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SECTION 7. DAM FAILURE

7.1 GENERAL BACKGROUND

7.1.1 Causes of Dam Failure

A "dam" is an artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material for the purpose of storage or control of water. Dam failure is a catastrophic type of failure characterized by the sudden, rapid, and uncontrolled release of impounded water or the likelihood of such an uncontrolled release. Dams can fail for one or a combination of the following reasons:

- Overtopping caused by floods that exceed the capacity of the dam
- Deliberate acts of sabotage
- Structural failure of materials used in dam construction
- Movement and/or failure of the foundation supporting the dam
- Settlement and cracking of concrete or embankment dams
- Piping and internal erosion of soil in embankment dams
- Inadequate maintenance and upkeep.

DEFINITIONS

Dam—Any artificial barrier and/or any controlling works, together with appurtenant works, that can or does impound or divert water.

Dam Failure—An uncontrolled release of impounded water due to structural deficiencies in dam.

Emergency Action Plan—A document that identifies potential emergency conditions at a dam and specifies actions to be followed to minimize property damage and loss of life. The plan specifies actions the dam owner should take to alleviate problems at a dam. It contains procedures and information to assist the dam owner in issuing early warning and notification messages to responsible downstream emergency management authorities of the emergency situation. It also contains inundation maps to show emergency management authorities the critical areas for action in case of an emergency. (FEMA 64)

High Hazard Dam—Dams where failure or operational error will probably cause loss of human life. (FEMA 333)

Significant Hazard Dam—Dams where failure or operational error will result in no probable loss of human life but can cause economic loss, environmental damage or disruption of lifeline facilities, or can impact other concerns. Significant hazard dams are often located in rural or agricultural areas but could be located in areas with population and significant infrastructure. (FEMA 333)

Dam failures in the United States typically occur in one of four ways:

- Overtopping of the primary dam structure, which accounts for 34 percent of all dam failures, can occur due to inadequate spillway design, settlement of the dam crest, blockage of spillways, and other factors.
- Foundation defects due to differential settlement, slides, slope instability, uplift pressures, and foundation seepage can also cause dam failure. These account for 30 percent of all dam failures.
- Failure due to piping and seepage accounts for 20 percent of all failures. These are caused by internal erosion due to piping and seepage, erosion along hydraulic structures such as spillways, erosion due to animal burrows, and cracks in the dam structure.
- Failure due to problems with conduits and valves, typically caused by the piping of embankment material into conduits through joints or cracks, constitutes 10 percent of all failures.

The remaining 6 percent of U.S. dam failures are due to miscellaneous causes. Many dam failures in the United States have been secondary results of other disasters. The prominent causes are earthquakes,

landslides, extreme storms, massive snowmelt, equipment malfunction, structural damage, foundation failures, and sabotage. Poor construction, lack of maintenance and repair, and deficient operational procedures are preventable or correctable by a program of regular inspections. Terrorism and vandalism are serious concerns that all operators of public facilities must plan for; these threats are under continuous review by public safety agencies.

7.1.2 Regulatory Oversight

The potential for catastrophic flooding due to dam failures led to passage of the National Dam Safety Act (Public Law 92-367). The National Dam Safety Program requires a periodic engineering analysis of every major dam in the country. The goal of this FEMA-monitored effort is to identify and mitigate the risk of dam failure so as to protect the lives and property of the public.

Massachusetts Department of Conservation and Recreation Office of Dam Safety

The Office of Dam Safety maintains records of dams located throughout the Commonwealth, ensures compliance with acceptable practices pertaining to dam inspection, maintenance, operation, and repair of dams. The current regulations, dated June 29, 2009, were promulgated in accordance with 2002 revisions of the Dam Safety Statute (MGL Chapter 253 §§ 44-50) identify the responsibilities of dam owners to register, inspect, develop emergency action plans for high hazard potential dams, and maintain dams in good operating conditions. Amendments to Dam Safety Regulations 302 CMR 10.00-10.16 became effective November 4, 2005 with minor revisions in 2009 and are reflective of the 2002 statutory changes.

In accordance with MGL Chapter 235, Section 45, and 302 CMR 10.05, dam owners must add their dams to the public record by completing a Dam Registration Form provided by the Office of Dam Safety. Upon receipt of the completed form, the Office of Dam Safety issues a Dam Registration Certificate to dam owners. The dam owner must record the certificate at the applicable registry of deeds as an attachment to the record deed that describes the parcel where the dam is located at provide the Office with a copy of the recorded certificate. When land ownership is transferred, a revised form must be submitted to the Office to initiate issuance of an updated Dam Registration Certificate that must be recorded.

The Office of Dam Safety has made available documents that serve as a template and guidelines for conducting compliant dam safety field inspections and filing complaint Dam Safety Phase I Inspection Reports. Owners of dams are required by 302 CMR 10.07 to hire a qualified engineer to inspect and report results every two years for high hazard dams, every five years for significant dams, and every 10 years for low hazard dams.

U.S. Army Corps of Engineers Dam Safety Program

The U.S. Army Corps of Engineers is responsible for safety inspections of some federal and non-federal dams in the United States that meet the size and storage limitations specified in the National Dam Safety Act. The Corps has inventoried dams; surveyed each state and federal agency's capabilities, practices and regulations regarding design, construction, operation, and maintenance of the dams; and developed guidelines for inspection and evaluation of dam safety (U.S. Army Corps of Engineers, 1997).

Federal Energy Regulatory Commission Dam Safety Program

The Federal Energy Regulatory Commission (FERC) has the largest dam safety program in the United States. The FERC cooperates with a large number of federal and state agencies to ensure and promote dam safety and, more recently, homeland security. There are 3,036 dams that are part of regulated hydroelectric projects are in the FERC program. Two-thirds of these are more than 50 years old. As dams age, concern about their safety and integrity grows, so oversight and regular inspection are important. FERC staff inspects hydroelectric projects on an unscheduled basis to investigate the following:

- Potential dam safety problems

- Complaints about constructing and operating a project
- Safety concerns related to natural disasters
- Issues concerning compliance with the terms and conditions of a license.

Every five years, an independent consulting engineer, approved by the FERC, must inspect and evaluate projects with dams higher than 32.8 feet or with a total storage capacity of more than 2,000 acre-feet.

FERC staff monitors and evaluates seismic research in geographic areas where there are concerns about seismic activity. This information is applied in investigating and performing structural analyses of hydroelectric projects in these areas. FERC staff also evaluates the effects of potential and actual large floods on the safety of dams. During and following floods, FERC staff visits dams and licensed projects, determines the extent of damage, if any, and directs any necessary studies or remedial measures the licensee must undertake. The FERC publication *Engineering Guidelines for the Evaluation of Hydropower Projects* guides the FERC engineering staff and licensees in evaluating dam safety. The publication is frequently revised to reflect current information and methodologies.

The FERC requires licensees to prepare emergency action plans and conducts training sessions on how to develop and test these plans. The plans outline an early warning system if there is an actual or potential sudden release of water from a dam due to failure. The plans include operational procedures that may be used, such as reducing reservoir levels and reducing downstream flows, as well as procedures for notifying affected residents and agencies responsible for emergency management. These plans are frequently updated and tested to ensure that everyone knows what to do in emergency situations.

7.2 HAZARD PROFILE

7.2.1 Location

There are 2,901 public and privately owned dams across Massachusetts. As infrastructure ages and maintenance and inspection costs increase, there is good reason to believe that there may be an increased risk for dam breaches or partial breaches.

The Massachusetts Office of Dam Safety, which is within the Department of Conservation and Recreation (DCR), maintains a database of all the publicly and privately owned dams in the Commonwealth. This information includes all the high-hazard dams currently listed the National Dam Inventory which is has been developed as part of the National Dam Safety Program under the U.S. Army Corps of Engineers (per Public Law 92-367). According to the spatial layer maintained by Office of Dam Safety and provided by MassGIS there are 2,901 dams located throughout the Commonwealth of Massachusetts. Table 7-1 represents the breakdown of dam hazard class by ownership type and Table 7-2 summarizes the number of dams by County. Figure 7-1 illustrates their locations.

TABLE 7-1.
NUMBER OF DAMS BY OWNER AND HAZARD IN MASSACHUSETTS

Owner	High Hazard	Significant Hazard	Low Hazard	NA	**Total**
Federal Agency	12	2	2	0	**16**
State	57	102	90	110	**359**
Municipality	174	295	146	248	**863**
Political Subdivision	14	10	5	5	**34**
Private	70	319	269	896	**1,554**
Private Association or other non-profit	3	17	18	37	**75**
Total	**330**	**745**	**530**	**1,296**	**2,901**

Source: MassGIS
Note: Two additional dams were provided in the GIS shape file, however they were located outside the state boundary.

TABLE 7-2.
NUMBER OF DAMS BY COUNTY IN MASSACHUSETTS

County	High Hazard	Significant Hazard	Low Hazard	N/A	Total
Barnstable	0	14	11	32	57
Berkshire	41	41	52	103	237
Bristol	25	45	31	53	154
Dukes	0	1	5	11	17
Essex	32	56	49	102	239
Franklin	14	43	28	73	158
Hampden	24	49	46	113	232
Hampshire	19	33	28	77	157
Middlesex	44	84	55	71	254
Nantucket	0	0	0	0	0
Norfolk	17	57	38	44	156
Plymouth	11	73	52	234	370
Suffolk	1	3	0	2	6
Worcester	102	246	135	381	864
Total	**330**	**745**	**530**	**1,296**	**2,901**

Source: MassGIS, 2012
Note: Two additional dams were provided in the GIS shape file, however they were located outside the state boundary.

Source: MassGIS, 2012

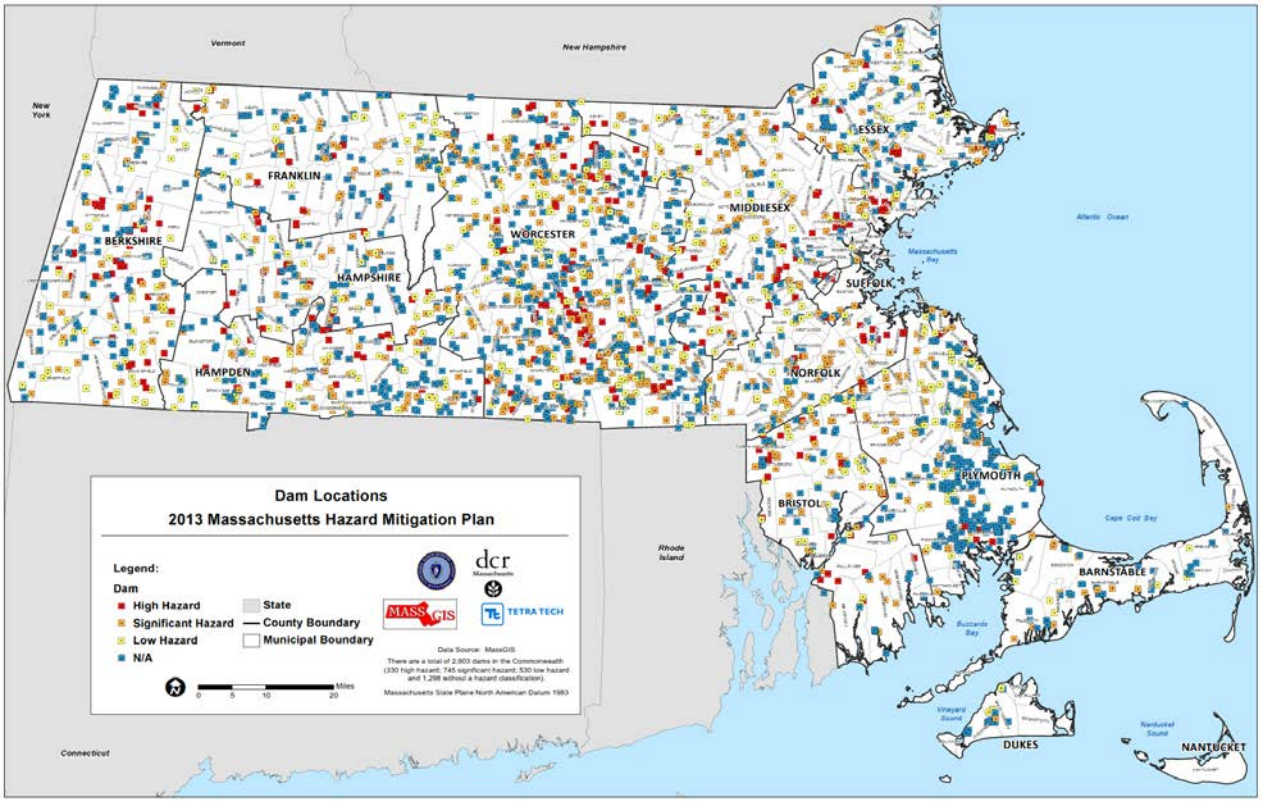

Figure 7-1 Dam Locations in the Commonwealth of Massachusetts.

Each dam is classified by hazard potential as follows:

- High Hazard Potential dam refers to dams located where failure will likely cause loss of life and serious damage to homes, industrial or commercial facilities, important public utilities, main highways, or railroads.
- Significant Hazard Potential dam refers to dams located where failure may cause loss of life and damage homes, industrial or commercial facilities, secondary highways, or railroads or cause interruption of use or service of relatively important facilities.
- Low Hazard Potential dam refers to dams located where failure may cause minimal property damage to others. Loss of life is not expected.

7.2.2 Previous Occurrences

There is no reliable or consistent information on complete dam failures that would be pertinent to this analysis at this time; however, several noteworthy events have influenced the analysis for this section.

On May 16, 1874, the Williamsburg Reservoir in Williamsburg, Massachusetts, broke and flooded a valley in the town which contained factories and farms. The flood resulting from the dam failure killed 139 people which made it the deadliest dam failure in the United States at the time. The dam failure was blamed on negligence by the mill owners who owned the dam.

On April 20, 1886, the Mud Pond Dam in East Lee, MA, failed and heavy damaged or destroyed approximately 12 shops and industries along Greenwater Brook. This failure killed seven people. The cause of the failure was unknown.

On January 7, 1909, the Ashley Dam in Massachusetts failed due to piping during the first filling. No additional information regarding this failure was provided.

On March 24, 1968, the Lee Lake Dam near East Lee, Massachusetts failed, destroying six homes, damaging 20 homes and one manufacturing plant. The failure caused two fatalities. The cause of the failure was unknown.

During September 1999, Hurricane Floyd caused two dam failures and one overtopping in Massachusetts. One complete failure of a run of the river cyclopean structure almost took out a campground. The first overtopping was of an earthen dam that unraveled and exposed a water line that services a major city. The second overtopping was a roadway dam overtopping and failed; a road had to be closed and a pond was drained in a state park. Information regarding the location of these dam failures and overtopping were not provided.

On April 4, 2004, the Smiths Pond Dam in Leominster, Massachusetts failed due to heavy rains. The dam overtopped and the spillway was clogged by debris. Divers from the Leominster EMA and crane operators worked to clear the spillway.

Whittenton Pond Dam, Taunton, an aged timber crib structure, was excessively stressed on October 18, 2005. Around 11.5 inches of rain fell across the Mill River watershed during October 2005. Most of this rain fell within a 6 hour time period. This resulted in the threat of an imminent catastrophic failure of the dam. A dam expert team decided construction of a rock dam/spillway downstream of the aged dam should occur, with a subsequent disassembly of Whittenton Pond Dam. Days later the new spillway was completed, just prior to another significant rainfall episode. The dam did not breach and no one in Taunton was harmed during this incident; however, approximately 2,000 people were evacuated, including a housing development for the elderly.

Forge Pond Dam, Freetown, is an earth filled dam more than 200 years old. In February 2010, heavy rains caused the dam to overtop and become unsafe. The DCR Office of Dam Safety determined that the dam posed a serious threat to public safety. Emergency actions were taken to stabilize the privately owned dam and no major damage occurred.

7.2.3 Frequency

Dam failure events are infrequent and usually coincide with events that cause them, such as earthquakes, landslides, excessive rainfall, and snowmelt. There is a “residual risk” associated with dams. Residual risk is the risk that remains after safeguards have been implemented. For dams, the residual risk is associated with events beyond those that the facility was designed to withstand. However, the probability of any type of dam failure is low in today’s regulatory and dam safety oversight environment.

7.2.4 Severity

The U.S. Army Corps of Engineers developed the classification system shown in Table 7-3 for the hazard potential of dam failures. The Corps of Engineers hazard rating systems is based only on the potential consequences of a dam failure; it does not take into account the probability of such failures.

TABLE 7-3.
CORPS OF ENGINEERS HAZARD POTENTIAL CLASSIFICATION

Hazard Category[a]	Direct Loss of Life[b]	Lifeline Losses[c]	Property Losses[d]	Environmental Losses[e]
Low	None (rural location, no permanent structures for human habitation)	No disruption of services (cosmetic or rapidly repairable damage)	Private agricultural lands, equipment, and isolated buildings	Minimal incremental damage

Significant	Rural location, only transient or day-use facilities	Disruption of essential facilities and access	Major public and private facilities	Major mitigation required
High	Certain (one or more) extensive residential, commercial, or industrial development	Disruption of essential facilities and access	Extensive public and private facilities	Extensive mitigation cost or impossible to mitigate

a. Categories are assigned to overall projects, not individual structures at a project.
b. Loss of life potential is based on inundation mapping of area downstream of the project. Analyses of loss of life potential should take into account the population at risk, time of flood wave travel, and warning time.
c. Indirect threats to life caused by the interruption of lifeline services due to project failure or operational disruption; for example, loss of critical medical facilities or access to them.
d. Damage to project facilities and downstream property and indirect impact due to loss of project services, such as impact due to loss of a dam and navigation pool, or impact due to loss of water or power supply.
e. Environmental impact downstream caused by the incremental flood wave produced by the project failure, beyond what would normally be expected for the magnitude flood event under which the failure occurs.

Source: U.S. Army Corps of Engineers, 1995

7.2.5 Warning Time

Warning time for dam failure varies depending on the cause of the failure. In events of extreme precipitation or massive snowmelt, evacuations can be planned with sufficient time. In the event of a structural failure due to earthquake, there may be no warning time. A dam's structural type also affects warning time. Earthen dams do not tend to fail completely or instantaneously. Once a breach is initiated, discharging water erodes the breach until either the reservoir water is depleted or the breach resists further erosion. Concrete gravity dams also tend to have a partial breach as one or more monolith sections are forced apart by escaping water. The time of breach formation ranges from a few minutes to a few hours (U.S. Army Corps of Engineers, 1997).

Dam owners are required to have established protocols for flood warning and response to imminent dam failure in the flood warning portion of its adopted emergency operations plan. These protocols are tied to the emergency action plans also created by the dam owners. These documents are customarily maintained as confidential information, although copies are required to be provided to the Commonwealth of Massachusetts for response purposes.

7.3 SECONDARY HAZARDS

Dam failure can cause severe downstream flooding, depending on the magnitude of the failure. Other potential secondary hazards of dam failure are landslides around the reservoir perimeter, bank erosion on the rivers, and destruction of downstream habitat.

7.4 CLIMATE CHANGE IMPACTS

Dams are designed partly based on assumptions about a river's flow behavior, expressed as hydrographs. Changes in weather patterns can have significant effects on the hydrograph used for the design of a dam. If the hygrograph changes, it is conceivable that the dam can lose some or all of its designed margin of safety, also known as freeboard. If freeboard is reduced, dam operators may be forced to release increased volumes earlier in a storm cycle in order to maintain the required margins of safety. Such early releases of increased volumes can increase flood potential downstream. Throughout the west, communities downstream of dams are already increases in stream flows from earlier releases from dams.

Dams are constructed with safety features known as "spillways." Spillways are put in place on dams as a safety measure in the event of the reservoir filling too quickly. Spillway overflow events, often referred to

as "design failures," result in increased discharges downstream and increased flooding potential. Although climate change will not increase the probability of catastrophic dam failure, it may increase the probability of design failures.

7.5 EXPOSURE

To understand risk, the assets exposed to the hazard areas are identified. Dam failure inundation maps and downstream hazard areas are considered sensitive information and were not available to conduct a quantitative risk assessment. The following discusses the Commonwealth of Massachusetts' exposure, in a qualitative nature, to the dam failure hazard including:

- Population
- State facilities
- Critical facilities
- Economy

7.5.1 Population

All populations in a dam failure inundation zone would be exposed to the risk of a dam failure. The potential for loss of life is affected by the capacity and number of evacuation routes available to populations living in areas of potential inundation.

7.5.2 State Facilities

All state-owned and state-leased facilities in a dam failure inundation zone would be exposed to the risk of a dam failure.

7.5.3 Critical Facilities

All critical facilities and infrastructure in a dam failure inundation zone would be exposed to the risk of a dam failure.

7.5.4 Economy

All buildings and infrastructure located in the dam failure inundation zone are considered exposed and vulnerable. Figure 7-2 illustrates the location of the high hazard dams throughout the Commonwealth. Refer to Table 7-2, which summarizes the number of high hazard dams in each County. In summary, Worcester County has the greatest number of high hazard dams compared to the remainder of the Commonwealth (102 high hazard dams).

Reservoirs held behind dams affect many ecological aspects of a river. River topography and dynamics depend on a wide range of flows, but rivers below dams often experience long periods of very stable flow conditions or saw-tooth flow patterns caused by releases followed by no releases. Water releases from dams usually contain very little suspended sediment; this can lead to scouring of river beds and banks.

The environment would be exposed to a number of risks in the event of dam failure. The inundation could introduce many foreign elements into local waterways. This could result in destruction of downstream habitat and could have detrimental effects on many species of animals.

7.6 VULNERABILITY

A quantitative vulnerability assessment could not be completed to estimate potential losses from a dam failure event. The Commonwealth's vulnerability to the dam failure hazard is discussed qualitatively below.

7.6.1 Population

Vulnerable populations are all populations downstream from dam failures that are incapable of escaping the area within the needed time frame. This population includes the elderly and young who may be unable to get themselves out of the inundation area. Economically disadvantaged populations are more vulnerable because they are likely to evaluate their risk and make decisions to evacuate based on the net economic impact to their family. The population over the age of 65 is also highly vulnerable because they are more likely to seek or need medical attention which may not be available due to isolation during a flood event and they may have more difficulty evacuating.

Source: MassGIS

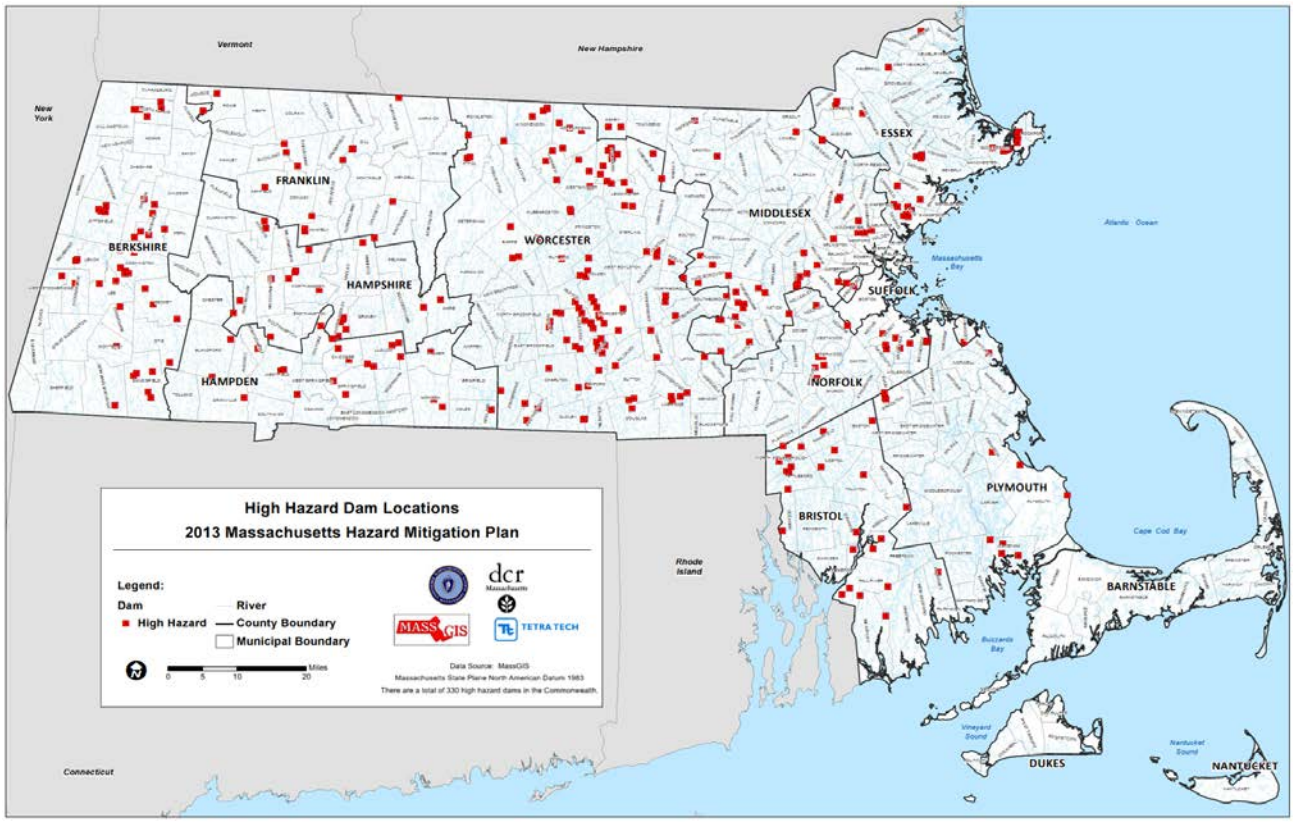

Figure 7-2. High Hazard Dams in the Commonwealth

There is often limited warning time for a dam failure event. While dam failure is rare, when events do occur, they are frequently associated with other natural hazard events such as earthquakes, landslides, or severe weather, which limits their predictability and compounds the hazard. Populations without adequate warning of the event from a television or radio emergency warning system are highly vulnerable to this hazard.

7.6.2 State Facilities

All state facilities in the dam failure inundation zone are vulnerable to damage. Buildings and property located closest to the dam inundation zone have the greatest potential to experience the largest, most destructive surge of water.

7.6.3 Critical Facilities

All critical facilities and transportation infrastructures in the dam failure inundation zone are vulnerable to damage. Flood waters may potentially cut off evacuation routes, limit emergency access, and create

isolation issues. Utilities such as overhead power lines, cable and phone lines in the inundation zone are also vulnerable. Loss of these utilities could create additional isolation issues for the inundation zones.

7.6.4 Economy

Damage to buildings can impact a community's economy and tax base. As previously stated, buildings and property located closest to the dam inundation zone have the greatest potential to experience the largest, most destructive surge of water.