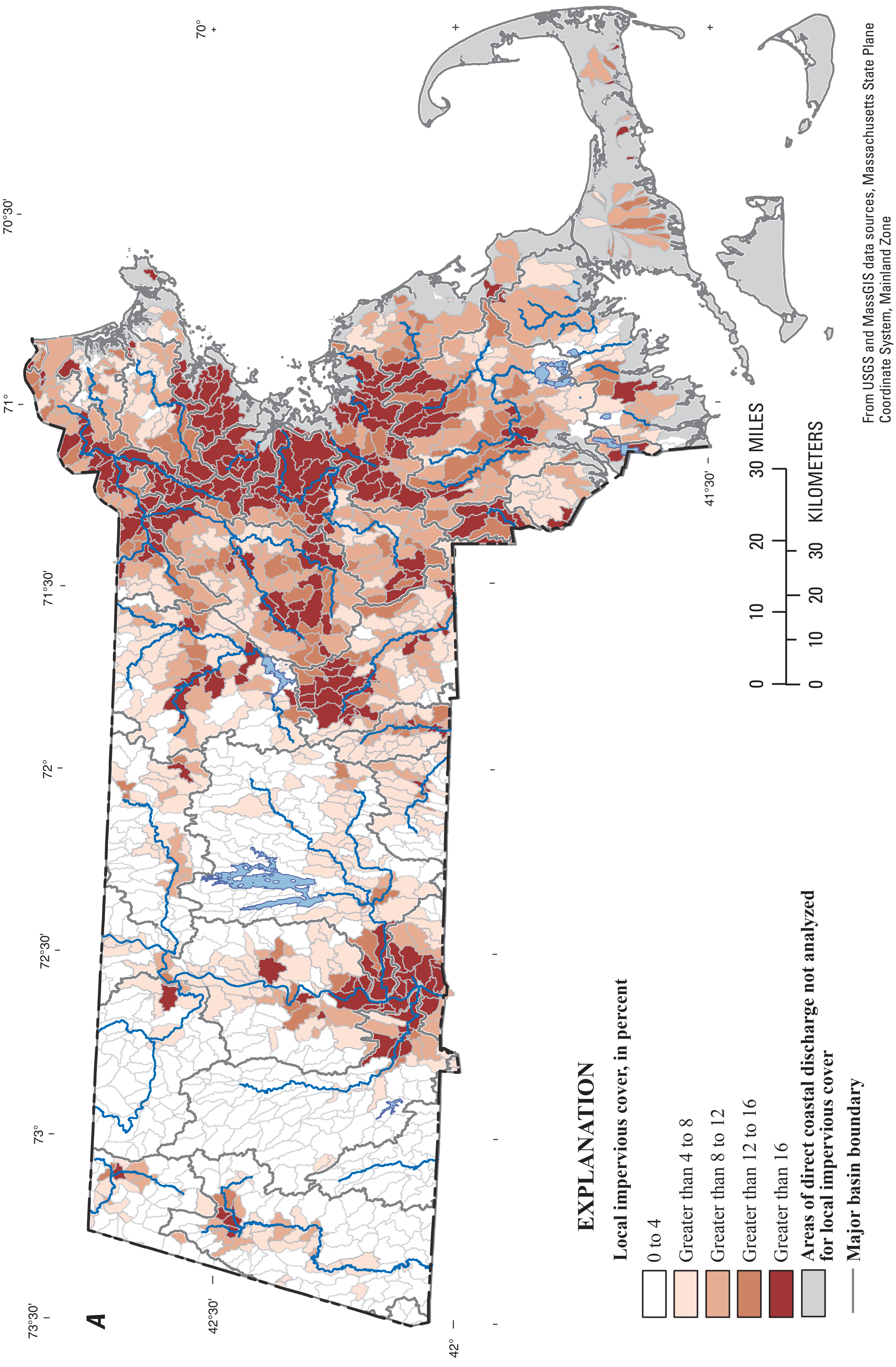

Figure 23. *(A)* Local percent impervious cover in Massachusetts subbasins. *(B)* Local percent impervious cover in Massachusetts 12-digit Hydrologic Unit Code (HUC-12) basins.

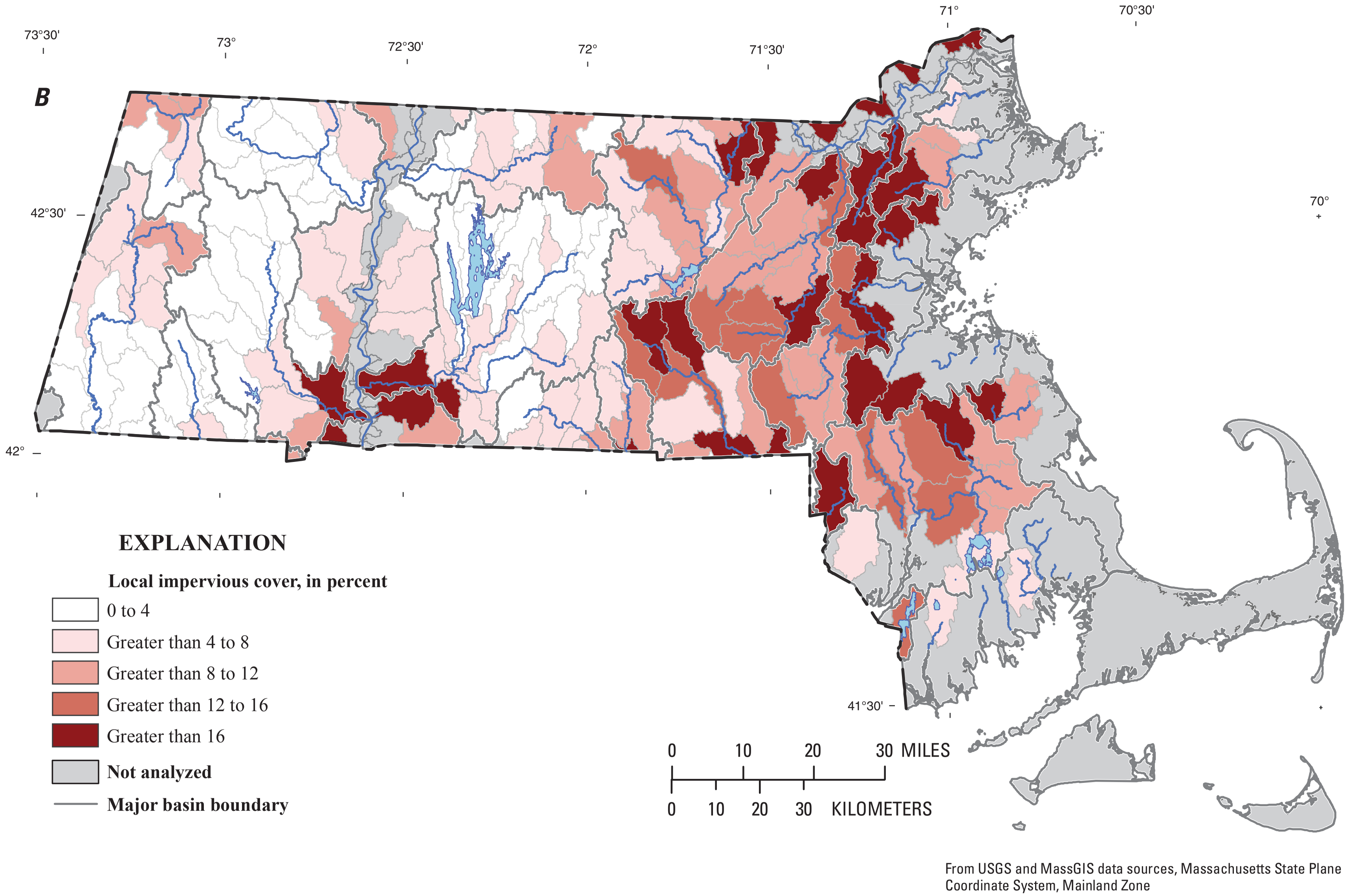

Figure 23. *(A)* Local percent impervious cover in Massachusetts subbasins. *(B)* Local percent impervious cover in Massachusetts 12-digit Hydrologic Unit Code (HUC-12) basins.—Continued

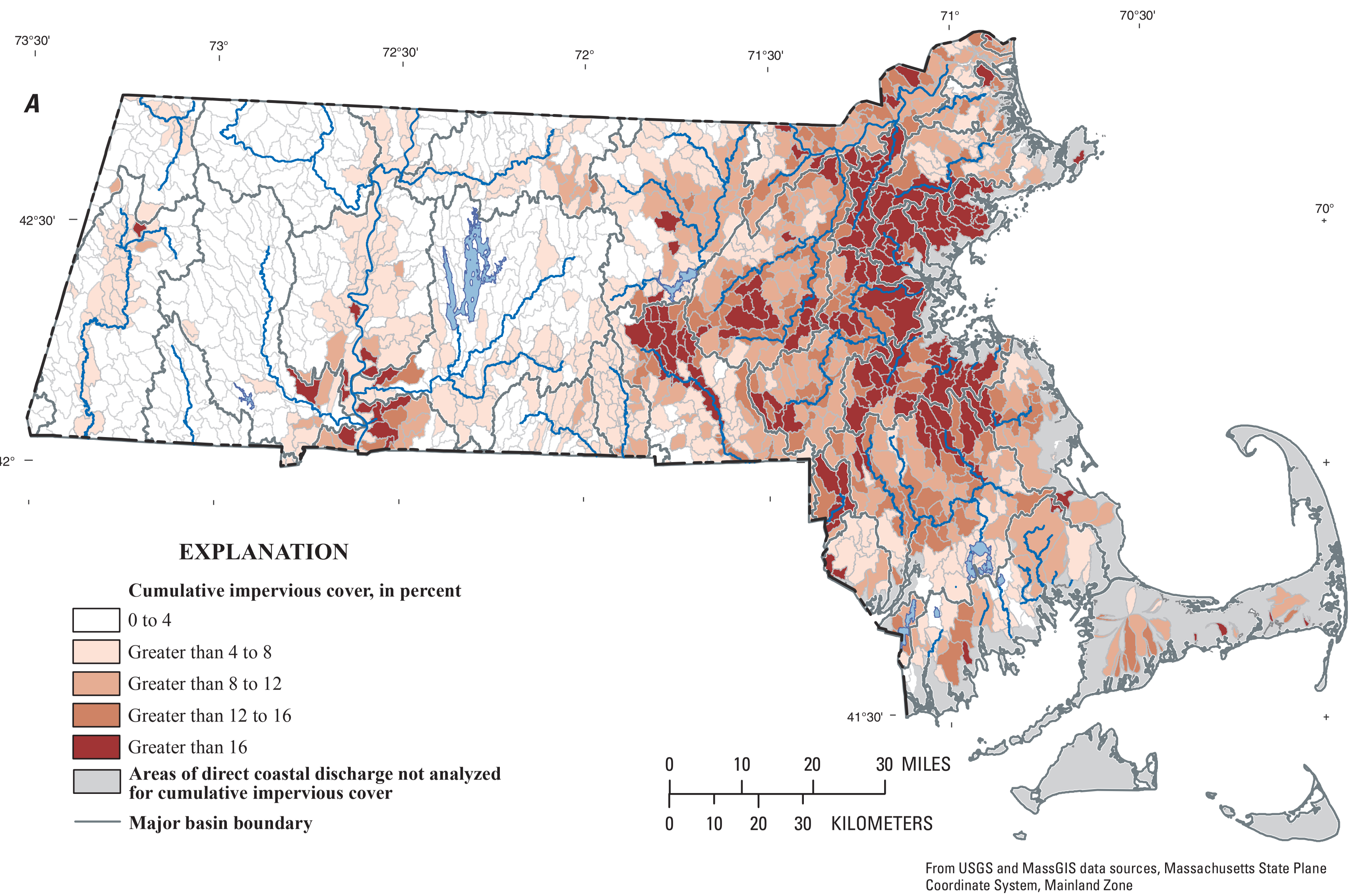

Figure 24. *(A)* Cumulative percent impervious cover in Massachusetts subbasins. *(B)* Cumulative percent impervious cover in Massachusetts 12-digit Hydrologic Unit Code (HUC-12) basins.

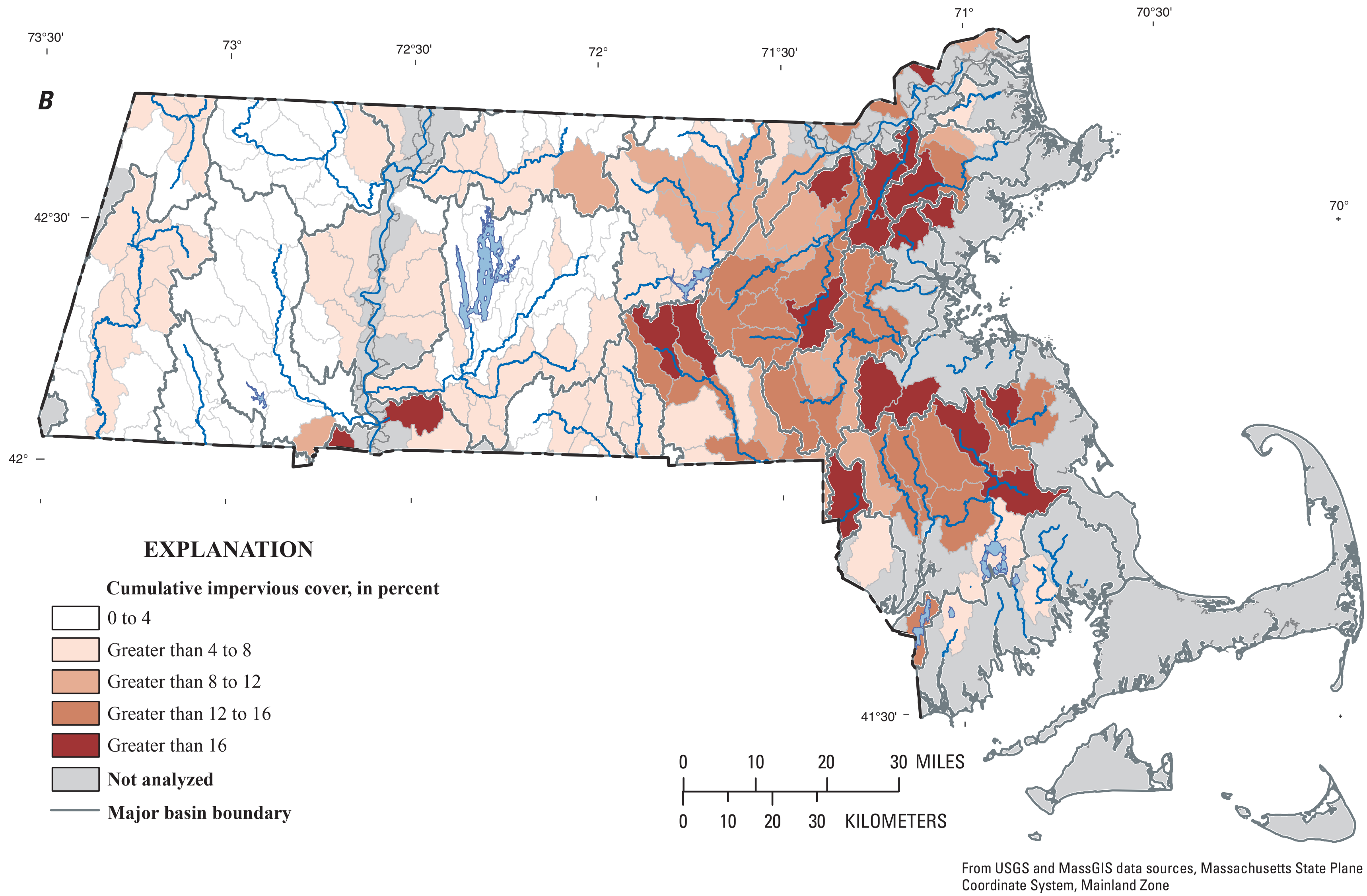

Figure 24. *(A)* Cumulative percent impervious cover in Massachusetts subbasins. *(B)* Cumulative percent impervious cover in Massachusetts 12-digit Hydrologic Unit Code (HUC-12) basins.—Continued

For the purposes of this study, the WBS2002 datalayer was combined with the NHD stream datalayer to create a 1:25,000-scale datalayer of Massachusetts perennial streams. All information about segment identification and water-quality status for the 2,675 stream miles from the WBS2002 datalayer was maintained in the combined datalayer. The line segments of the NHD stream datalayer that overlapped or coincided with the streams in the WBS2002 datalayer were deleted. Combination of the NHD and WBS2002 datalayers was possible because the NHD and WBS2002 are both based on the MassGIS 1:25,000-scale centerline hydrography. The combined stream datalayer was intersected with the datalayer of hydrologic units to create a new datalayer that contained attribute information from the stream datalayer about the lengths and water-quality status of the streams within each hydrologic unit. The WBS2002 stream segments were divided at hydrologic-unit boundaries by this process. The new hydrologic-unit datalayer included three large hydrologic units for areas along the main stems of the Connecticut and Merrimack Rivers. Although these hydrologic units were excluded from analyses of flow alteration—because the Massachusetts SYE application was not designed for use on these multistate rivers—they were included in the water-quality analysis because appropriate information was available for them in the WBS2002 datalayer.

WQ Assessed and WQ Impaired indicators, in percent, were calculated for each hydrologic unit as follows: the WQ Assessed indicator was set equal to the total assessed stream miles in the hydrologic unit divided by the total stream miles in the hydrologic unit. The total assessed stream miles was the sum of lengths of all stream reaches from segments that were described with WBS2002 attributes as “attaining” or “impaired” for one or more designated uses (categories 2, 4a, 4b, 4c, and 5; Massachusetts Office of Geographic and Environmental Information, 2005); stream reaches from segments described as having insufficient or no data to determine if any uses were attained (category 3; Massachusetts Office of Geographic and Environmental Information, 2005) were not included as assessed streams. The total stream miles in the hydrologic unit was the sum of the lengths of all stream reaches, including those originally from either the NHD or WBS2002 datalayers. This included the lengths of centerline stream reaches that extended through water bodies. As noted previously, the WQ Impaired indicator was equal to the total impaired stream miles in the hydrologic unit divided by the total assessed stream miles in the hydrologic unit. The total impaired stream miles in the hydrologic unit was the sum of lengths of all stream reaches from segments described as impaired by contaminants (referred to as “pollutants” by the State; see categories 4a, 4b, and 5; Massachusetts Office of Geographic and Environmental Information, 2005). Contaminants included nutrients, metals, organic compounds, organic enrichment (low dissolved oxygen), salinity (dissolved solids or chloride), pH, other contaminants, and impairments from unknown causes. Streams impaired only by flow or other habitat alteration were not included in the WQ Impaired indicator, because these alterations are assessed through the other indicators in the present study. Note that this excluded only a small number of impaired segments, because most of the segments that were considered impaired because of flow or other habitat alteration were also impaired by contaminants.

Indicator Results: Percent Assessed and Percent Impaired Stream Miles

Assessed stream miles accounted for less than 50 percent of total stream miles in most (88 percent) of the hydrologic units. About half (56 percent) of the hydrologic units had no assessed stream miles (fig. 25). Many of the unassessed streams are small and (or) unnamed streams (Massachusetts Department of Environmental Protection, Division of Watershed Management, 2007b). The distribution of basins with some assessed streams is fairly even across the state, with exceptions along the Connecticut Valley and in southeastern Massachusetts (fig. 26A); water-quality assessments in these areas after 2002 included additional streams (W.R. Dunn, Massachusetts Department of Environmental Protection, Division of Watershed Management, written commun., 2007), which had not been incorporated into a georeferenced datalayer at the time of the present study.

Many of the streams that were assessed were considered impaired by one or more contaminants, and as such did not support one or more of the designated uses of the streams (figs. 25 and 26B). In nearly three-fourths (72 percent) of the hydrologic units with assessed streams, more than half of the assessed streams were considered impaired. All of the assessed streams were considered impaired in about two-thirds (66 percent) of the hydrologic units with assessed streams. It should be noted, however, that many of the streams historically assessed by MDEP are those that are likely to be impaired; they often were the subject of monitoring because of known or suspected water-quality problems (DeSimone and others, 2001). Large streams, such as the main stems of rivers that made up most of the assessed stream miles in the WBS2002 datalayer, also are in many cases the receiving waters for treated wastewater discharges and for this reason may be more susceptible to water-quality problems than smaller streams. Like the distribution of hydrologic units with assessed stream miles, hydrologic units with large fractions of assessed stream miles that are considered impaired are distributed across the state, but may be more concentrated in eastern Massachusetts (fig. 26B).

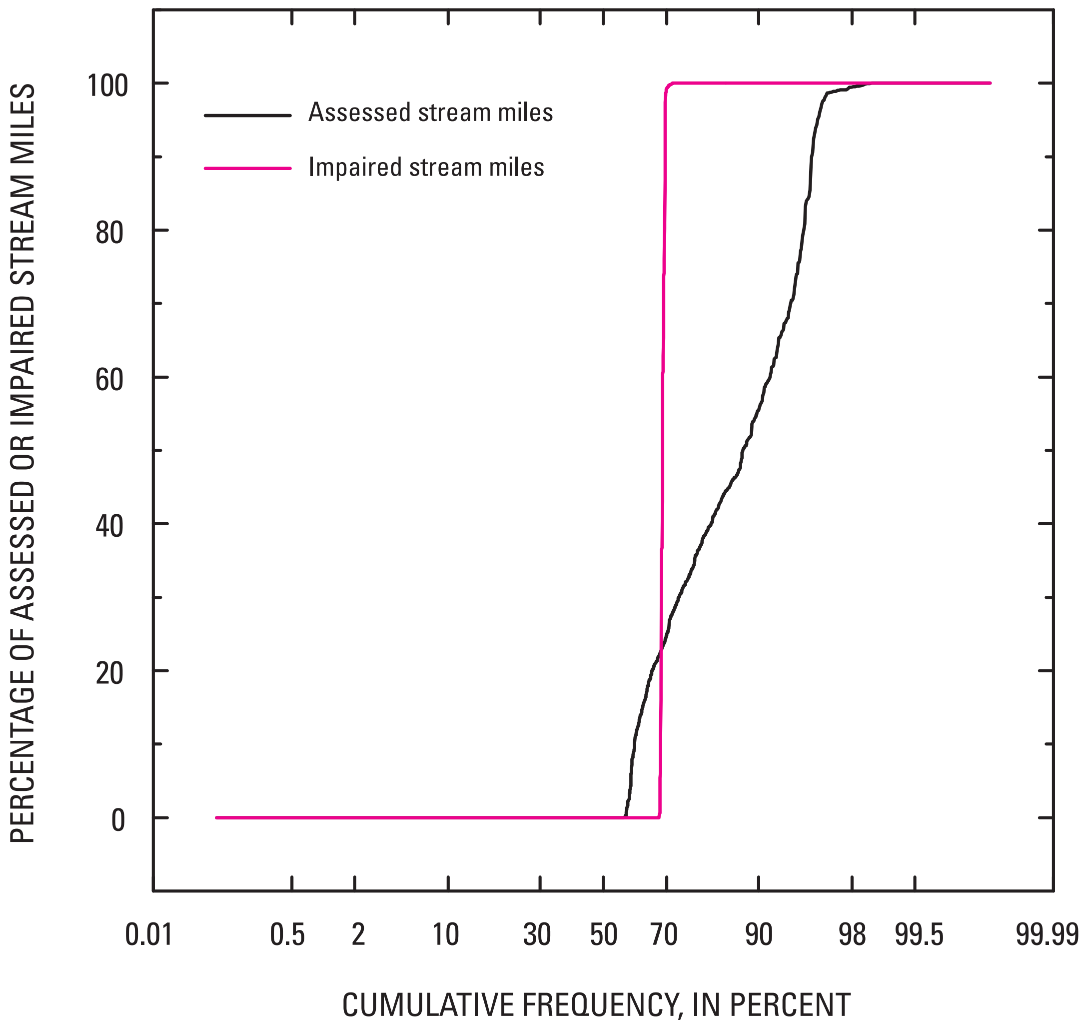

Figure 25. Cumulative frequency distributions of the percentages of total stream miles that were assessed and impaired in the hydrologic units and groundwater contributing areas in Massachusetts, 2002. Impaired stream miles are percentages of assessed stream miles.

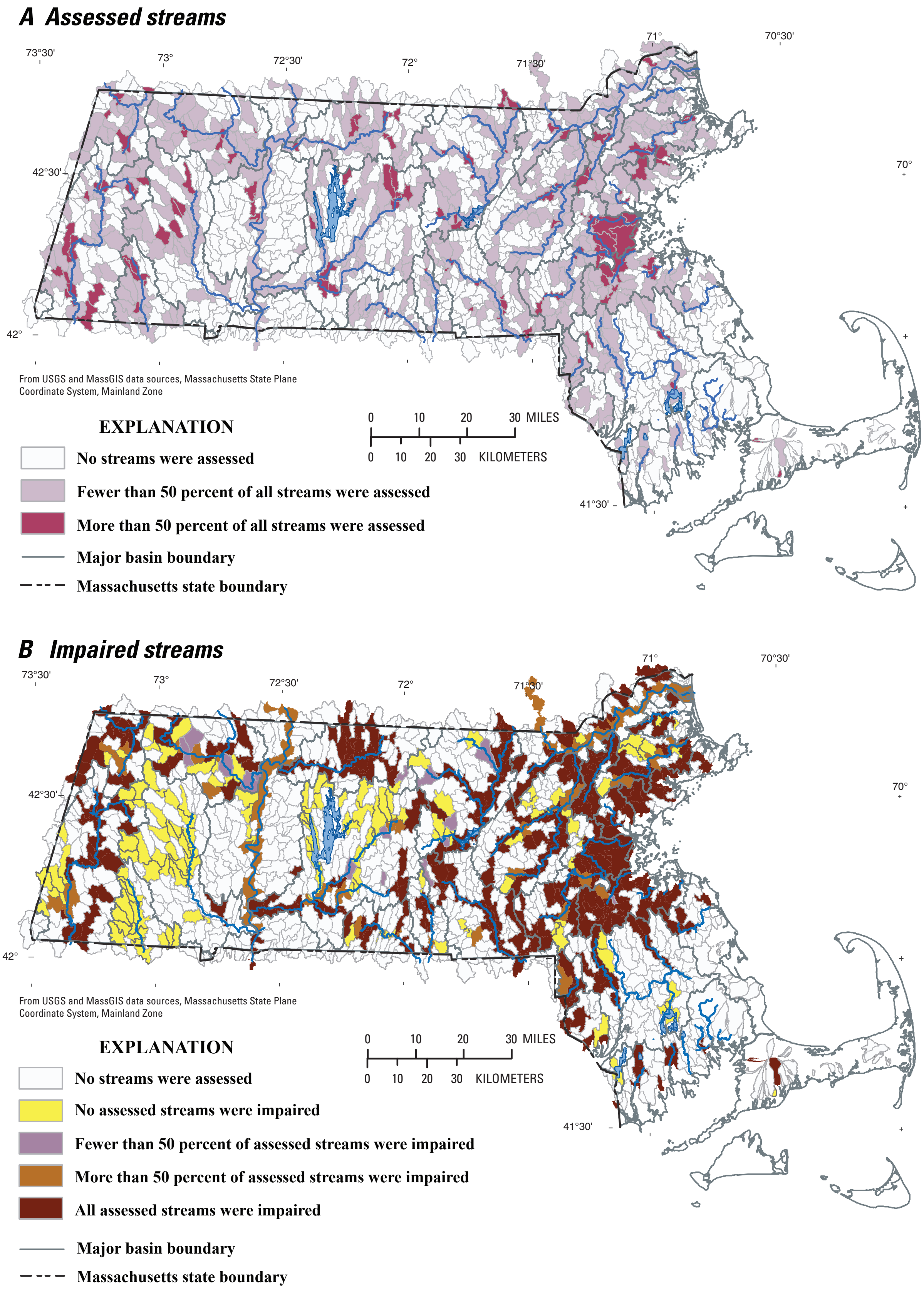

Figure 26. Percentages of *(A)* total stream miles that were assessed, and *(B)* assessed stream miles that were impaired in the hydrologic units and groundwater contributing areas in Massachusetts, 2002.

Limitations of the Basin-Alteration Indicators

The indicators of streamflow alteration, impounded storage, dam density, impervious cover, and water quality that were defined, compiled, and mapped for this study have limitations that are important to consider in the interpretation of water-resources conditions in Massachusetts. These limitations are discussed in this section of the report.

Streamflow Alteration by Withdrawals and Discharges

Use of the Sustainable Yield Estimator

The Sustainable Yield Estimator application (SYE version 1.0) produces daily estimates of unaffected and water-use-affected streamflows for any period of interest between 1961 and 2004 (Archfield and others, 2010). The inherent uncertainty of the streamflow estimates at the daily time scale was reduced by reliance upon long-term, temporally aggregated statistics in the analysis (such as the median annual 7-day minimum streamflow and median monthly streamflows; see table 3). In addition, it should be noted that the drainage areas of approximately 4 percent of the subbasins in the present study exceed 294 mi^2, the drainage area of the largest reference streamgage used to develop the SYE regression equations (Archfield and others, 2010). However, comparisons of observed and SYE-estimated streamflows at the mouths of the largest basins in the present study (such as the Chicopee, Concord, Millers, and Nashua Basins) showed generally good agreement after adjustment for net water use. The level of agreement was similar to the results of observed-versus-SYE-simulated streamflow comparisons conducted at southern New England reference streamgages by Archfield and others (2010, fig. 7).

Water-use-affected streamflows were estimated using water-use data reported to the MDEP and estimates of private domestic-well withdrawals and septic-system discharges estimated from U.S. census data. Although care was taken to correct obvious errors and inconsistencies in the reported data, the overall accuracy of the reported data likely differs from municipality to municipality.

Effects of Groundwater Withdrawals and Discharges on Streamflow (Water-Use Scenario 1)

The simulation of time-varying groundwater withdrawals and discharges by SYE version 1.0 at the statewide scale is subject to limitations. The SYE application provides the option of using the STRMDEPL computer program (Archfield and others, 2010; Barlow, 2000) to simulate the damping and temporal lagging of net streamflow alteration from a time series of varying groundwater withdrawals and discharges (net water use) in a subbasin. However, STRMDEPL requires site-specific data concerning the hydraulic properties of the aquifers underlying each subbasin (storativity and transmissivity), but these data are not available statewide. In this situation, the user may use two different methods, neither of which require any information concerning the aquifer hydraulic properties of the subbasins, to estimate streamflow alteration from net water use at the monthly time scale. The first method requires the user to assume that streamflow alteration for a given month is equal to the net water use for that month (that is, streamflow alteration occurs rapidly, without any damping or lagging of the depletion or surcharging, with respect to temporal variations in net water use). The second method requires the user to assume that the streamflow effects of monthly variations in net water use in each subbasin are completely damped and lagged, that is, that streamflow alteration from net water use in any given month is equal to the long-term mean annual, or equilibrium, value of streamflow alteration for that subbasin. In order to evaluate the differences between these two methods under median August streamflow and water-use conditions, both methods were applied to the 221 subbasins of the Concord, Ipswich, and Blackstone state planning basins—three basins that represent the wide range of potential flow-alteration conditions across Massachusetts. Figure 27 shows the results of this comparison for August, a low-flow month in which the potential effects of withdrawals and discharges on streamflow can be expected to be greatest.

It is evident that the instantaneous-alteration method, when applied in August, gives a somewhat higher estimate of streamflow depletion in subbasins with overall net depletion, and a somewhat lower estimate of streamflow surcharging in subbasins with overall net surcharging, than the equilibrium method (fig. 27). However, the absolute difference between the two methods was generally less than 10 percent, except in the small fraction of basins that were highly surcharged. The actual degree of month-to-month streamflow alteration from water use in any given subbasin would be expected, under typical conditions, to be between the two end members represented by these two methods. However, in order to provide the best indicator of potential streamflow alteration for the large majority of subbasins in the state with either near-natural flow conditions or net depletion and also take full advantage of available information concerning month-to-month variation in groundwater demand in Massachusetts (fig. 2; table 2), the first method was selected for this study. For areas where extensive streamflow alteration from groundwater withdrawals and discharges was indicated (that is, greater than 40 percent alteration on a monthly or shorter-term basis), detailed modeling studies may be appropriate for simulating the interaction between groundwater and surface water and for formulating optimal water-management strategies for meeting human and ecosystem needs.

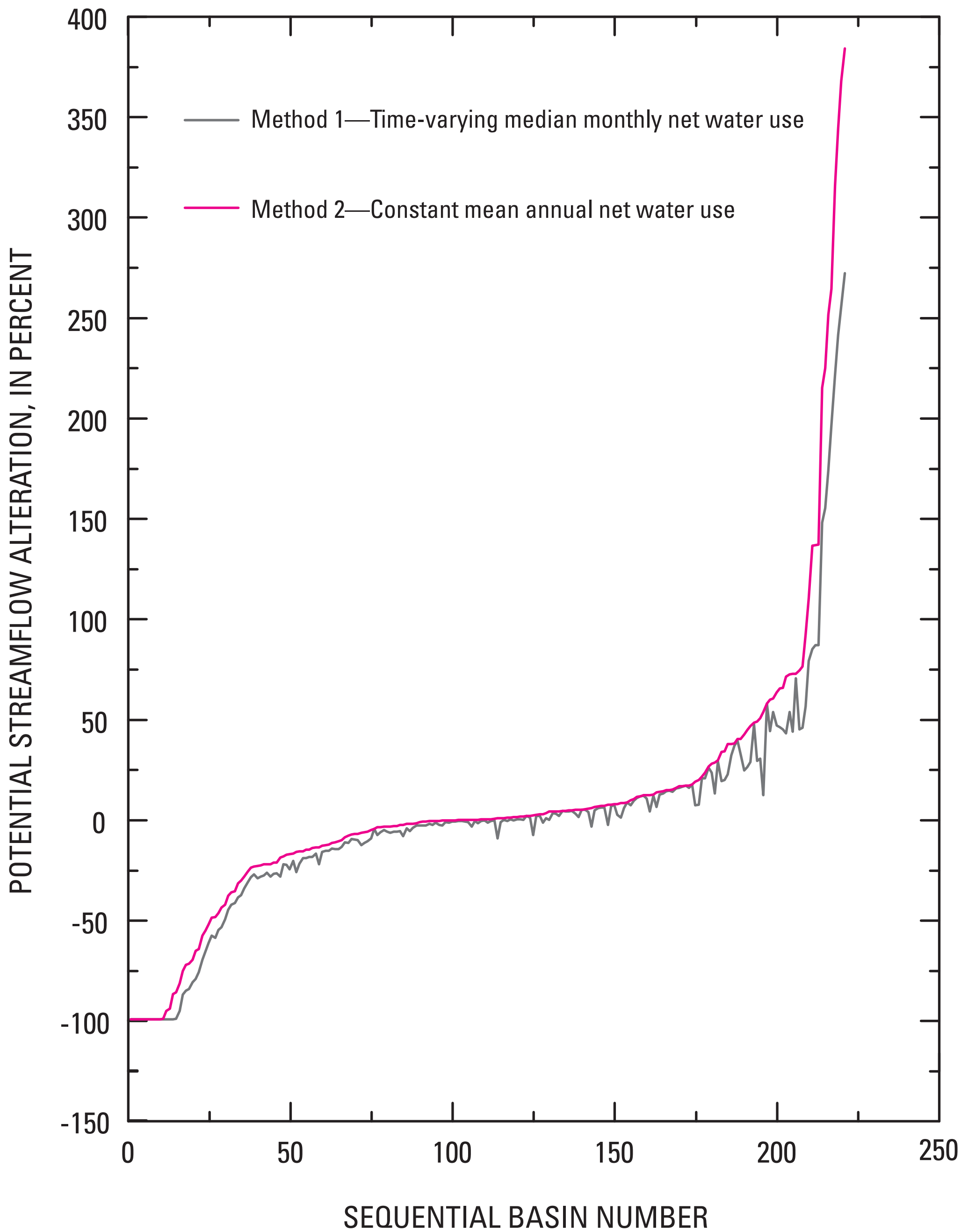

Figure 27. Paired comparison of two methods of estimating the net effects of water-use scenario 1 on median August streamflows at the outlets of 221 subbasins of the Concord, Ipswich, and Blackstone state planning basins. Method 1 (time-varying median monthly net water use) was used for this study.

Effects of Surface-Water-Reservoir Withdrawals on Streamflow (Water-Use Scenario 2)

As previously noted, the SYE version 1.0 application does not represent the effects of time-varying surface-water-reservoir withdrawals on reservoir storage and downstream flows. This limitation was addressed by quantifying the long-term mean annual RND (see equation 3) for all subbasins under a water-use scenario that includes surface-water-reservoir withdrawals. Long-term RND is insensitive to the transient effects of changing reservoir storage on downstream flows and serves as a indicator of the overall magnitude of surface-water-reservoir withdrawals in comparison to unaffected flows from a subbasin. In subbasins with extensive streamflow alteration (long-term RND greater than 20 percent, water-use scenario 2), the evaluation of optimal water-management alternatives for a given subbasin may call for detailed, reservoir-specific modeling studies that account for dam-outlet structures, operational practices and the stage-storage-discharge relation of the reservoirs in the subbasin.

Other Limitations in Estimating Streamflow Alteration from Water Use

The potential effects of cranberry-bog water-management practices at the subbasin scale were not considered in this study, which followed the approach of a recent USGS investigation of the Plymouth-Carver aquifer system (Masterson and others, 2009). Most water management in cranberry cultivation consists of the localized diversion and impoundment of streamflow, rather than pumping and exporting of water for use at a distance from withdrawal sources. Where groundwater withdrawals for cranberry irrigation do occur, they typically take place adjacent to cultivated bogs, and capture water that otherwise would have discharged naturally to the bogs. For these reasons, the effects of cranberry-bog withdrawals on streamflows at the outlets of the 34 groundwater contributing areas analyzed in the present study were not considered.

Water-use data in this study were limited to reported information concerning point withdrawals and discharges for the 2000–2004 period. Information linking withdrawal locations to water-supply service areas and wastewater-discharge locations to areas of wastewater collection was not available statewide in electronic form. Hence, the net surcharging or depletion of streamflow at the mouth of each subbasin was inferred from the sum of the withdrawals and discharges in the subbasin. The year 2004 was the most recent period for which MDEP-reported withdrawal data was electronically available and quality-assured.

Changes in reported withdrawals and discharges since 2004 (including, for example, the replacement of selected municipal groundwater withdrawals in the Upper Ipswich River Basin by out-of-basin sources) were not included in the analysis. In addition, it was not possible to assess the potential effects on streamflow of inflow and infiltration (I/I) to wastewater-collection structures from adjacent aquifers on a statewide basis, because the necessary infrastructure data was not available in electronic form. Excluding possible I/I effects may cause underestimation of net streamflow depletion in sewered subbasins served by wastewater-treatment facilities if those facilities are downstream of the subbasin outlet. Finally, it should be emphasized that actual month-to-month patterns of groundwater withdrawals can be expected to vary from community to community and from year to year in comparison to the median monthly values used in this study (fig. 2).

Storage Ratio and Dam Density

The limitations of these two indicators derive from the limitations of the databases used to develop them. Storage information is available only for the 1,497 relatively large Massachusetts dams in the NID (U.S. Army Corps of Engineers, 1996). To be included in this database, a dam must be either (1) greater than 6 ft high with more than 50 acre-feet (2,178,000 ft^3) of storage, (2) greater than 25 ft high with more than 15 acre-feet (653,400 ft^3) of storage, or (3) pose a significant downstream threat to human lives or property. Because smaller dams are not included in the NID, the subbasin SRs presented in this report should be considered underestimates. Locations are presently available for a total of 2,682 dams in the database of the Massachusetts Riverways Program (C. Leuchtenberg, Massachusetts Riverways Program, written commun., 2009); however, this database may not contain all of the smaller dams in the state. Moreover, other types of barriers to biotic passage, such as road culverts, are not included in this database.

Local and Cumulative Impervious Cover

The two scales of IC values used in this study are mean values averaged over the local and cumulative areas draining to each subbasin outlet. Hence, some portions of each subbasin can be expected to have higher or lower values of percent IC than the subbasin average. For subbasins that extend outside the state, the percent IC was estimated from regression of data from the NLCD against data from the MassGIS impervious cover datalayer (fig. 21). As a result, the percent IC value is less precise for subbasins with upstream areas outside of the state.

Water Quality

The 2002 Massachusetts List of Impaired Waters (Massachusetts Office of Geographic and Environmental Information, 2005) contains no water-quality information for the 56 percent of the state's stream miles that were unassessed as of 2002. In addition, the stream segments that were assessed as of this date were concentrated on the larger streams and rivers, many of which received discharges of treated wastewater; the water quality of smaller streams was less well defined. Finally, although more recent water-quality information is available—from the 2006 Massachusetts List of Impaired Waters (Massachusetts Department of Environmental Protection, 2007b)—it was not used for this study because the 2006 data are not georeferenced and were collected after the 2000–2004 period for the water-use database used in this study.

Summary

The stream basins of Massachusetts have been altered by a variety of human activities. To improve understanding of basin alteration in the state, the U.S. Geological Survey conducted a study of these alterations in cooperation with the Massachusetts Department of Conservation and Recreation. A series of basin indicators was developed from publicly available, georeferenced, statewide data maintained in electronic form by state and Federal agencies. The indicators characterize four major classes of basin alteration for 1,429 subbasins and groundwater contributing areas across Massachusetts: (1) streamflow alteration from water withdrawals and wastewater return flows from treatment plants and septic systems; (2) alteration of streamflow and aquatic habitat by dams and impoundments; (3) local and cumulative extent of impervious cover; and (4) known water-quality impairments.

Streamflow alteration was estimated using available water-use information and the Massachusetts Sustainable Yield Estimator (SYE), a computer application for estimating natural streamflows at ungaged sites in the state (Archfield and others, 2010). Streamflow alterations were estimated under two scenarios. Water-use scenario 1 incorporated all publicly reported groundwater withdrawals and discharges and withdrawals and discharges directly from and to streams for 2000–2004 and estimated domestic-well withdrawals and septic-system discharges. Water-use scenario 2 incorporated all of these types of water use, as well as average annual withdrawals from public-supply reservoirs for 2000–2004.

Streamflow alteration was assessed under water-use scenario 1 (excluding surface-water-reservoir withdrawals) for seven ecologically significant, seasonal flow statistics: January, April, August, and October median monthly flows, the median annual 7-day minimum flow, and the median count and duration of low-flow pulses. Statewide, a majority of the 1,429 subbasins and groundwater contributing areas were indicated to have relatively small (less than 10 percent) flow alterations under water-use scenario 1, even under natural low-flow conditions. For example, 67 percent of subbasins were indicated to have less than 10 percent alteration of the August median flow. However, a minority of subbasins showed extensive alteration, with 12 percent showing greater than 40 percent alteration for the August median flow. Most of the subbasins with extensive flow alteration were immediately to the north, west, and south of the inner metropolitan Boston region. Statewide, streamflow depletion was most commonly indicated for headwater subbasins, and streamflow surcharging was most pronounced in main-stem subbasins, although some smaller tributary basins were also surcharged. Potential flow alterations were less pronounced for high-flow months such as April, when only 4.8 percent of basins showed more than 10 percent alteration. The indicated degree of flow alteration in October and January was between that of August and April. Alteration in the low-pulse statistics was similar in magnitude to the August flow alterations.

The additional effects of surface-water-reservoir withdrawals on streamflows were estimated under water-use scenario 2. Under this scenario, extensive depletion of mean annual flows was indicated for a relatively small number of basins statewide. Depletion of mean annual flows is to be expected under this scenario because a number of Massachusetts subbasins have reservoirs (and associated watersheds) that were designed, constructed, and managed over the past 160 years for the specific purpose of supplying drinking water to cities (Weiskel and others, 2005). The seasonal effects of surface-water-reservoir withdrawals on downstream flows were not estimated in the present study because the site-specific information required to assess these effects is unavailable statewide. The seasonal effects of withdrawals on flows downstream of a particular reservoir may be greater than, similar to, or less than the effects from long-term average water use (water-use scenario 1), depending upon how the particular reservoir is managed. Water-use intensity, an indicator of the overall magnitude of withdrawals and discharges compared to natural flows in a subbasin, was also calculated statewide on a mean annual basis. Water-use intensity differed over several orders of magnitude between the relatively undeveloped and developed portions of the state.

Massachusetts has one of the highest concentrations of dams in the United States. Storage ratio and dam density were used to indicate the potential impact of known dams and their impoundments on streamflow regimes and aquatic habitat. The subbasin storage ratio, defined as the volume of impounded storage in a subbasin divided by its mean annual predevelopment outflow, indicates potential alteration of streamflow, sediment transport, and temperature regimes in a subbasin. Storage ratios were relatively low (less than 1 day) in 33 percent of the subbasins. However, about 40 percent of the subbasins had storage ratios greater than 1 month, and 3.2 percent (45 subbasins) had large storage ratios greater than 1 year. These subbasins generally contain public-water-supply reservoirs serving urban centers.

Dam density, an indicator of one major type of stream-habitat fragmentation, was assessed using a more detailed database of dam locations than was available for the storage-ratio analysis. Dams in Massachusetts have an average density of 1 dam per 6.7 stream miles across the statewide perennial-stream network of 11,740 miles. Consistent with previous national analyses, the highest dam densities were in Worcester County, where development of water power for industry has been extensive since the 18th century. High dam densities, likely associated with cranberry cultivation, are also found in the Plymouth-Carver region and in western Cape Cod.

Impervious cover (IC) has become a widely used indicator of urban land use and potential stormwater impact. Basin IC has been shown to be negatively correlated with the health of stream ecosystems, likely affecting stream biota by altering flow regimes, habitat, and water quality. Local IC was defined by this study in relation to the local hydrologic unit; cumulative IC, by contrast, was defined in relation to the entire area upstream of a given subbasin outlet (the entire subbasin area). Local IC ranged from 0 to 74 percent at the 7- to 10-mi^2 scale of the hydrologic units. About 33 percent of the state's hydrologic units are relatively undeveloped (less than 4 percent IC), and another 25 percent have 4 to 8 percent IC. At the high end of the IC range, 10 percent of hydrologic units have 12 to 16 percent IC, and 18 percent of the statewide total are highly developed, with local IC greater than 16 percent. The range of cumulative or subbasin IC was smaller than that of local IC, reaching a maximum value of 55 percent. In some urban areas near the mouths of large stream basins, cumulative IC showed the mitigating effect of undeveloped upstream area. In other relatively undeveloped areas, cumulative IC was greater than local IC because of the effect of upstream urban development. Both local and cumulative IC were highest in metropolitan Boston and other major Massachusetts cities. IC was also high along the transportation corridors linking the major urban centers.

The water-quality status of Massachusetts streams is assessed periodically by the Massachusetts Department of Environmental Protection pursuant to the requirements of Section 303(d) of the Federal Clean Water Act. The percentage of assessed stream miles in each hydrologic unit that is listed as impaired by one or more contaminants is an indicator of subbasin water quality. The distribution of hydrologic units with some assessed streams is fairly even across the state, although approximately half of the state's stream miles have not been assessed. Many of the streams that were assessed were considered impaired by one or more contaminants and thus did not support one or more of their designated uses. In nearly three-fourths (72 percent) of the hydrologic units with assessed streams, more than half of the assessed streams were considered impaired. All of the assessed streams were considered impaired in about two-thirds (66 percent) of the hydrologic units with assessed streams.

Many of the streams historically assessed by the state are those that are likely to be impaired; they were the subject of monitoring because of known or suspected water-quality problems. Large streams, such as the main stems of rivers that made up most of the assessed stream miles, also are in many cases the receiving waters for discharges of treated wastewater, and for this reason may be more susceptible to water-quality problems than smaller streams. Like the distribution of subbasins with assessed stream miles, subbasins with large fractions of assessed stream miles that are considered impaired are distributed across the state, but are somewhat more concentrated in eastern Massachusetts.

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Appendix 1. Tables of Alteration Indicators and Water-Use Information for Massachusetts Stream Basins

CD–ROM

[In pocket]

Tables

Appendix 2. Digital Map Viewer of Massachusetts Stream Basins, Alteration Indicators, and Water-Use Information

CD–ROM

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