Comprehensive Water Resources Report

Phase 1 – Preliminary Assessment

Town of Boxborough | October 2025

EXECUTIVE SUMMARY

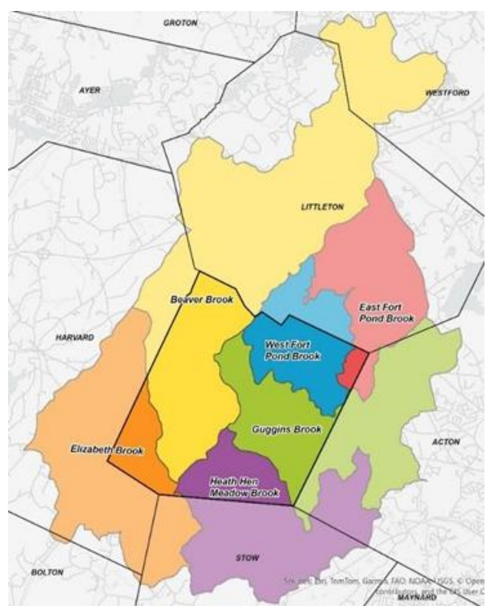
The Town of Boxborough is dedicated to understanding and managing its water resources as development expands. This report is the first phase in implementing Action 1.1.4.2 of the Town's Master Plan: "Plan for long-term water supply and wastewater management." Without a municipal water or sewer system, the town relies on a decentralized network of private and small community wells for drinking water needs and private and community septic systems to manage wastewater. As most of these systems are private, comprehensive water resource planning is challenging. As a step towards future drinking water and wastewater planning, Boxborough has developed this Comprehensive Water Resources Report which includes:

- An analysis of the Town's projected population (under current and under full buildout conditions);
- An inventory of water resources and potential water quality threats to these resources;
- An assessment of current and future drinking water demand and groundwater recharge;
- An assessment of current and future wastewater needs and limitations based on environmental conditions; and
- A review of water-related regulatory requirements that guide water management decisions.

Boxborough Population and Buildout Potential	
Current Population (2020)	5,506
Population Projections (2050)	6,996
Additional Dwelling Units based on Current Zoning	263

Drinking Water Resources and Recharge

Boxborough is located within the Merrimack River and Concord River subbasins, classified by the USGS. At a smaller subsurface scale, the Town's water supply originates from six groundwater basins, relying primarily on private groundwater wells and small community water systems serving residential, municipal, and commercial users. Limited areas receive water through interconnections with adjacent Littleton and Acton water systems.



Groundwater Basins in the Boxborough area

Estimated Town-Wide Current and Future Drinking Water Demand				
Water Usage	Current Demand (MGY)	Future Usage – Low (MGY)	Future Usage – High (MGY)	Projected Percent Increase (Range)
Residential	130	146	166	12% - 27%
Commercial	59	59	441	0% - 648%
Total Usage	**189**	**205**	**607**	8% - 221%

Groundwater Withdrawals (MGY)	Recharge Rates (MGY)
979	6,780 to 15,996

Understanding recharge, or the process of replenishing the groundwater supply as water moves downward from the surface into the groundwater aquifers, is important to determine if the water supply is adequate for future demand. Recharge for surficial deposits in the Boxborough area were estimated on a basin-scale through a GIS-based analysis combining regional surficial geologic mapping, groundwater basins, and published recharge data. These rates were then compared to estimated withdrawals at both the basin-wide scale.

Wastewater Assessment

Boxborough relies primarily on onsite septic systems for wastewater management. Management of all systems is essential to protect the quality of groundwater. An assessment of environmental and soil conditions indicated that some of these systems are located in DEP Zone I, in areas with limited soils, within FEMA flood zones, and within a 100-feet of a waterbody or wetland ("Tier 1"). Available septic system records of properties in the most vulnerable areas indicate that many of these systems are over twenty years old. Future residential septic systems are estimated to increase the septic system flow from approximately 236 to 268 MGY.

Environmental Risk Category for 1,357 Septic Systems in Boxborough		
Risk Assessment Category	Category Description	Number of Properties
Tier 1	Properties situated within DEP Zone I; properties situated on limited soils, within the 1% FEMA Flood Zone, and located within the 100-foot buffer of a water body or wetland.	168
Tier 2	Properties situated on limited soils and located within the 100-foot buffer of a water body or wetland.	491
Tier 3	Properties not meeting criteria for Tier 1 or Tier 2 classifications.	701

Summary and Recommendations

Based on this analysis, groundwater *quantity* appears to be sufficient for current and future drinking water needs, under current practices whereby most properties are served by their own private wells. However, further analysis of groundwater *quality* is needed to evaluate whether clean drinking water is available for all. Furthermore, if Boxborough had to develop a municipal water system, it is not clear whether a well(s) of sufficient capacity, and meeting the State's requirements, could be developed to access the water. The following recommendations may enhance Boxborough's water resource management and planning capabilities.

1. Develop educational materials for homeowners discussing septic system maintenance and drinking water well sampling.
2. Develop a townwide drinking water sampling program to assess the water quality of private wells.
3. Add to the septic inventory by reviewing town files and Title 5 inspection forms for all properties.
4. Expand this study beyond Boxborough's town boundaries to include more accurate withdrawal assessments for the entire groundwater basins.
5. Identify additional properties to be placed under protection for water supply purposes.
6. Evaluate the Town's firefighting-related water needs.

7. Continue to discuss regional water supply options with neighboring towns, including an interconnection with the Massachusetts Water Resources Authority (MWRA).
8. Follow up with further evaluations recommended in this report, including additional work needed to address the water-related Actions in the Town's Master Plan.

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1.0 INTRODUCTION

The Town of Boxborough is committed to responsible water resource management to provide adequate water supply for current and future residents. Residents in Boxborough rely on onsite wastewater treatment and private drinking water wells. Protecting these resources is essential to the future growth of the town.

Comprehensive Water Resources Report

This Comprehensive Water Resources Report provides a planning-level analysis of Boxborough's water resources, future growth projections, and a review of existing town regulations. The goal of this plan is to guide future decision making for water system planning and management.

This report includes:

Number	Section Title	Contents
2	Boxborough Profile	Geographic and environmental information including land use, impervious cover, soils, geology, surface and groundwater resources, amongst others.
3	Potential Threats to Water Resources	Information on point and nonpoint source pollution in Boxborough including information on permitted discharges, septic systems, landfills, amongst others.
4	Population Projections and Buildout Analysis	Current and future population projections and results from a Buildout Analysis to determine spatial extent of future development.
5	Drinking Water Assessment	Current and future drinking water demand; recharge estimates, potential alternative drinking water supplies.
6	Wastewater Assessment	Current and future estimates of septic system flow; Environmental Risk Assessment
7	Regulations	Review of current state and local drinking and septic system regulations.
8	Recommendations	Recommended next steps.

It should be noted that all estimates in this report have limitations. These planning-level estimates are based on established literature values and industry standards, providing a reasonable approximation of current and future population, drinking water demand, septic system flow rates, and others. The estimates do not account for variability between properties and seasons and could be further refined through detailed metering, groundwater studies, seasonal demand analysis, and site-specific usage assessments. In addition, all projections are based on current zoning and town regulations. If there are changes to these regulations, these projections and future estimates may no longer be valid.

Watershed Descriptions used in this Report

Boxborough's surface water resources are distributed across several hierarchical watershed systems, each representing increasingly detailed classifications of watershed geography (described in greater detail in Section 2.6.1). HUC-8 is the largest system, while HUC-12 is the smallest. The term "watershed" refers broadly to any water drainage area, regardless of size, however the USGS has determined terminology for the Watershed Boundary Dataset as follows:

- HUC-8: subbasins
- HUC-10: watersheds
- HUC-12: subwatersheds

From a regulatory standpoint, the HUC-8 subbasins are most commonly used to delineate surface water boundaries. Boxborough is located within the Merrimack River and Concord River subbasins. However, to understand the subsurface water characteristics, this analysis was conducted on the groundwater basin level.

Two data sources were used to create the groundwater basin boundaries and data that is used in this analysis: Massachusetts Water Indicator (MWI) watersheds and Sustainable Water Management Initiative (SWMI) groundwater basin delineations. The MWI watershed boundaries, which delineate areas where surface water drains to a common point, intersect significantly with the SWMI Groundwater Category delineations, which map areas based on groundwater availability and potential. Overlap between MWI watersheds and SWMI Groundwater Categories create what is referred to as "groundwater basins" within this report. These groundwater basins do not adhere to town boundaries, as they are delineating groundwater flow. The difference between groundwater basins and HUC-8 subbasins can be seen in Figure 1.1 below. Additional detail on groundwater basins can be found in Section 2.6.3.

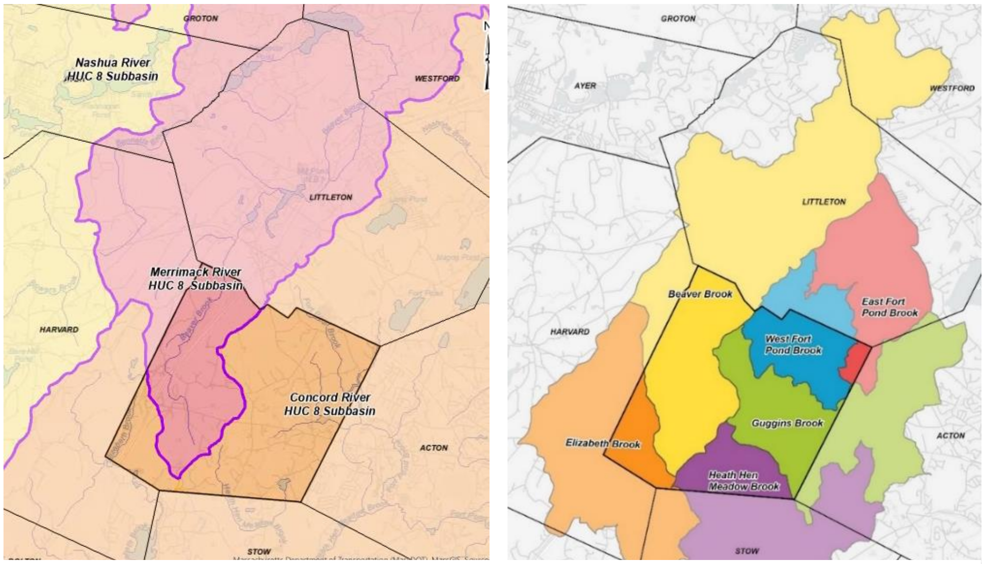
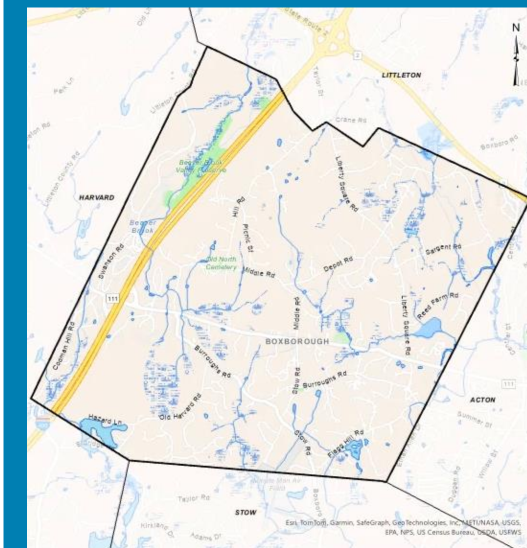


Figure 1.1 HUC 8 Subbasins (left), Groundwater Basins (right)

2.0 BOXBOROUGH PROFILE

2.1 Town Profile

Boxborough Statistics



Land Area: 10.4 square miles/6,656 acres

Major Land Uses

- Residential (41%)
- Open Space (30%)
- Commercial/Industrial (11%)
- Agriculture (3%)
- Forest (2%)
- Other (13%)

Impervious Cover: 8%

Population (2020): 5,506

The Town of Boxborough, Massachusetts is a small town in Middlesex County, set within the central highlands at the headwaters of the Merrimack River and Concord River.[1] The town is located at the crossroads of Interstate 495 and Route 111, just south of Route 2. Its location provides residents with easy access to surrounding areas and major commuting routes. Boxborough is a predominately rural and residential town that covers an area of 10.4 square miles and has a population of approximately 5,500 residents. Bordering towns include Littleton, Acton, Stow, and Harvard. Boxborough is within commuting distance of Boston, Lowell, Lawrence, Leominster, Fitchburg, Worcester, Framingham, and Nashua.

Incorporated in 1783, Boxborough has a history rooted in agriculture and traditional New England town governance. The current economic base of Boxborough is diversified, incorporating a mix of technology firms, small businesses, and local services. This diversification is supported by the town's location within the broader Route 128 technology belt. The presence of high-performing schools and a focus on conservation and open space contribute to the town's appeal as a residential community.

Many Boxborough residents rely on private wells as the town does not have a municipal water supply or associated infrastructure. More detailed information on Boxborough's drinking water can be found in Section 5 of this report. Littleton Electric Light and Water Departments serve as Boxborough's municipal utility company, providing electricity. National Grid is the primary gas utility company that serves Boxborough. Boxborough internet service providers include Xfinity, Verizon, and Viasat.

Boxborough's classification as a "Country Suburb" by the Metropolitan Area Planning Council (MAPC) reflects its distinct development patterns. Characterized by very low housing density, Boxborough lacks a significant mixed-use town center and compact neighborhoods. The town owns substantial tracts of potentially developable land, some of which may also be suitable for conservation. Recent growth trends typically involve conventional low-density residential subdivisions constructed on vacant land, alongside the development of auto-oriented office and industrial parks. Consistent with the characteristics of a Country Suburb, Boxborough is generally experiencing a period of rapid growth.

[1] DCR, 2006. Boxborough Reconnaissance Report.

2.2 Land Use and Impervious Cover

The term "land use" describes how people are using the land. It reflects human activity and the intended purpose for which land is used. The predominant land use in Boxborough is residential (41%). Residential land use includes single family, multi-family, and mixed-use that is primarily residential. Open space is the second largest land use in Boxborough at 30% (Figures 2.1 and 2.2). "Other" land use includes recreation, right-of-way, and tax exempt. Although agriculture played a large role in the Town's history, agriculture declined after World War II and now comprises just over 3% of land use. The rural character of the town is an important part of the town's character and multiple farms and open spaces can still be seen along the many scenic roads. The hilly topography of the town provides many scenic vistas. The stone walls that exist within the town are evidence of historically cleared land and are an important part of the landscape.

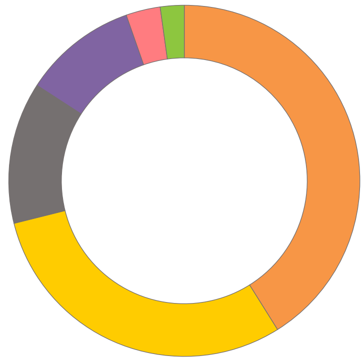


Figure 2.1. 2016 Land Use[1]

Table 2.1 Boxborough Land Use and Land Cover[2]		
Type	Land Use	Land Cover
Residential	41%	3%
Forested	2%	53%
Open Space	30%	14%
Commercial/Industrial	11%	2%
Water/Wetlands	N/A	24%
Agriculture	3%	<1%
Other	13%	4%

Land Use vs. Land Cover

While **land use** describes how people are actually using the land, **land cover** indicates what is actually on the land, as categorized by the MassGIS Land Cover/Land Use layer *(created through land cover mapping from 2016 aerial imagery and land use derived from standardized assessor parcel information).* For instance, **while residential land use is approximately 41% of the town, residential land cover, referring to the physical materials that cover areas designated for housing, is much smaller at just 3%.** Though only 2% of Boxborough is "used" for forests, the land cover in Boxborough is 53% forested, indicating that over 50% of the town is covered by forest vegetation. The difference between land use and land cover in Boxborough is shown in Table 2.1 and Figures 2.2 and 2.3.

[2] MassGIS, 2016. Land Cover/Land Use.

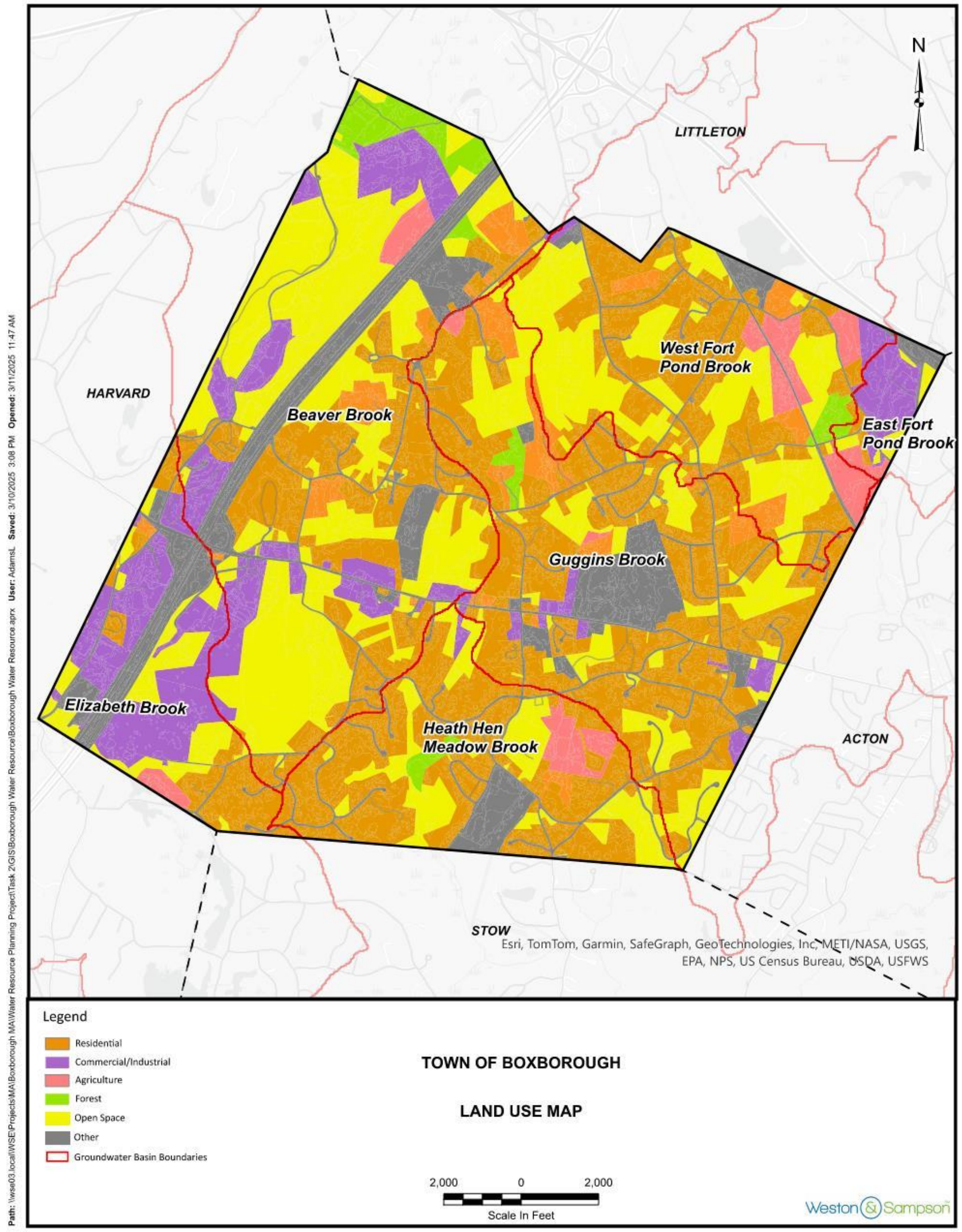


Figure 2.2. Land Use Map[3]

[3] MassGIS, 2016. Land Cover/Land Use.

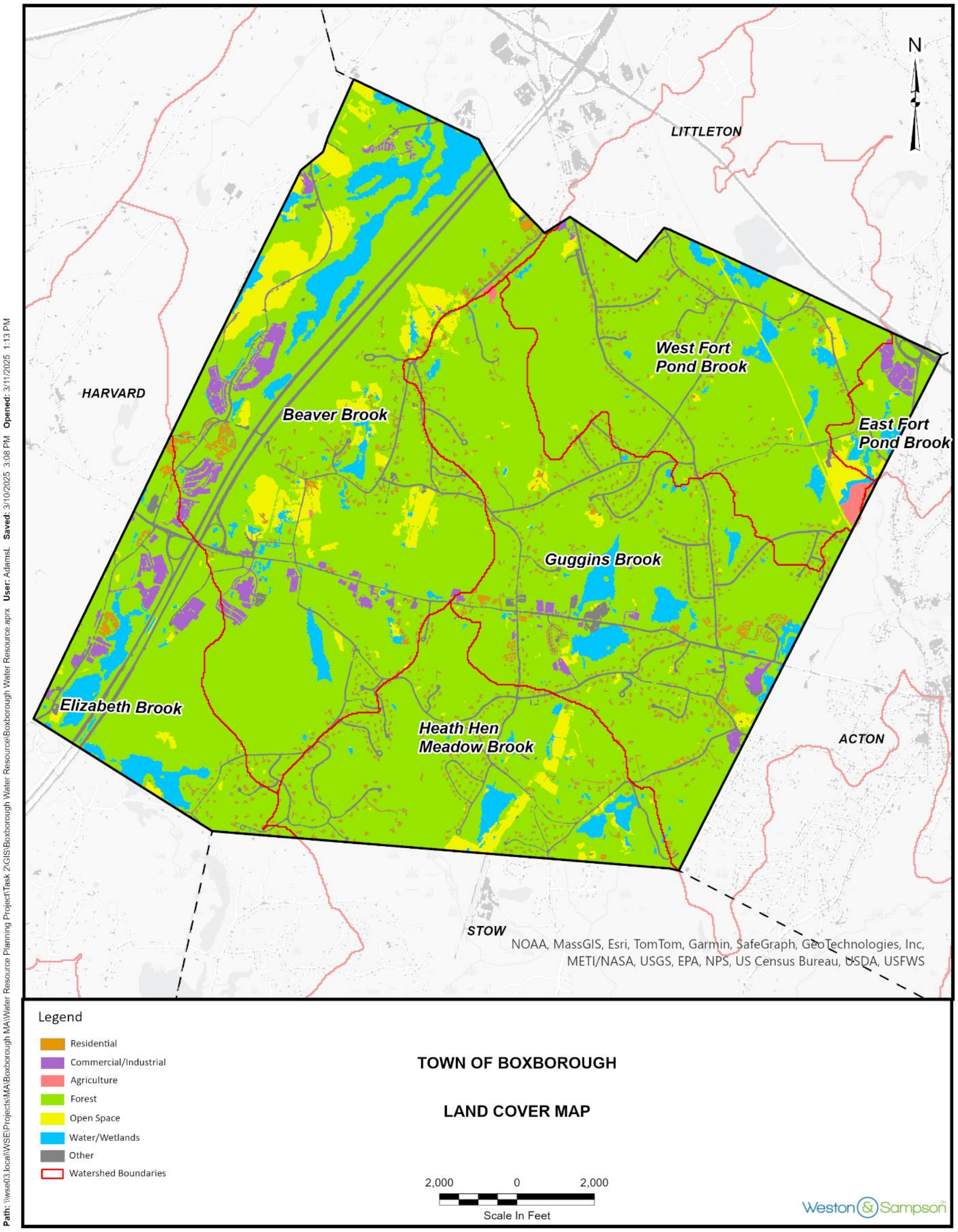


Figure 2.3. Land Cover Map[4]

[4] MassGIS, 2016. Land Cover/Land Use.

Impervious cover is any surface in the landscape that cannot effectively absorb or infiltrate rainfall or snowmelt. This includes buildings, roads, parking lots, sidewalks, and other man-made features that do not allow precipitation to infiltrate. Impervious cover is specifically anthropogenic in this classification, and non-anthropogenic impervious cover is classified as "open space". As shown in Figure 2.4, **Boxborough's impervious cover is 8%.** Section 3.3 contains further discussion of the impervious cover has on Boxborough's surface and groundwater.

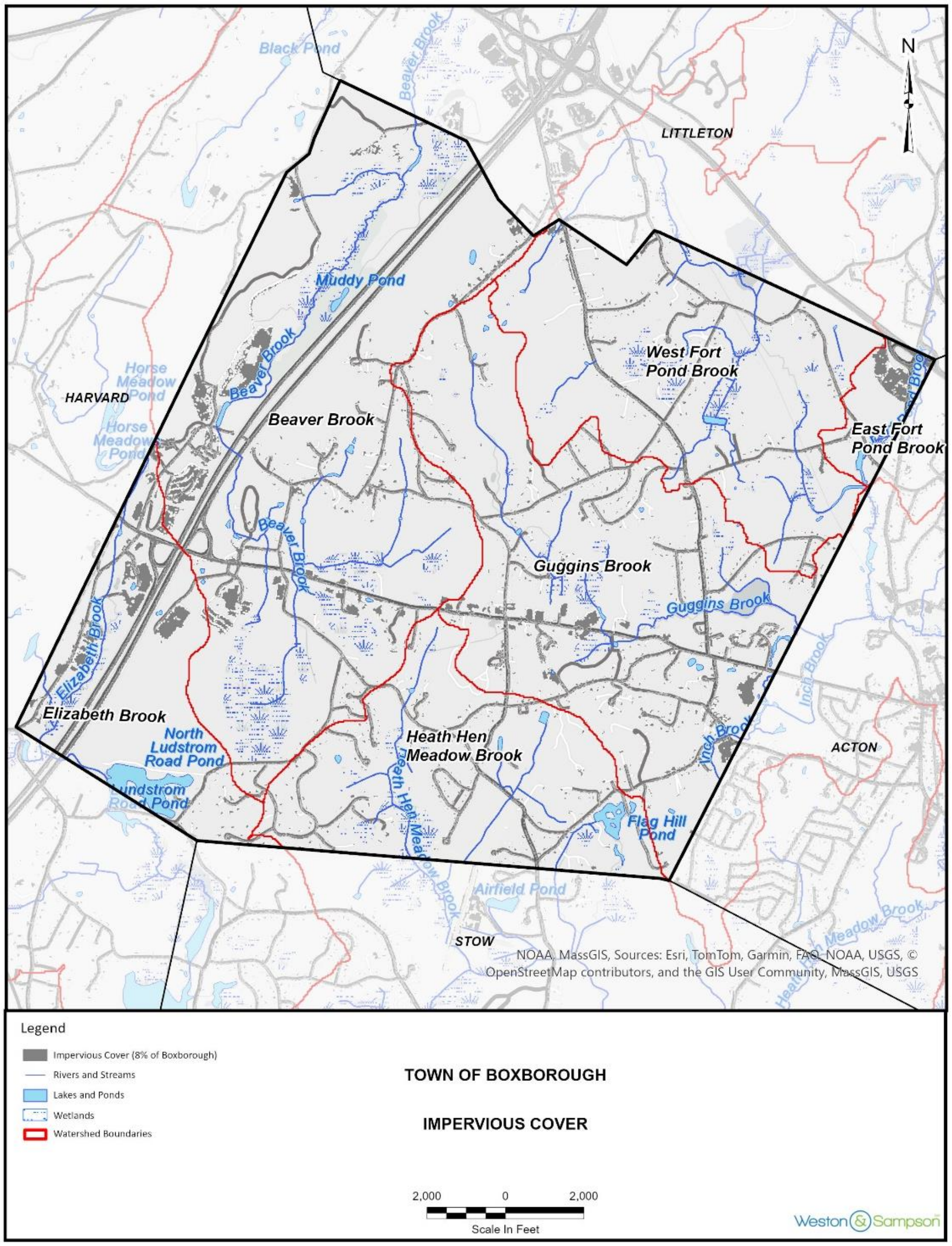


Figure 2.4. Impervious Cover Map[1]

2.3 Soils & Geology

2.3.1 Natural Resources Conservation Service (NRCS) Soils

Soils in Boxborough include a range of soil types which generally fall into one of four classes:

- Group A - sand, loamy sand, or sandy loam types of soils. It has low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission.
- Group B - silt loam or loam. It has a moderate infiltration rate when thoroughly wetted and consists chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.
- Group C - sandy clay loam. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine structure.
- Group D - clay loam, silty clay loam, sandy clay, silty clay or clay. This soil group has the highest runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material.

Less than half (47.6%) of all soils in Boxborough fall into Group A, which has a high infiltration rate and are well to excessively drained. Approximately 34% of soils are classified as Group B, which have a moderate infiltration capacity and are moderately drained. Just over 17% of soils in Boxborough are classified as Group C, and under 1% as Group D (Figure 2.5).

Almost half of the soils in Boxborough are classified as Group A, indicating they are well to excessively drained.

2.3.2 Surficial Geology

Surficial geology refers to the unconsolidated materials, such as sand, gravel, and till, that overlie the bedrock. These materials play a significant role in influencing local hydrology, soil development, and land use potential. Boxborough's surficial geology is dominated by 59% till, a heterogeneous mixture of unsorted sediment deposited directly by glaciers (Figure 2.6). Till areas often exhibit complex topography with drumlins, eskers, and moraines, features evident in the map's varied landscape. Another prominent surficial material is 23% of glacial stratified deposits, likely deposited by glacial meltwater streams. These sand and gravel deposits are often associated with aquifers, which are crucial for groundwater resources in Boxborough. There are large areas of swamp deposits (17%), indicating saturated soils and hydric vegetation. Wetlands are important components of the landscape, contributing to water quality, flood control, and wildlife habitat, which is discussed further in Section 2.6.2 Additionally, there are small areas of bedrock outcrops, where the underlying bedrock is exposed at the surface. These outcrops provide valuable insights into the geological formations beneath the surficial materials.

2.3.3 Bedrock Geology

The bedrock in Boxborough is predominantly metamorphic, accounting for 98.8% of the underlying rock. This indicates a history of intense heat and pressure that has transformed pre-existing rocks. A smaller component, 1.2%, is comprised of granite, an igneous rock formed from cooled magma. Granite bedrock is found in a small sliver in the eastern corner of town in the Fort Pond Brook watersheds (Figure 2.7). The metamorphic bedrock, formed by the transformation of existing rock under intense heat and pressure, typically exhibits a complex network of fractures and fissures. These fractures serve as the primary conduits for groundwater flow, creating a heterogeneous and often unpredictable aquifer system. Unlike sedimentary bedrock with abundant pore spaces, metamorphic rock generally has limited porosity, meaning groundwater storage and movement are largely controlled by the density and connectivity of these fractures. This fractured bedrock characteristic has significant implications for well productivity and groundwater quality in Boxborough. The quantity of water available at a given location, as well as the depth of water-bearing zones, can be highly variable and difficult to predict. Wells drilled in areas with dense, interconnected fractures may yield ample water, while those in less fractured zones may produce limited quantities.

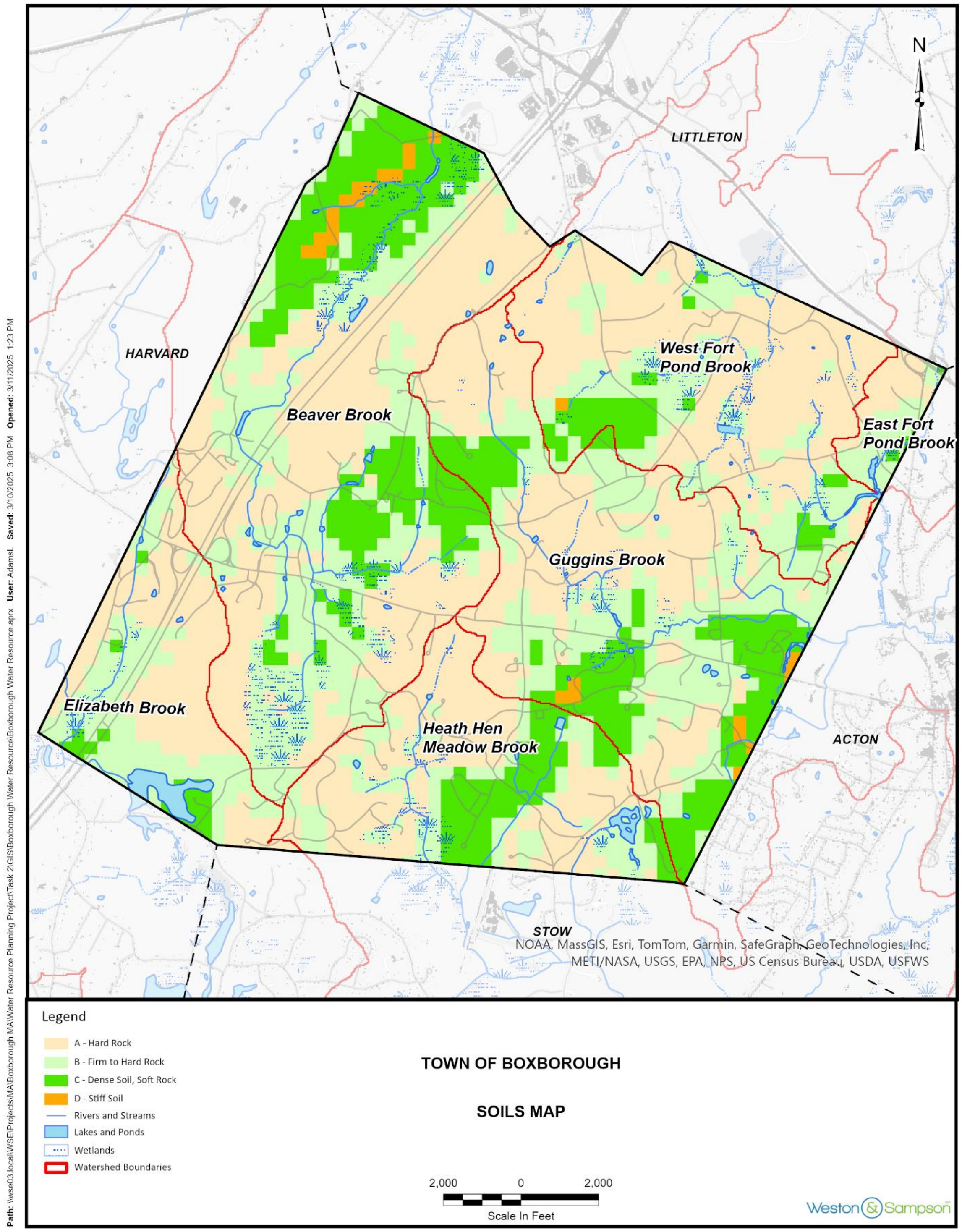


Figure 2.5. Soils Map[5]

[5] MassGIS, 2023. NEHRP Soil Classifications.

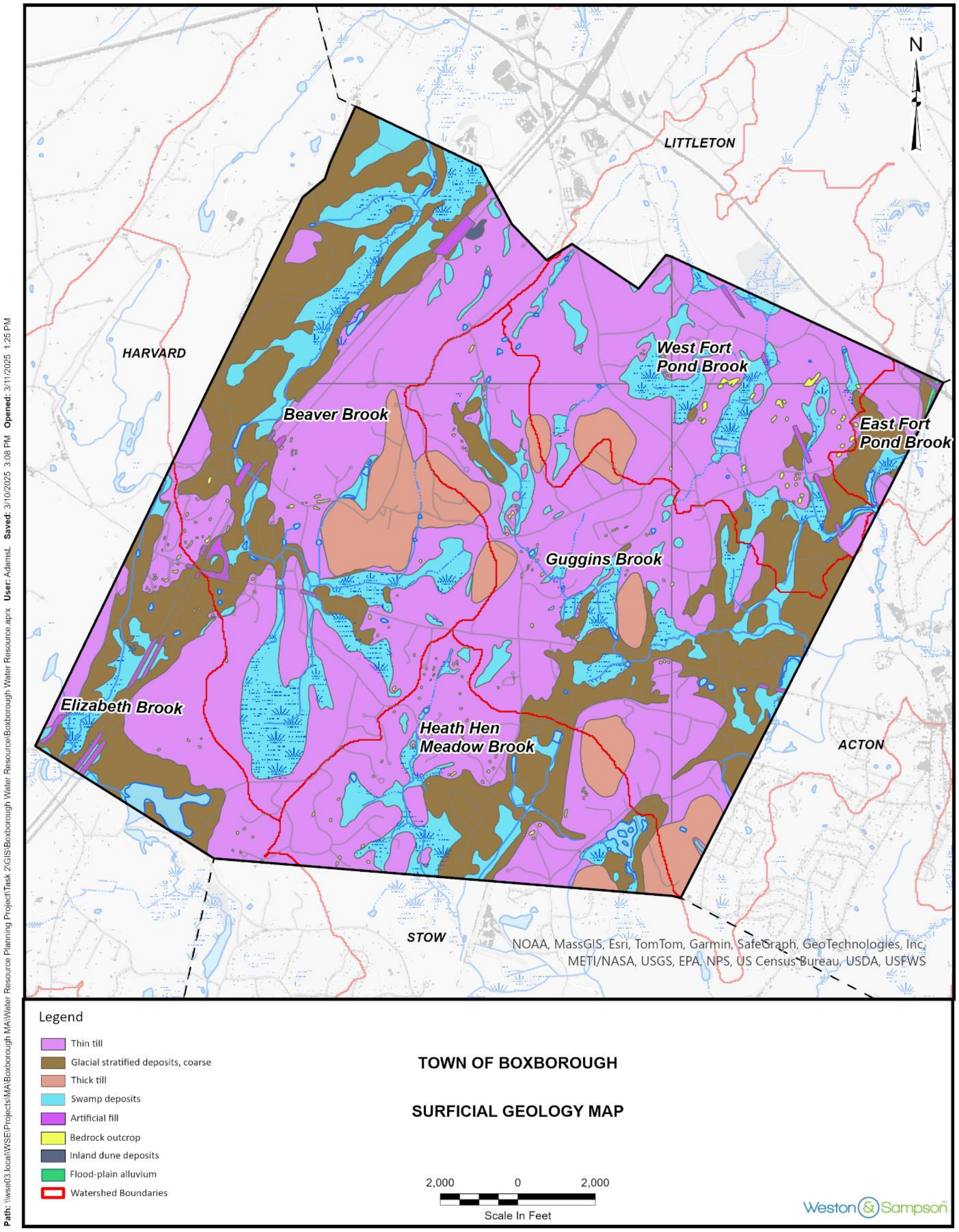


Figure 2.6 Surficial Geology Map[6]

[6] MassGIS, 2022. USGS 1:24,000 Surficial Geology.

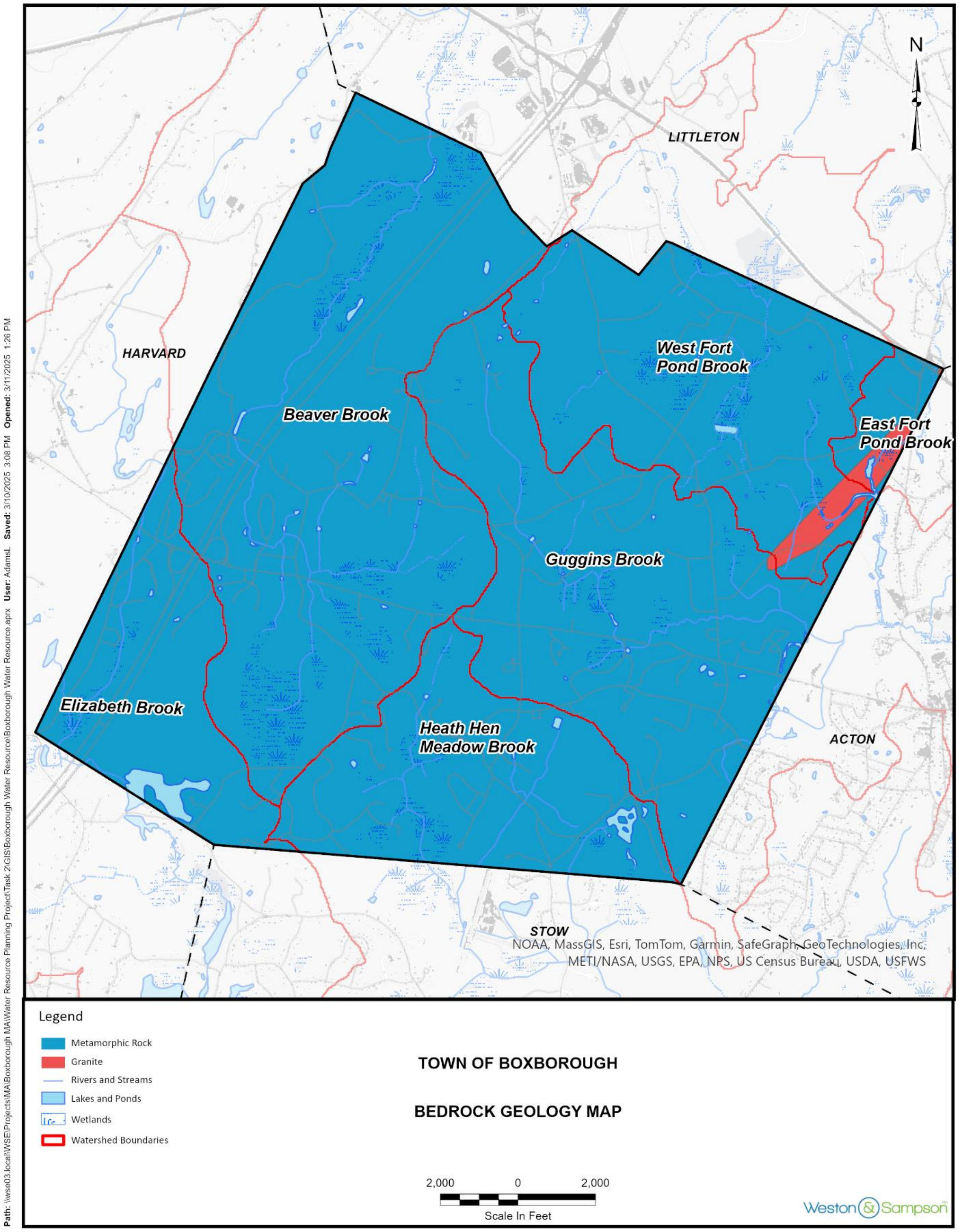


Figure 2.7. Bedrock Geology Map[7]

[7] MassGIS, 2004. Bedrock Lithology.

2.4 Flood Hazard Areas

Boxborough has areas designated as flood hazard zones by the Federal Emergency Management Agency (FEMA). These zones, depicted on Flood Insurance Rate Maps (FIRMs) indicate areas with varying types and degrees of flood risk. Flood hazard areas are classified as follows (Figure 2.8):

- A/AE – areas with high risk for flooding; 1% annual chance (1 in 100 years) of flooding
    - A – base flood elevation is unknown
    - AE – base flood elevation is known
- X – Moderate risk for flooding; 0.2% annual chance (1 in 500 years) of flooding

Boxborough is represented by nine FIRM Panels, eight of which have an effective date of 7/7/2014 and one with an effective date of 6/4/2010.[8] Approximately 5% of Boxborough is located in Zone X (moderate flood risk), while Zone A and AE cover 4% and 9% of the town, respectively (Figure 2.8).

Boxborough faces challenges related to localized flooding, particularly at road low points and areas adjacent to surface waters, wetlands, and floodplains. The 2021 Boxborough Community Resilience Building Workshop highlighted this issue, noting that many roads experience flooding, a problem expected to worsen with climate change. Several specific locations have been identified as areas of concern, including a key transportation corridor, Route 111, a state-owned road managed by Massachusetts Department of Transportation (MassDOT). These problem areas, as documented in the workshop report, include:

- Littlefield Road near Central Street;
- Depot Road near the Wildlife Management Area and its intersection with Liberty Square Road;
- Davidson Road;
- Burroughs Road near Wolf Swamp;
- Sargent Road;
- The intersection of Hill Road and Cunningham Road;
- Route 111 crossing of Elizabeth Brook;
- The intersection of Hill Road and Barteau Lane; and
- The northern end of land near the Cisco campus, near the Harvard Sportsman's Club border.

Route 111 has a history of flooding due to low spots, and while MassDOT and the town are undertaking improvements, including sidewalk installation, further assessment of remaining low spots is recommended upon completion of these improvements. Additionally, flooding may restrict access to the transfer station on Codman Hill Road, given its single access point.

[8] FEMA, 2025. Flood Insurance Rate Maps.

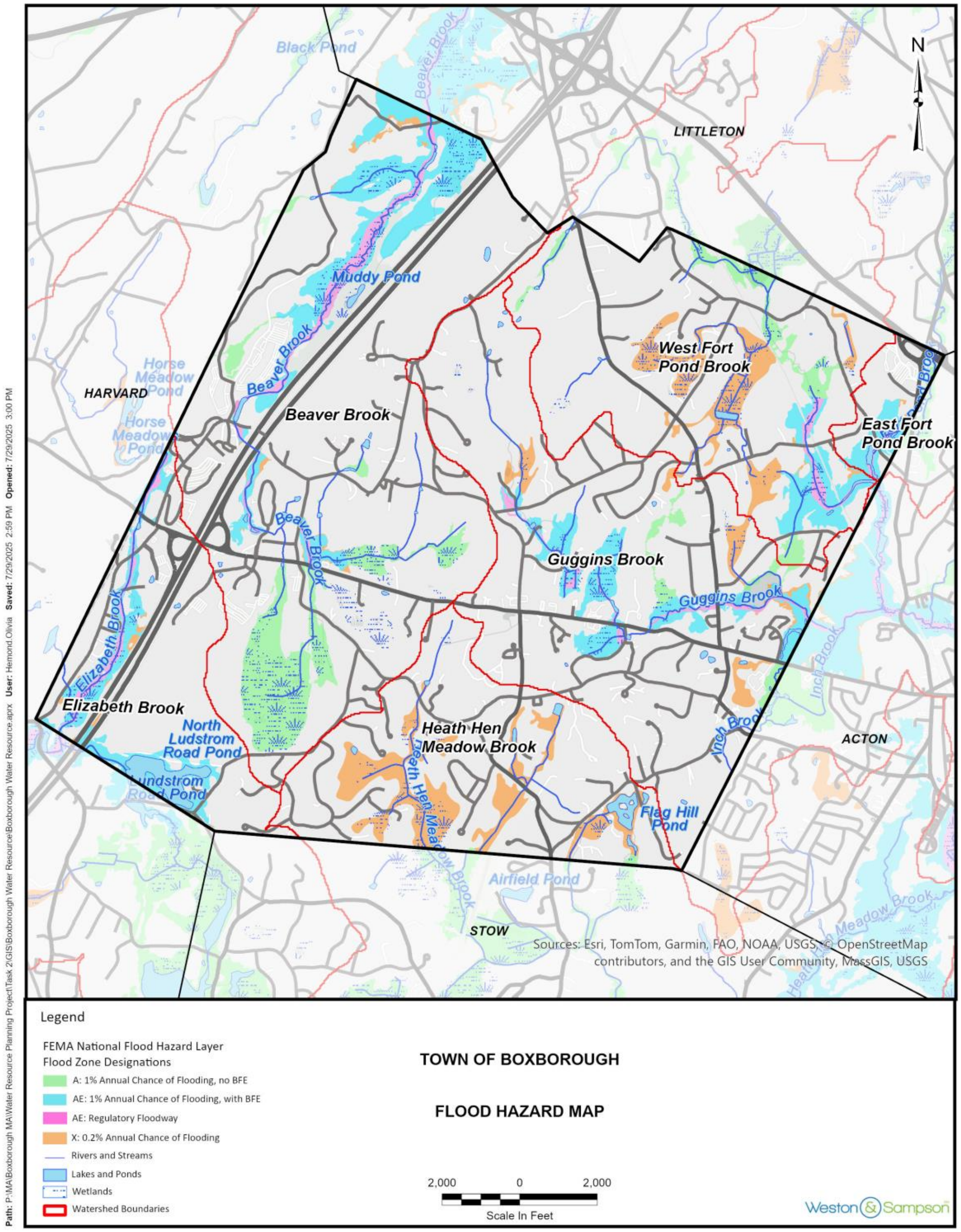


Figure 2.8. Flood Hazard Map[9]

[9] FEMA, 2025. Flood Insurance Rate Maps.

2.5 Open Space & Conservation Land

Approximately 22% of Boxborough's land is designated as conservation land.

In Boxborough, approximately 22% of the town's approximately 6,600 acres are designated as conservation land (Figure 2.9). This includes both lands owned outright and those protected by conservation easements. Detailed breakdowns of conservation land by watershed are available in town planning documents and show that several watersheds boast over 30% of their land area under conservation protection. Specifically, 45% of Boxborough's conservation lands are owned by the town, ensuring direct management for water resource preservation. An additional 30% are owned by other entities, contributing to the overall protected area. Town-held conservation easements account for 15%, while easements held by other organizations make up 10%, further solidifying the town's commitment to safeguarding its water resources through diverse conservation strategies.

The Conservation Commission manages approximately 827 acres of land in Boxborough. Many of these parcels include trails and the Boxborough Land Stewardship Committee (a subcommittee of the Boxborough Conservation Commission) publishes a trail guide with trail maps and information about each parcel. Boxborough has close to 30 miles of conservation trails.

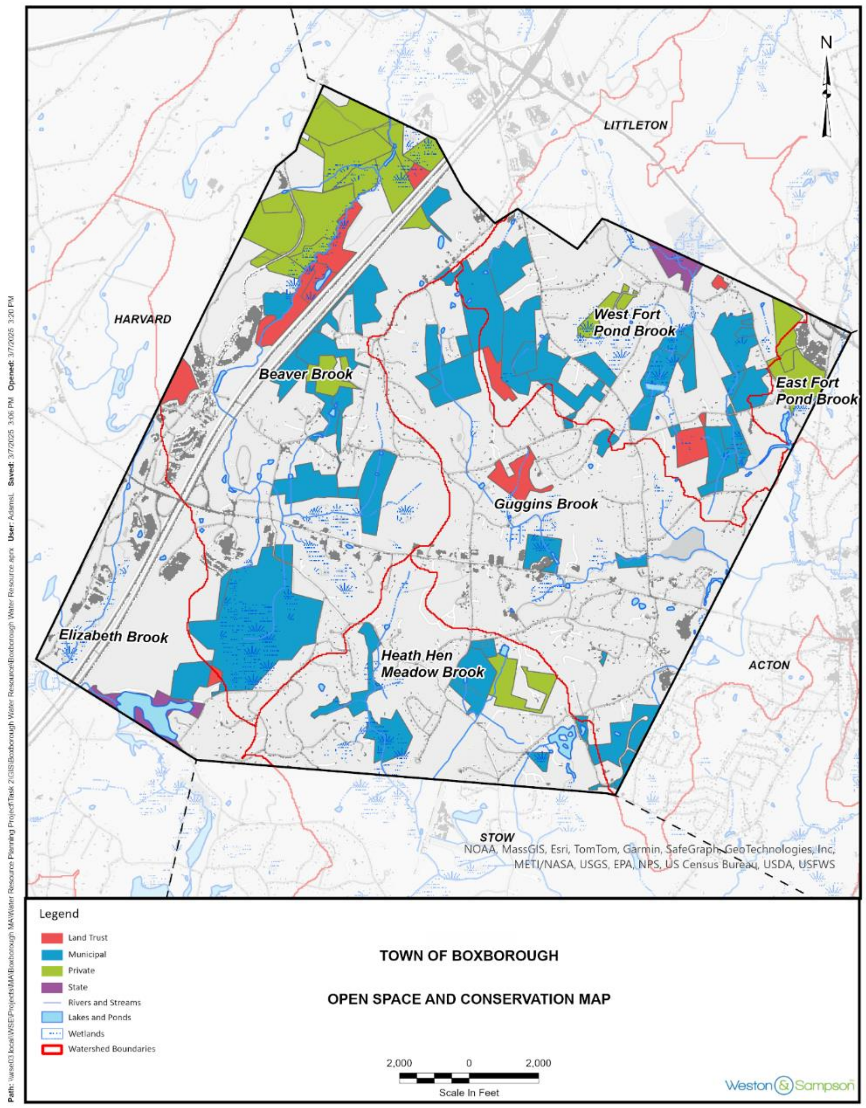


Figure 2.9. Open Space & Conservation Map[10]

[10] MassGIS, 2025. Protected and Recreational Open Space.

2.6 Water Resources

2.6.1 Surface Water

Boxborough's surface water resources are distributed across several hierarchical watershed systems, defined by Hydrologic Unit Codes (HUC), the U.S. Geological Survey's (USGS) Watershed Boundary Dataset[11], each representing increasingly detailed classifications of watershed geography, with HUC-12 as the smallest system, and smaller numbers equating to larger systems. The term "watershed" refers broadly to any water drainage area, regardless of size, however the USGS has determined terminology for the Watershed Boundary Dataset as follows:

- HUC-8: subbasins
- HUC-10: watersheds
- HUC-12: subwatersheds

These water boundaries also hold regulatory importance. The Inter-basin Transfer Act (ITA) designates 14 major river basins as the fundamental regulatory units for governing interbasin water transfers. These basins correspond to HUC-8 subbasins in the USGS hydrologic classification system. The ITA's "basins" represent the state's largest-scale watershed delineations for water transfer regulation. The Massachusetts Water Quality Standards (314 CMR 4.00) similarly reference river basins but may apply the terminology more broadly to include both major basins and smaller tributary watersheds nested within them.

As shown in Figure 2.10, the town straddles two HUC-8 subbasins. The Merrimack River subbasin covers north and central Boxborough. The Sudbury-Assabet-Concord subbasin (SuAsCo) flows in the east and southwest portions of town. These two subbasins are state-designated and have important regulatory implications in Boxborough, such as the Interbasin Transfer Act[12]. At the HUC-10 level, the watershed boundaries in Boxborough follow the same boundaries as HUC-8. At a more granular level, Boxborough's water flows through three HUC-12 subwatersheds. These include the Stony Brook subwatershed in the center of the town, the Assabet River – Elizabeth Brook to mouth subwatershed in the southwest, and the Fort Pond Brook subwatershed in the east. HUC12 watersheds in Massachusetts are typically on the order of 10-40 thousand acres.

Land cover in Boxborough is approximately 36 acres, or 1%, water (Figure 2.3). These surface waters include network of small streams and brooks. Major surface waters include:

- **Beaver Brook** flows through the eastern portion of Boxborough. It is approximately 2.5 miles long within the town boundaries, and forms part of the town's eastern border with Littleton.
- **Guggins Brook** is located in central Boxborough. It is approximately 1.5 miles long and is a tributary to Heath Hen Meadow Brook.
- **Heath Hen Meadow Brook** is located in southwestern Boxborough and feeds into the Health Hen Meadow Conservation Area. Roughly 1.8 miles of this brook flow within town limits.

[11] USGS, 2022. Federal Standards and Procedures for the National Watershed Boundary Dataset.
[12] DCR Division of Water Supply Protection, 2025. Interbasin Transfer Act. https://www.mass.gov/interbasin-transfer-act#:~:text=The%20Office%20of%20Water%20Resources,the%20river%20basin%20of%20origin.

- **Elizabeth Brook**, in the western portion of Boxborough, is about 2 miles long within town boundaries. It forms part of the town's western border with Harvard.
- **Fort Pond Brook** flows through the eastern portion of Boxborough for approximately 1.2 miles within Boxborough's boundaries. The brook originates at Fort Pond in Littleton before flowing through Boxborough and continuing into Acton, and eventually into the Assabet River.

These waterways are vital components of the local ecosystem, typically meandering through wooded areas and serving as drainage pathways for the surrounding land. Several ponds and impoundments dot the landscape, often formed by historical damming of streams. These surface waterbodies are interconnected with the groundwater system, making them susceptible to influences from subsurface conditions.

Though Boxborough has no lakes or ponds of significant size, several smaller ponds provide recreational opportunities and wildlife habitat. These include:

- **Flerra Pond** (¾ acres) located at Flerra Meadow,
- **Flagg Hill Pond** (12 acres) owned primarily by the Town,
- **Eldridge Pond** (2 acres) located where Elizabeth Brook widens,
- **Muddy Pond** (1 acres) located between the esker and I-495,
- **Fort Pond Brook Pond** (2 acres) located on Fort Pond Brook branch 2, tributary 2, on the Acton-Boxborough town line.

Surface water flows out of Boxborough in multiple directions, meaning land use decisions within the town can impact water quality in neighboring communities like Acton, Littleton, Stow, and Harvard. Conversely, surface water also flows into Boxborough, notably as runoff from the hills in Harvard into Beaver Brook Valley and from wetlands associated with the Littleton Heron Rookery, located just south of Route 2, which drain into Boxborough near the Littleton town line. All of Boxborough's named brooks eventually drain via tributaries into the Merrimack River.

Boxborough has no listed impaired waters (waterbodies that do not meet water quality standards for one or more designated use(s) such as recreation or aquatic habitat) within the boundaries of the Town's regulated area based on the Final 2022 Massachusetts Integrated List of Waters[13], produced by MassDEP. However, as shown in Figure 2.11 Long Pond, to the north of Boxborough, is impaired for algae, dissolved oxygen, and phosphorus. Mill Pond in Littleton, located along the flow path of Beaver Brook, is impaired for Macrophytes. The Unnamed Tributary, eastern inlet of Mill Pond and locally known as Reedy Meadow Brook, is impaired for ambient bioassays – Chronic Aquatic Toxicity. South of Boxborough, Elizabeth Brook is impaired for *E.coli*.

Boxborough relies on a network of surface water features specifically designed for fire protection. The Town maintains a system of 28 cisterns and 17 fire ponds strategically located throughout the town. See Figure 2.13 for locations. These fire ponds, ranging in capacity from 60,000 to two million gallons, are key components of the town's fire protection infrastructure, including[14]:

[13] MassDEP, 2024. Integrated List of Waters.
[14] Town of Boxborough, 2023. Open Space and Recreation Plan 2022-2027.

- Massachusetts Avenue
- Pine Hill Road
- Stow Road
- Burroughs Road
- Old Harvard Road
- Paddock Lane
- Beaver Brook Road

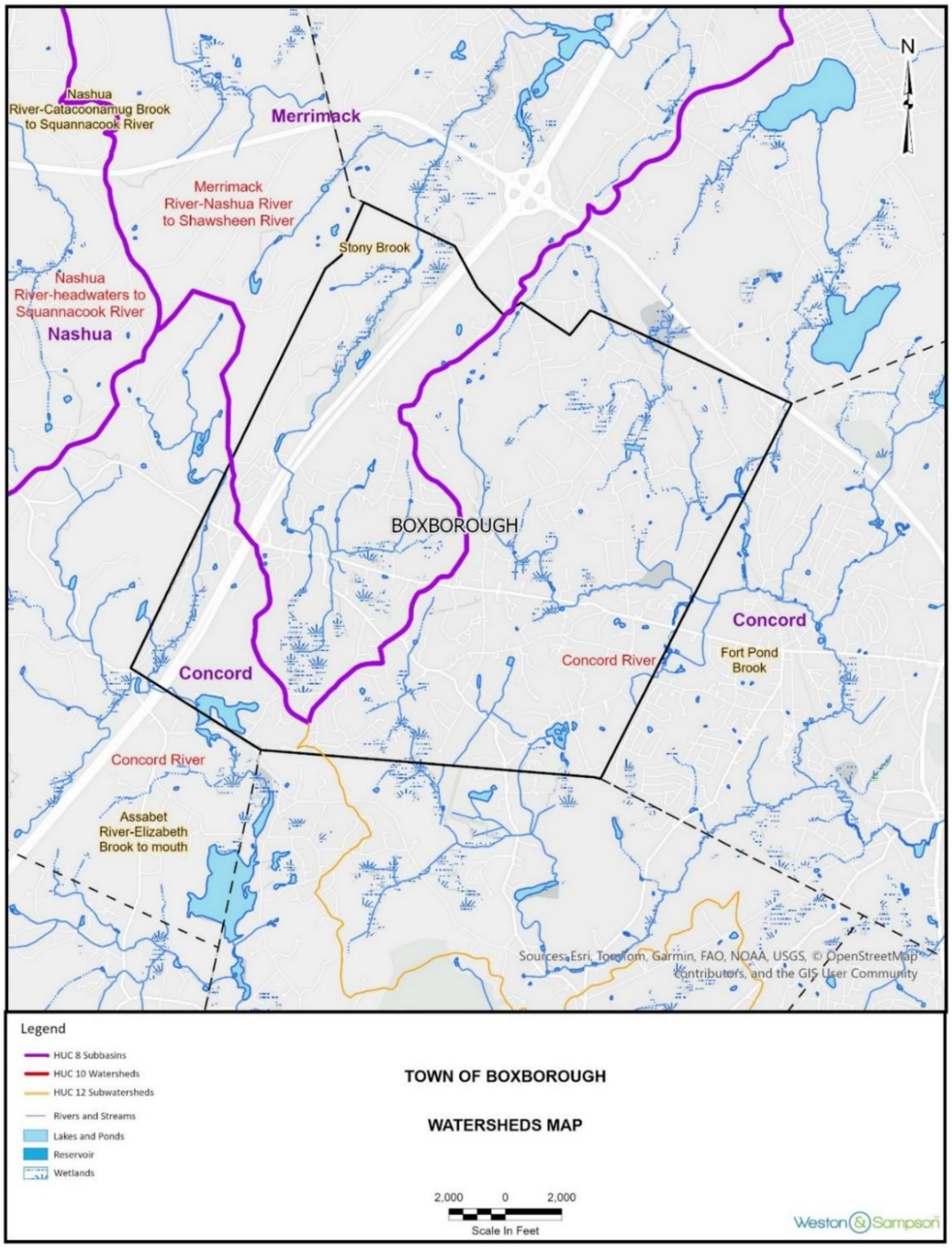


Figure 2.10. Watersheds Map[15]

[15] USGS, 2022. Watershed Boundary Dataset.

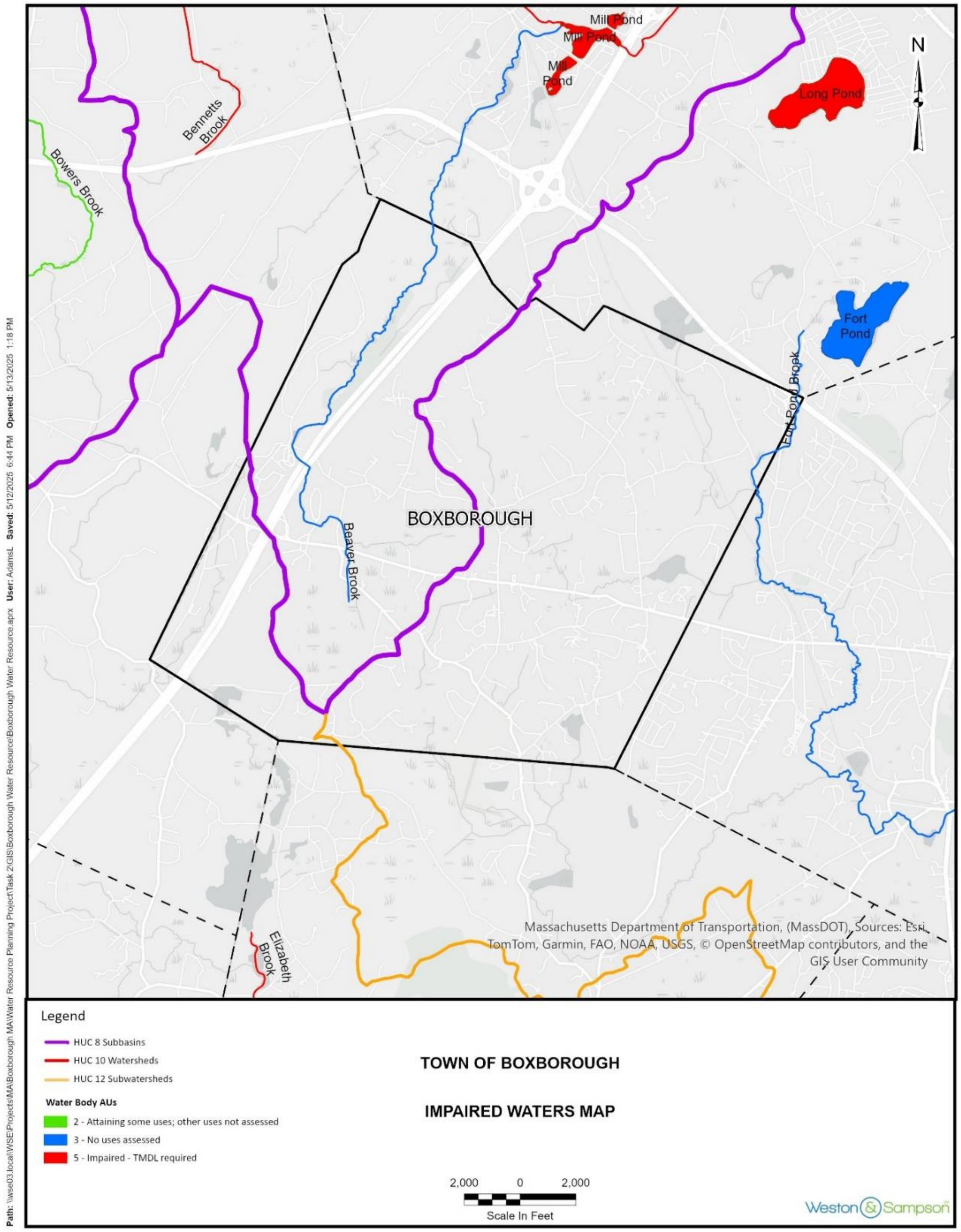


Figure 2.11 Impaired Waters Map[16,17]

[16] USGS, 2022. Watershed Boundary Dataset.
[17] MassDEP, 2024. Integrated List of Waters.

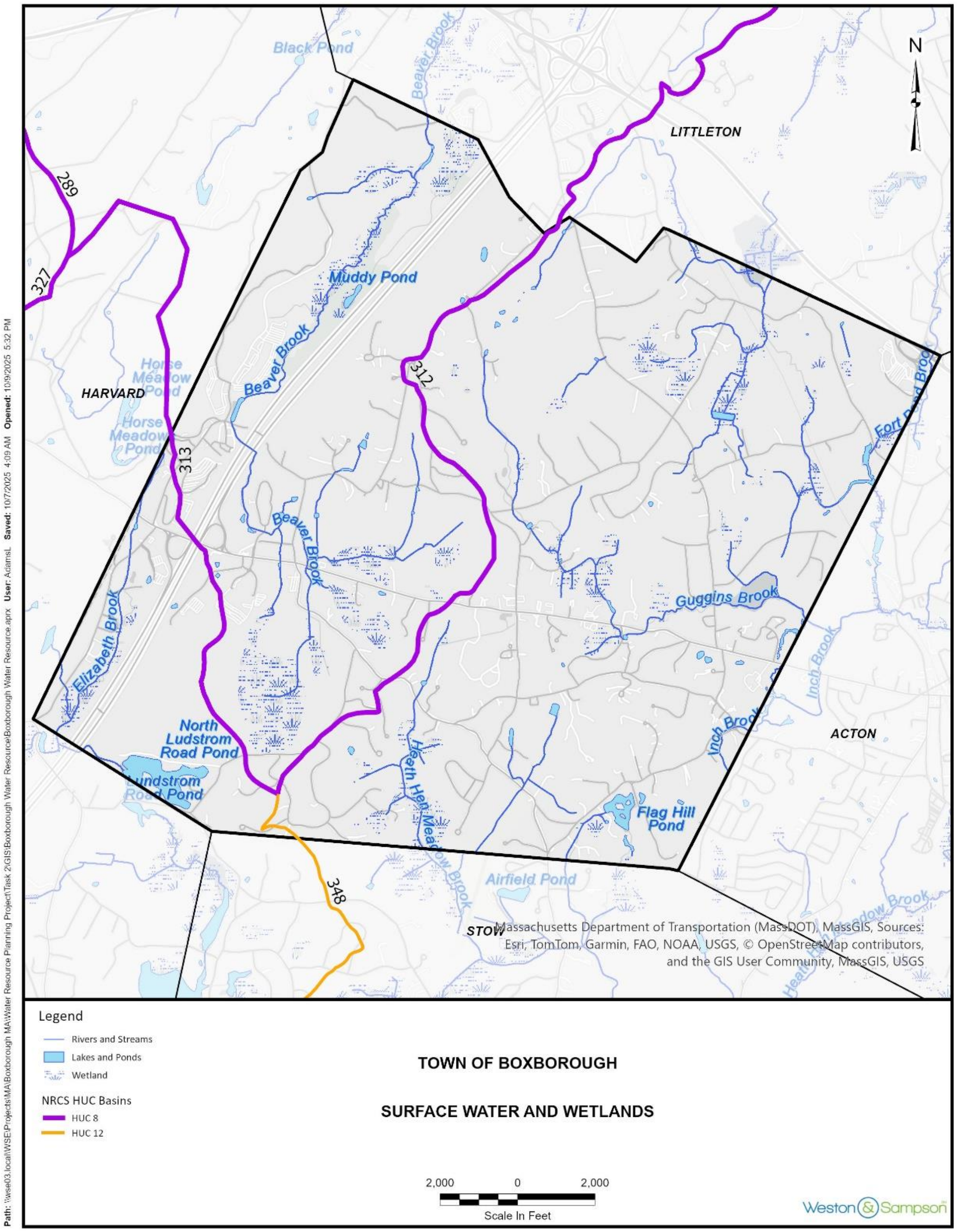


Figure 2.12. Surface Water and Wetlands Map[18]

[18] MassGIS, 2019. MassDEP Hydrography (1:25,000).

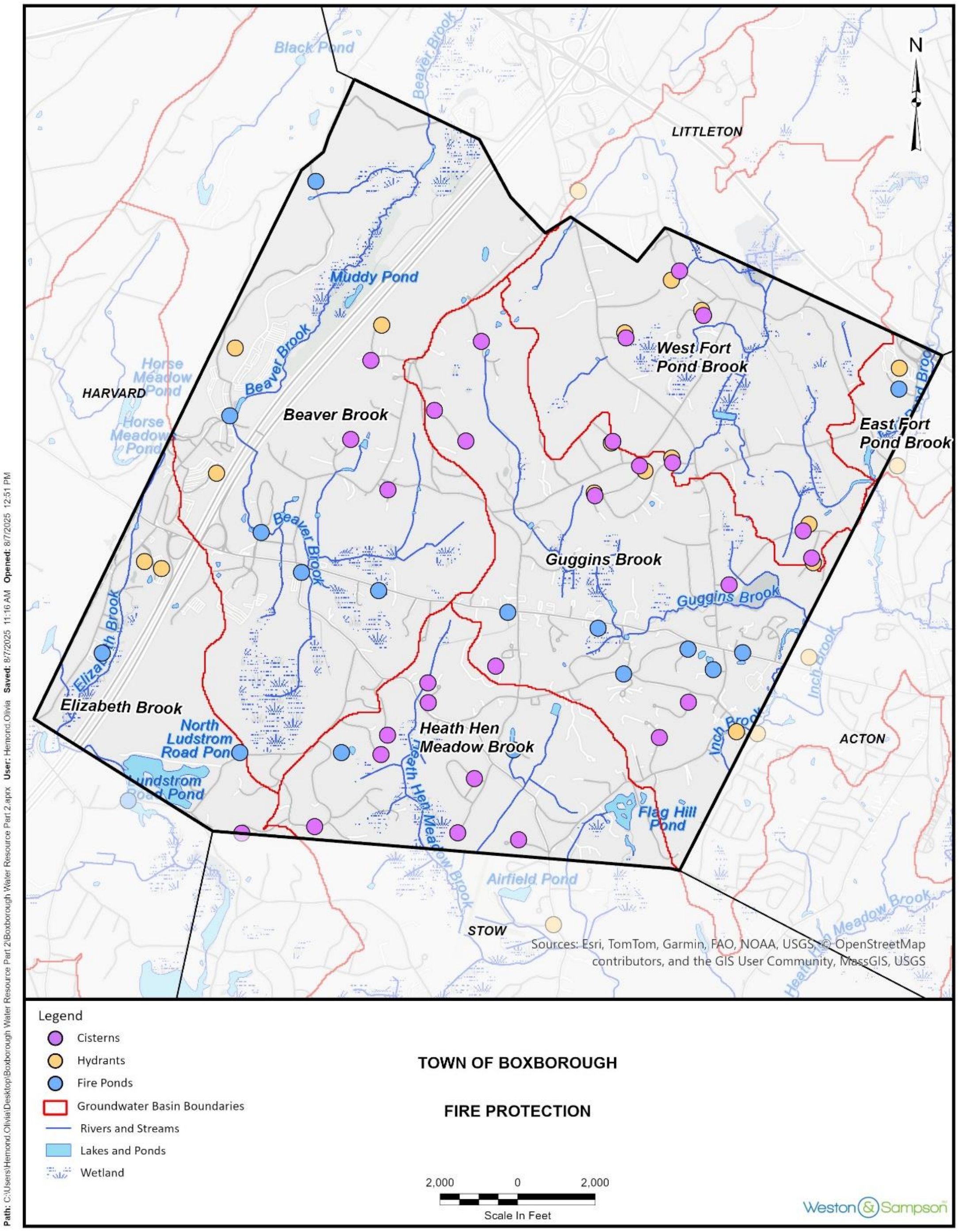


Figure 2.13. Fire Protection Map[19]

[19] Town of Boxborough, 2025. Hydrant and Cistern Locations.

2.6.2 Wetlands

Wetlands occupy approximately 1,451 acres, or 22% of the town's land cover (Figure 2.12). The majority of these wetlands are considered wooded marsh. Wetlands are a prominent feature of Boxborough's landscape and play a vital role in its ecological health. There are several larger wetland complexes including Wolf Swamp, the Heath Hen Meadow Brook wetlands, the Beaver Brook wetlands, and the Guggins Brook wetlands. These diverse wetland types, which include swamps, marshes, and vernal pools, perform several crucial functions including acting as natural filters, removing sediment, nutrients, and other pollutants from rainwater runoff and road runoff, thus contributing to improved water quality. During periods of heavy rainfall or flooding, wetlands serve as temporary water storage, helping to mitigate flood peaks and reduce downstream flooding. Conversely, during drier periods, wetlands contribute to maintaining stream flow by slowly releasing stored water and aid in groundwater recharge, ensuring a more consistent water supply.

Beyond these core functions, Boxborough's wetlands provide essential habitat for a wide array of plant and animal species, contributing to the town's biodiversity. They support various wildlife, including birds, amphibians, reptiles, mammals, and invertebrates. Vernal pools, a specific type of wetland, are particularly important breeding grounds for certain amphibians and invertebrates. The ecological health and functionality of these wetlands are therefore critical to the overall health of Boxborough's environment. Wetlands are sensitive ecosystems and are protected under both state and federal regulations, including the Massachusetts Wetlands Protection Act and the federal Clean Water Act. Boxborough also has The Boxborough Wetland Bylaw, which is a local regulation enacted to provide enhanced protection for the town's wetlands and water resources beyond the provisions of the Massachusetts Wetlands Protection Act. Activities within or near wetlands are often regulated to minimize impacts and preserve their valuable functions.

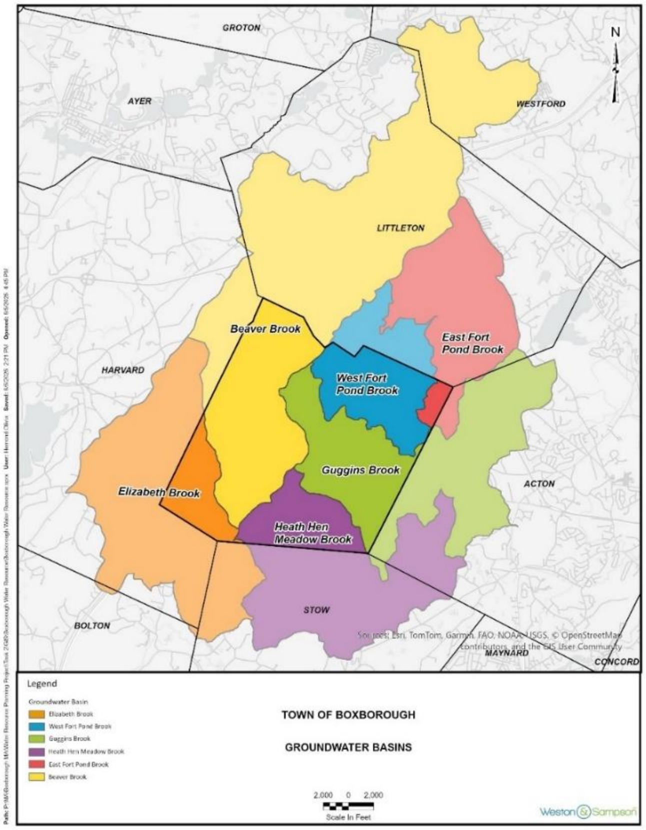
2.6.3 Groundwater

This report utilizes Massachusetts Water Indicators (MWI) and Sustainable Water Management Initiative (SWMI) groundwater basin delineations. The MWI watershed boundaries, which delineate areas where surface water drains to a common point, intersect significantly with the SWMI Groundwater Category delineations, which map areas based on groundwater availability and potential. These delineations are used rather than traditional Hydrologic Unit Code (HUC) watersheds due to the focus of the analysis on Boxborough's groundwater resources that support drinking water supplies and wastewater capacity. Unlike traditional watershed boundaries that primarily track surface water flow patterns, these groundwater basin delineations integrate both surface drainage and subsurface groundwater movement.

Future drinking water and wastewater needs are based on the delineation of groundwater basins to determine stresses on water resources throughout town.
(Further discussed in Sections 5 and 6)

The coincident overlap between MWI watersheds and SWMI Groundwater Categories create what is referred to as "groundwater basins" within this report. Using these basins for analysis framework allows the tracking of water from withdrawal, through use, and back to the environment as a complete cycle. Table 2.2 provides the approximate area of each groundwater basin and the percentage of Boxborough they cover.

Table 2.2 Boxborough Groundwater Basins		
Groundwater Basin	Acres	% of Town
Beaver Brook	2,237	33.6%
Guggins Brook	1,581	23.8%
Heath Hen Meadow Brook	881	13.3%
East Fort Pond Brook	126	1.9%
West Fort Pond Brook	1,171	17.6%
Elizabeth Brook	653	9.8%
Total	**6,649**	**100.0%**



Groundwater Basins in the Boxborough area

Groundwater is a critical resource in Boxborough, as the town relies entirely on groundwater for its water supply. With no municipal water system, residents depend almost exclusively on private bedrock wells. Boxborough's drinking water usage will be discussed in more detail in Section 5.

Recognizing the importance of groundwater protection, Boxborough has implemented several measures to protect this resource. In 1984, the town established an Aquifer Protection Overlay Zoning District Bylaw, which prohibits certain land uses within aquifer zones, limits septic discharge rates, and sets a maximum lot coverage standard. In March 2021, the Board of Health adopted a Groundwater Protection Regulation applicable to facilities within Zone II and Interim Wellhead Protection Areas. This regulation outlines prohibited activities that could release pollutants into groundwater resources and establishes penalties for violations and is discussed more in Section 7. In addition, Zone II areas for municipal drinking water wells in both Littleton and Acton extend into Boxborough as groundwater resources extend across town boundaries.

*An in-depth discussion of Boxborough's groundwater resources, including an **evaluation of recharge rate by groundwater basin**, is provided in Section 5.*

3.0 POTENTIAL THREATS TO WATER RESOURCES

Since passage of the federal Clean Water Act (CWA) in 1972, advances have been made to protect U.S. waters from pollution. The CWA focused initially on point source discharges, or direct discharges from identifiable sources like industrial pipes or sewage treatment facilities. Today, nonpoint source (NPS) pollution is the leading cause of water quality problems. NPS pollution originates from many diffuse sources and is caused by rainfall or snowmelt moving over and through the ground, carrying pollutants and ultimately depositing them into lakes, rivers, and groundwater. Sources of this type of pollution are described below.

***Water quality** concerns the chemical, physical, and biological characteristics of water and its suitability for a specific use, while **water quantity** refers to the volume or amount of water available for various needs*

3.1 Point Source Pollution

Point sources of pollution are regulated by the National Pollutant Discharge Elimination System (NPDES) program and regulated by the Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (MassDEP). The NPDES and Massachusetts Surface Water Discharge Permits do not list any active discharge permits from individual facilities discharging directly into Boxborough's waterbodies.

Boxborough is regulated under the Municipal Separate Storm Sewer Systems (MS4) permit. This program regulates the discharge of stormwater from outfalls in MS4 communities and requires these communities to implement Stormwater Management Programs (SWMPs) and Best Management Practices (BMPs) to mitigate the effects of stormwater discharges. Boxborough is required to submit an annual report to EPA outlining the progress of their MS4 program. A description of Boxborough's MS4 program is provided on their Stormwater Management Program webpage.

3.2 Nonpoint Source Pollution

Unlike point source pollution, nonpoint source (NPS) pollution stems from the cumulative impact of various land use activities and natural processes. Some NPS contaminants are naturally occurring or even necessary nutrients, but human activity can make them problematic. The following pollutants, commonly associated with NPS pollution, can pose risks to Boxborough's water quality:

- Sediment: Erosion from unpaved roads, construction sites, and disturbed land contributes to sediment loading in water bodies. This sedimentation increases turbidity, hindering aquatic plant photosynthesis and potentially leading to low oxygen conditions. Furthermore, sediment acts as a carrier for other pollutants, including metals, nutrients, and pathogens.
- Oil and Grease: Leaky vehicles, improper disposal of oil and grease, and spills from fuel storage areas contribute to contamination of surface and groundwater. Runoff transports these pollutants into water bodies, posing risks to aquatic life and water quality.

- **Fertilizers, Pesticides, and Herbicides:** Overuse or improper application of these chemicals on lawns, gardens, and roadsides can lead to runoff contamination. These pollutants can harm aquatic organisms, contribute to algal blooms, and accelerate eutrophication.
- **Road Deicers and Anti-icing Agents (Deicing Chemicals):** Deicing chemical runoff increases sodium and chloride concentrations in surface and groundwater, negatively impacting aquatic ecosystems and potentially affecting drinking water supplies.
- **Debris:** Litter, including food containers, yard waste, and construction debris, degrades water quality and harms aquatic life.
- **Nutrients (Nitrogen and Phosphorus):** Excess nutrients, particularly nitrogen and phosphorus, fuel excessive algal growth and eutrophication. Nitrogen can also pose human health risks, especially to infants. Phosphorus, while often a limiting nutrient, can become problematic when soil saturation occurs.
- **Pathogens:** Runoff from septic systems, pet waste, and wildlife can introduce harmful bacteria, viruses, and parasites into water bodies, posing health risks to humans and animals.
- **Solid and Hazardous Wastes:** Improper disposal of solid waste and hazardous materials, including household chemicals and industrial byproducts, can contaminate surface and groundwater.
- **Petroleum Hydrocarbons (PHCs) (Gasoline, Oil, Fuel):** Leaks from aboveground and underground storage tanks, as well as spills during transport and handling, can contaminate water resources with gasoline, oil, and other fuels.

3.2.1 Stormwater Runoff

Stormwater runoff occurs when rainfall or snowmelt flows over land or impervious surfaces such as paved streets, parking lots, and building rooftops rather than soaking into the ground. As this water travels, it picks up debris, chemicals, sediment, and pollutants before eventually flowing into nearby wetlands, streams, and other water bodies. Stormwater quality deteriorates as it flows across Boxborough's landscape, collecting contaminants from various sources including roadways, residential areas, agricultural operations, and construction sites. These runoff waters accumulate a range of pollutants, such as sediments, petroleum products, excess fertilizers, pesticides, and microbial pathogens. Without proper management, these pollutants discharge directly into Boxborough's waterbodies, degrading their ecological health and recreational value.

Increased development has led to more impervious surfaces, generating greater volumes of runoff during storm events and potentially causing localized flooding in areas like the Blanchard Road corridor. Additionally, runoff from roadways, particularly during winter months when deicing chemicals are applied, has affected water quality in local waterbodies including Beaver Brook and Fort Pond Brook. Erosion along stream banks threatens infrastructure, particularly at road crossings and culverts throughout the town. As a community dependent on groundwater for drinking water supplies, protection of aquifer recharge areas from contamination while ensuring sufficient infiltration occurs to maintain groundwater levels is important for the town.

Hydrologically, the increased volume and velocity of surface runoff contribute to heightened peak flow rates in local streams and rivers. This increases erosion and sedimentation, destabilizing stream banks and degrading aquatic habitats. The flash-flood potential is also increased, posing risks to infrastructure and property located within the floodplain. Concurrently, the reduced groundwater recharge leads to a decline in baseflow during dry periods, diminishing streamflow and potentially impacting the ecological integrity of the watershed. The cumulative effect of reduced aquifer replenishment may lead to a sustainable yield reduction, impacting the long-term water availability for Boxborough's population.

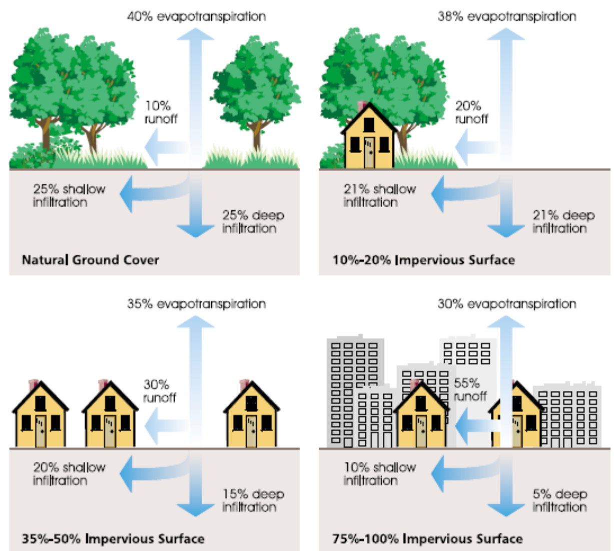


Figure 3.1 Relationship Between Impervious Cover and Surface Water Runoff

Increased urbanization directly correlates with a rise in total impervious cover (IC). The Center for Watershed Protection's Impervious Cover Model[20] provides a framework for understanding the ecological consequences of this trend, indicating that receiving water quality and biological integrity are significantly "impacted" when watershed IC values fall within the 10-25% range. Boxborough's current IC levels are estimated to be 8% based on the National Oceanic and Atmospheric Administration's Impervious Cover Layer[21] developed in 2016.

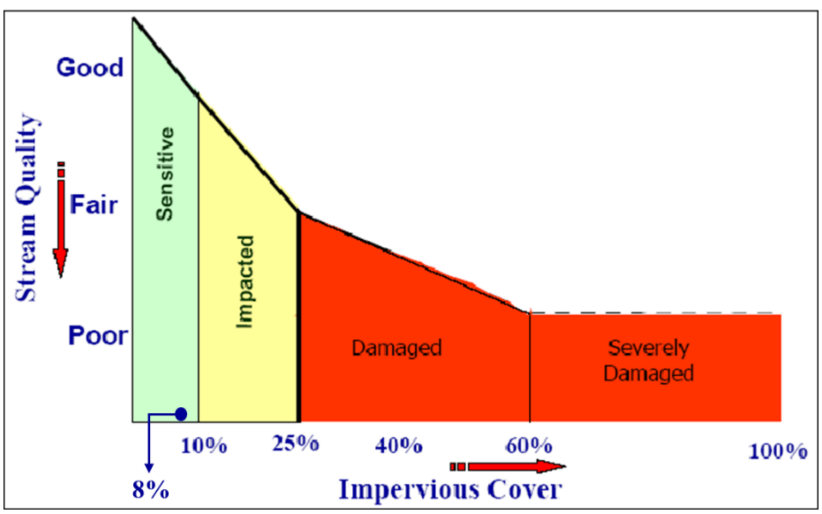


Figure 3.2. Impervious Cover Model

Note: Boxborough's current Impervious Cover is indicated on the graphic (8%)

[20] Center for Watershed Protection, 2003. Impervious Cover Model.
[21] NOAA, 2016. C-CAP Regional Land Cover.

3.2.2 Deicing Chemicals and Snow Dumps

Beyond increasing runoff volume, Boxborough's roadway network presents a significant source of NPS pollution, particularly due to winter maintenance practices. Deicing chemical application, while necessary for public safety, introduces elevated concentrations of sodium and chloride into the local environment. During thaw cycles and rainfall events, these compounds are carried into Boxborough's wetlands, ponds, streams, and eventually infiltrate into groundwater supplies. These salt-laden waters can disrupt aquatic ecosystems by altering water chemistry and negatively impacting sensitive species.

Boxborough's Department of Public Works (DPW) oversees the maintenance of approximately 45 miles of town roadways. The town procures and stores winter maintenance materials at the Highway Department facility on Massachusetts Avenue, situated within the Elizabeth Brook watershed.[22] Salt and deicing material storage protocols include covered storage facilities and mixing operations conducted on impervious surfaces with proper containment to minimize environmental contamination.[23] There are two deicing material storage facilities in Boxborough. One is located at the DPW Garage and contains 600 tons of road salt (sodium chloride) and liquid magnesium chloride. The other storage facility is at the MassDOT Maintenance Facility on Swanson Road.

Boxborough does not designate snow dumping sites where plowed snow from roadways and municipal properties is collected. This distributed approach to snow management prevents concentrated pollution hotspots.

MassDOT salt storage sheds in Boxborough, specifically in the western portion, have been identified as a source of groundwater and water supply contamination. Improperly stored deicing chemicals from the MassDOT sheds leached into groundwater and impacted drinking water supplies in Boxborough. MassDOT established the Highway Salt Remediation Program to address complaints of salt impacts on drinking water caused by MassDOT winter maintenance operations.[24] MassDOT has committed to contributing $6.5M toward the construction costs of the Boxborough-Littleton Water Line Extension Project as compensation for water quality degradation. The Boxborough Water Supply Extension consists of extending the water line from Littleton to properties west of I-495 in Boxborough so that clean treated water from Littleton Water Department can address the PFAS and sodium chloride contamination of 11 public water systems in Boxborough.[25]

3.2.3 Wastewater Disposal

Septic systems are the primary method for treating wastewater in areas without a sewer system. If properly installed and maintained, septic systems remove many of the pollutants that cause water quality problems. However, if systems are not working properly, nutrients and bacteria could enter nearby waterbodies.

In Boxborough, all residences and businesses rely on septic systems to treat their wastewater as they do not have access to public sewer. An in-depth discussion and analysis of septic systems in Boxborough is provided in Section 6.

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[22] Town of Boxborough, 2023. Public Works Department Annual Report.
[23] MassDEP, 2023. Best Management Practices for Salt Storage and Handling.
[24] MassDOT, 2025. Highway Salt Remediation Program.
[25] Town of Boxborough, 2025. Boxborough-Littleton Water Line Extension Project.

3.2.4 Agriculture

Agriculture encompasses a range of land and water-based activities focused on crop production and livestock management, including the handling of materials such as animal feed, fertilizers, pesticides, and agricultural wastes. While many agricultural operations in Boxborough implement voluntary BMPs to control NPS pollution, certain practices can still contribute to water quality degradation through various pathways, listed below.[26]

Cropland Operations:

- Nutrient runoff from excessive application of commercial fertilizers and manure, introducing water-soluble nitrogen compounds that leach into groundwater or less soluble compounds (e.g. phosphorus) that flow into surface waters.
- Pesticide and herbicide contamination resulting from improper application or equipment rinsing practices.
- Soil erosion via sheet, rill, and gully formation when stormwater runoff is inadequately managed, leading to sediment deposition and associated pollutant loading in nearby water bodies.

Animal Management Areas:

- Direct runoff of animal wastes containing nutrients and bacteria into surface water.
- Contamination from manure storage areas located near water resources or in areas with high water tables.
- Degradation of vegetative cover at animal watering and feeding locations, creating erosion hotspots.
- Wash water from animal facilities entering water systems without proper treatment.

Grazing Practices:

- Overgrazing near waterways and removal of riparian vegetation.
- Direct discharge of animal waste into streams and ponds.
- Physical damage to stream banks and channels from livestock access, destabilizing waterways and increasing erosion.

Irrigation and Drainage Systems:

- Excess irrigation water mobilizing chemicals and nutrients to surface waters.
- Subsurface drainage systems like field tiles creating direct conduits for pollutants to reach both surface and groundwater.

Boxborough's agricultural sector comprises approximately 3% of the town's land use and less than 1% of the town’s land cover, concentrated primarily in the Heath Hen Meadow Brook and Elizabeth Brook

[26] MassDEP, 2023. Massachusetts Nonpoint Source Pollution Management Manual.

watersheds. Agriculture land use covers 2.4% of the area of Elizabeth Brook within Boxborough. Notable operations include small-scale vegetable farms, orchards, and equestrian facilities.[27]

While agricultural operations are strongly encouraged to adhere to best management practices determined by the US Department of Agriculture (USDA) Natural Resources Conservation Service, the University of Massachusetts (UMass) Extension, and the Massachusetts Department of Agricultural Resources (MDAR), Boxborough has taken additional steps to support agricultural conservation through:

- Establishment of an Agricultural Commission under MGL Chapter 40, Section 8L, providing education and advocacy for sustainable farming practices
- Participation in the Farm Viability Enhancement Program which provides technical assistance for implementing water quality protection measures
- Collaboration with the Middlesex Conservation District to promote soil health practices that reduce runoff.[28]

In watersheds where agricultural land use exceeds 2%, such as portions of the Elizabeth Brook watershed, agriculture should be considered a potential source of NPS pollution requiring targeted monitoring and management strategies.[29] The 2023 Open Space and Recreational Plan references the 2016 MassGIS land use data.

3.2.5 Erosion and Sediment Control

Construction activities often involve disturbing soils and the clearing of vegetation. When managed improperly, these activities can become major contributors to NPS pollution in the town's streams, ponds, and wetlands. Vegetation typically stabilizes soil and facilitates stormwater infiltration. When removed during construction, exposed soil becomes vulnerable to erosion.

Federal regulations require all land disturbance activities exceeding one acre to obtain a Construction General Permit from the EPA. For Boxborough's water resources, construction activities present three primary environmental concerns:

- **Erosion** occurs when stormwater dislodges and transports exposed soil particles from disturbed areas. This process accelerates when land is altered through excavation, filling, and paving operations. Beyond sediment transport, erosion facilitates the movement of nutrients, particularly phosphorus, which adheres to soil particles and can be carried into Boxborough's sensitive water resources, contributing to water quality degradation.
- **Sedimentation** results when eroded particles settle in downstream locations. In Boxborough's waterbodies, sediment deposition can impact aquatic ecosystems by increasing turbidity, reducing water depth, smothering fish spawning habitat, and stimulating excessive algal growth. These impacts could pose a threat to Boxborough's high-quality cold water fisheries and vernal pool habitats.

[27] Town of Boxborough, 2023. Open Space and Recreation Plan (2022-2027).
[28] Middlesex Conservation District, 2024. Agricultural Technical Assistance Program Annual Report.
[29] Mass DER, 2022. Watershed-Based Planning for Agricultural Areas.

- **Construction-related pollutants** beyond sediment present additional hazards to Boxborough's water resources. These include pesticides and fertilizers applied during landscaping, petroleum hydrocarbons from construction equipment (oils, gasoline, hydraulic fluid), toxic building materials (paints, sealants, preservatives), and improperly managed construction waste. Concrete washout facilities and appropriate waste containment are essential elements of responsible construction site management in Boxborough's watersheds.

Proper implementation of erosion and sediment controls, along with responsible materials management, can help to protect Boxborough's water resources during property development.

3.2.6 Other

- **Recreational Facilities**: Golf courses represent potential nonpoint pollution sources in Boxborough's watersheds. Course maintenance typically involves regular application of nutrients (primarily nitrogen (N), phosphorus (P), and potassium (K)) to address soil deficiencies and maintain turf quality. Without proper management practices, these nutrients may infiltrate groundwater or be carried into surface waters during rainfall events. Additionally, the various pesticides applied to golf courses, including herbicides, insecticides, and fungicides, pose contamination risks to both ground and surface waters.
- **Wildlife Contributions**: Wildlife populations can impact water quality, particularly when human activities alter natural behaviors. Concentrations of birds such as Canada geese, mallards, and other waterfowl around Boxborough's ponds and wetlands, can contribute substantial bacterial loads when these animals deposit waste directly into water bodies or on adjacent shorelines where runoff can transport pollutants during rainfall events.

  Human activities that artificially concentrate wildlife, such as feeding waterfowl or creating favorable habitat adjacent to water bodies, increase these impacts.[30] Additionally, stormwater infrastructure that efficiently channels runoff from natural areas to water bodies may accelerate the transport of wildlife-associated bacteria to receiving waters.

3.2.7 Solid Waste Disposal Facilities

Solid waste disposal facilities, including landfills, pose a potential threat to water quality due to the generation of leachate. Leachate, a liquid byproduct of decomposing waste, can contain heavy metals and volatile organic compounds (VOCs) and other contaminants, potentially contaminating groundwater and surface water. Modern landfills mitigate this risk through engineered systems, including liners and leachate treatment, significantly reducing the likelihood of direct leachate contamination of surface and groundwater.

There is no municipal residential trash pick-up in Boxborough. Residents may dispose of solid waste through commercial contract services or at the Town’s transfer and recycling station on Codman Hill Road which is run by the Department of Public Works. The Town facility is for residential waste only, not commercial waste. Boxborough participates in Household Hazardous Waste Days to manage potentially hazardous materials, such as paints, oil, fertilizers, pesticides, chemicals, and other

[30] Town of Boxborough, 2023. Open Space and Recreation Plan (2022-2027).

hazardous wastes, thus reducing the risk of these substances entering the environment and impacting water resources.

The municipal landfill located on Codman Hill Road was closed in 1986 and capped in 1987. The closed municipal landfill on Codman Hill Road is located on the west side of 495 and near Elizabeth Brook. The Town's former landfill on Codman Hill Road has been capped and is now the site of the Town's transfer station. The transfer station is where solid waste and recycling is collected and disposed of out of town.[31]

3.2.8 Brownfield and Superfund Sites

A "Brownfield" is any land in the United States that is abandoned, idled, or under used because redevelopment and/or expansion is complicated by environmental contamination that is either real or perceived. Superfund is the informal name given to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) established to address abandoned hazardous waste sites. A Superfund site is a contaminated site due to hazardous waste being dumped, left out in the open, or otherwise improperly managed. Superfund sites can include manufacturing facilities, processing plants, landfills and mining sites. Brownfields differ from Superfund sites in the degree of contamination. Superfund sites pose a real threat to human health and/or the environment. Brownfields, on the other hand, do not pose as serious health or environmental threat compared to Superfund sites. Brownfields represent more of an economic or social threat, since they prevent development and therefore stifle local economies. There are no EPA monitored Brownfield or Superfund sites in Boxborough or in surrounding towns. However, there is one location with a Massachusetts Contingency Plan (MCP), the framework for assessing and cleaning contaminated sites in Massachusetts. This location has a Remedial Action Outcome (RAO), the final stage of the cleanup process under the MCP. Two additional properties are included in the Massachusetts Brownfields List[32] provided by MassDEP.

3.2.9 Waste Sites and Reportable Releases

MassDEP collects information on waste sites and reportable releases of oil and hazardous materials to the environment. According to the MassDEP Energy & Environmental Affairs Data Portal: Waste Site & Reportable Releases[33], there are 45 hazardous waste release sites in Boxborough, encompassing various issues, although primarily oil spills. Seven sites are open, 38 sites are closed, and no sites are closed with use limitations.

3.2.10 PFAS

Per- and polyfluoroalkyl substances (PFAS) are a group of man-made chemicals used in a wide range of products. PFAS can enter the environment through industrial discharges, landfills, consumer products, agricultural use, and firefighting. Drinking water supplies can become contained from industrial sites, landfills, and firefighting foams. PFAS are chemicals used in firefighting foams, as well as in firefighter gear. Aqueous Film-Forming Foam (AFFF) is a common firefighting foam that contains PFAS. However, AFFF is being phased out due to health concerns associated with PFAS. Firefighting gear has shown that PFAS can be released more when the gear is worn and subjected to stress.

[31] Town of Boxborough, 2023. Open Space and Recreation Plan (2015-2022).
[32] MassDEP, accessed 2025. Find Brownfields Sites.
[33] MassDEP, accessed 2025. Energy & Environmental Affairs Data Portal.

PFAS are of concern because of their high persistence and their impacts on human and environmental health that are known or can be deduced from some well-studied PFAS. Currently, many different PFAS (on the order of several thousands) are used in a wide range of applications, and there is no comprehensive source of information on the many individual substances and their functions in different applications. For an effective management of PFAS, an overview of the use areas of PFAS, the functions of PFAS in these uses, and the chemical identity of the PFAS actually used is needed.[34] An article providing an overview of the uses of PFAS in the industry can be found in Appendix E.

MassDEP sent requests for information to industrial businesses on Swanson Road and Codman Hill Road to ask about potential PFAS sources because of the PFAS contamination of PWS wells at condominiums and other locations. A fire at or near CBK automotive on Mass Ave. DEP had been investigating this as a possible source of PFAS contamination.

[34] Royal Society of Chemistry, 2020. An overview of the uses of per- and polyfluoroalkyl substances (PFAS).

4.0 POPULATION PROJECTIONS AND BUILDOUT ANALYSIS

This section examines Boxborough's population growth patterns and growth potential to establish the foundation for drinking water and wastewater assessments. Understanding the pace and extent of potential growth is a first step in determining if Boxborough's groundwater resources can sustainably meet future demands without environmental degradation.

This analysis approaches future growth from both the numeric and spatial perspectives. First, an analysis of demographic trends through population projections provide insight into population changes through 2050, considering both regional economic conditions and Boxborough's historic growth. Second, a buildout analysis was conducted to determine the maximum development capacity under current zoning regulations. This analysis identifies how many new dwelling units could theoretically be accommodated on Boxborough's remaining developable land and where this development is likely to occur.

By comparing population projections with buildout capacity, it is possible to establish both near-term water demand expectations and long-term maximum potential demand. This approach is a step in evaluating whether Boxborough's groundwater resources can support various growth scenarios while maintaining sufficient quantity and quality for both human use and ecosystem needs. The findings in this section inform the subsequent assessments of water usage, groundwater availability, and water budget analysis in Boxborough.

4.1 Population Characteristics and History

The first population recorded for the Town of Boxborough dates to 1790 (412 people). Beginning as a small farming town, the total population decreased from 412 to 376 from 1790 to 1940. The decline in Boxborough's population was thought to be attributed to the availability of affordable and fertile land in the Midwest, particularly after the Homestead Act of 1862 and the strategic decision to locate the main railroad depot in West Acton instead of Boxborough. The location of the railroad depot contributed to West Acton serving as the local hub for retail, commerce, and industry, prompting many Boxborough residents to relocate.

Between 1940 and 2020, the population grew from 376 to 5,506, an increase of 5,130 people or an annual compounding increase of 3.4%, assuming linear growth. As shown in Table 4.1 below, the town's population growth was not linear, with a leap in growth during the 1960s. Since 2000, population growth has slowed down. This may be due in part to an aging population, which often leads to smaller household sizes. According to the Decennial Census[35], the population of residents aged 65 and above has increased from 3.8% in 1990, to 4.7% in 2000, to 10.3% in 2020.

Boxborough's population increased by 5,130 people between 1940 and 2020

[35] US Census Bureau, 2020. QuickFacts: Boxborough town, Middlesex County, Massachusetts.

During the 2020 census, the U.S. Census Bureau determined the population of Boxborough to be 5,506 people. Population estimates for 2023 were 5,468, showing the first decrease in Boxborough's population since 1940. While the decennial census is a complete count of the population, population estimates are an annual calculation that occurs based on births, deaths, and migration data. The decreased population could be due to varying methodology in collecting the data, but could also represent a higher death rate, lower birth rate, or greater migration out of Boxborough. See Table 4.1 for population statistics from 1940 to 2023.

Table 4.1 U.S Census Bureau Population[36]

Year	Population	Population Data Source	Average Annual Population Change
1940	376	U.S. Department of Commerce, 1950. Bureau of the Census: 1950 Census of Population, Preliminary Counts.	-
1950	437	U.S. Department of Commerce, 1950. Bureau of the Census: 1950 Census of Population, Preliminary Counts.	1.6%
1960	744	U.S. Department of Commerce, 1960. Bureau of the Census: 1960 Census of Population, Preliminary Counts.	7.0%
1965	1,163	Archive.org, 1970. Massachusetts Population.	11.3%
1970	1,451	Archive.org, 1970. Massachusetts Population.	5.0%
2000	4,868	United States Census Bureau, 2000. Decennial Census.	7.8%
2010	4,996	United States Census Bureau, 2010. Decennial Census.	0.3%
2020	5,506	United States Census Bureau, 2020. Decennial Census.	1.0%
2023	5,451[37]	United States Census Bureau, 2023. Population estimates.	-0.3%

[36] MAPC, 2008. MetroFuture: Making a Greater Boston Region.

4.2 Population Projections

Predicting future population growth is necessary for communities to plan for future demand of resources, particularly water supply capacity and infrastructure needs. Two resources in Eastern Massachusetts provide population projections for municipalities that inform the analysis of Boxborough's future development trajectory. The Metropolitan Area Planning Council (MAPC)'s MetroFuture: Making a Greater Boston Region plan offers population and household projections based on regional economic trends, housing production patterns, and demographic shifts in multiple development scenarios. The UMass Donahue Institute (UMDI)'s Population Estimates Program provides alternative projection methodology that incorporates natural population change, migration patterns, and housing development capacity.

Boxborough's population is estimated to increase 28% by 2050

MAPC's MetroFuture plan looks ahead to growth and development in the Metro Boston area through 2030. Two sets of projections were created: a "current trends" projection and a "MetroFuture" projection. The "current trends" scenario forecasts population and employment growth assuming existing patterns continue while the "MetroFuture" scenario estimates growth based on the successful implementation of the MetroFuture's plan recommendations, which emphasize directing growth to already developed areas like town centers and urban areas.

With support from the Massachusetts Secretary of the Commonwealth, the UMDI Population Estimates Program produced population projections by age and gender for all Massachusetts municipalities. The data is available in five-year increments from 2025 to 2050. Boxborough's projected population growth under the MAPC and UMDI programs is shown in Table 4.2, with both projections anticipating an increase in population.

Table 4.2 MAPC Population Projections for Boxborough, MA[38]		
Year	Scenario	Population
2020	Baseline	5,507[39]
2030	Current Trends Projection	5,884
2030	MetroFuture Projection	5,919
Future Projections (UMass Donahue Institute)[40]		
Year	Scenario	Population
2025	This year	5,802
2030	5-year	6,145
2035	10-year	6,498
2040	15-year	6,734
2045	20-year	6,853
2050	25-year	6,996

The UMDI estimates indicate that Boxborough's population is projected to increase to 6,996 by 2050. This represents a 1,528 person, or 28% increase from the 2023 Census Bureau population estimates of 5,451. The estimated growth trajectory is predicted over a 25-year period, which could create a significant demand on the town's water resources over a relatively short timeframe.

The projected 28% population growth would require new housing development, accelerating the conversion of undeveloped land to residential use. This land use change could impact groundwater recharge areas, potentially reducing the natural replenishment of aquifers while simultaneously increasing withdrawal demands. Population growth at this scale would generate increased wastewater requiring treatment and disposal, creating potential challenges for groundwater quality protection due to the addition of septic systems.

[38] MAPC, 2008. MetroFuture: Making a Greater Boston Region.
[39] US Census Bureau, 2022. Quick Facts.
[40] UMass Donahue Institute, 2024. Massachusetts Populations Projections.

4.3 Buildout Analysis

To further understand future development in Boxborough, a Buildout Analysis was conducted. While population projections can estimate increases in the number of residents, the actual location in Boxborough where these residents may reside is unknown. The information in this section is based on data that is available in the MassGIS Parcel data and the CommunityViz tool. There may be development restrictions that have been left out because they are not included in this tool.

*The **CommunityViz Buildout Analysis** is a scenario-based planning tool used to estimate the potential future development capacity of a community under current zoning and land use regulations. This GIS software integrates spatial data with dynamic modeling capacities and allows communities to visualize future development scenarios.*

A buildout analysis was conducted for the Town of Boxborough using CommunityViz. CommunityViz was used to evaluate how future development under current zoning regulations might impact the town's drinking water sources and wastewater disposal systems. By focusing strictly on development allowed under existing zoning (requiring no variances or special permits), a baseline understanding of Boxborough's development trajectory could be established.

CommunityViz calculates development capacity estimates at the parcel level, using existing data and other user-defined constraints to estimate development potential. The analysis incorporates both numeric and spatial components, calculating the maximum development potential quantitatively while also mapping where this development could physically occur through the town.

This buildout allows Boxborough to assess where and how much future development could occur based on existing zones and environmental constraints. Because the analysis is spatially referenced, it provides the ability to determine development impacts within each of the defined groundwater basins. These results, combined with an evaluation of recharge rate by groundwater basins (Section 5.5), highlight where groundwater withdrawals and septic loading may become concentrated, potentially exceeding the natural recharge capacity in those areas.

Numeric Buildout		Spatial Buildout
Provides a tabular estimate of potential development based solely on zoning regulations and minimum lot size.	**vs.**	Maps the locations where development could realistically occur by incorporating setbacks and existing building locations.

4.3.1 Data Sources

Table 4.3 lists the data used in this analysis.

Table 4.3 Data Sources			
Source Name	Origin	Date	Description
Property Tax Parcels[41]	MassGIS	2024	Fiscal Year 2024 tax assessment data.
Zoning Districts	Town of Boxborough Planning Department	2024	Boxborough zoning data, which was joined with the Tax Parcel dataset so that each parcel was assigned a zone. In cases where a parcel spanned two or more zoning districts, the parcel was assigned to the district that contained the majority of the land area.
Building Structures (2-D)[42]	MassGIS	2024	This layer was used to show the area covered by buildings in the town. Building footprints were converted to points to be used in the analysis.
Roadways	Town of Boxborough Planning Department	2024	Town roadways and right-of-way data.
MassDOT Roads layer[43]	MassGIS	2025	This layer was used to supplement the Town's roadways layer when necessary.
FEMA National Flood Hazard Layer[44]	MassGIS	2010, 2014	FEMA FIRM Panels from 2010 and 2014 representing the flood hazard layers in Boxborough.
NHESP Priority Habitats of Rare Species[45]	MassGIS	2024	Represents the geographic extent of habitat of state-listed rare species.
Protected and Recreational Open Space[46]	MassGIS	2025	Permanently protected open space land, town and state owned conservation land, semi-public lands (privately-owned recreation or conservation land) and chapter lands.
Town Conservation Land	Town of Boxborough Planning Department	2024	Supplement to the MassGIS Protected and Recreational Open Space layer.

[41] MassGIS, 2024. Property Tax Parcels.
[42] MassGIS, 2024. Building Structures (2-D).
[43] MassGIS, 2025. MassGIS-MassDOT Roads.
[44] MassGIS, 2025. Flood Insurance Rate Maps.
[45] MassGIS, 2021. NHESP Priority Habitats of Rare Species.
[46] MassGIS, 2025. Protected and Recreational Open Space.

Table 4.3 Data Sources			
Source Name	Origin	Date	Description
Chapter Land	MassGIS	2024	Parcels participating in programs authorized by MA General Laws Chapter 61, which reduce the tax burden for parcels in active forestry, agriculture, or recreation use. These parcels were identified through attributes in the Parcel dataset.
MassDEP Wetlands[47]	MassGIS	2024	A 100-foot buffer was added around all wetlands to represent protected areas.
MassDEP Hydrography[48]	MassGIS	2019	This layer represents rivers, streams, and waterbodies. A 100-foot buffer was added around all hydrological features to represent protected areas.

4.3.2 Constraints to Development

Features that prevent development or reduce the development capacity of a given parcel are considered constraints to development in the buildout analysis. While it might technically be possible in some constrained areas through special environmental permitting processes, this analysis focuses exclusively on by-right development potential under current zoning regulations without special approvals, permitting, or variances. The following data layers were used as constraints to development in the buildout analysis:

54% of Boxborough is considered "undevelopable" based on the constraints listed in this section.

- FEMA Flood Zones
- Priority Habitat
- Protected Open Space, including chapter land
- Wetlands areas, including a 100-foot buffer surrounding wetlands
- Hydrological features, including a 100-foot riverfront buffer

Areas of the town that were not constrained were called "buildable area". Of the 6,649 acres in Boxborough, 3,059 acres are considered buildable area. Figure 4.1 below shows the constrained and buildable areas in the town.

[47] MassGIS, 2024. MassDEP Wetlands.
[48] MassGIS, 2019. MassDEP Hydrography (1:25,000).

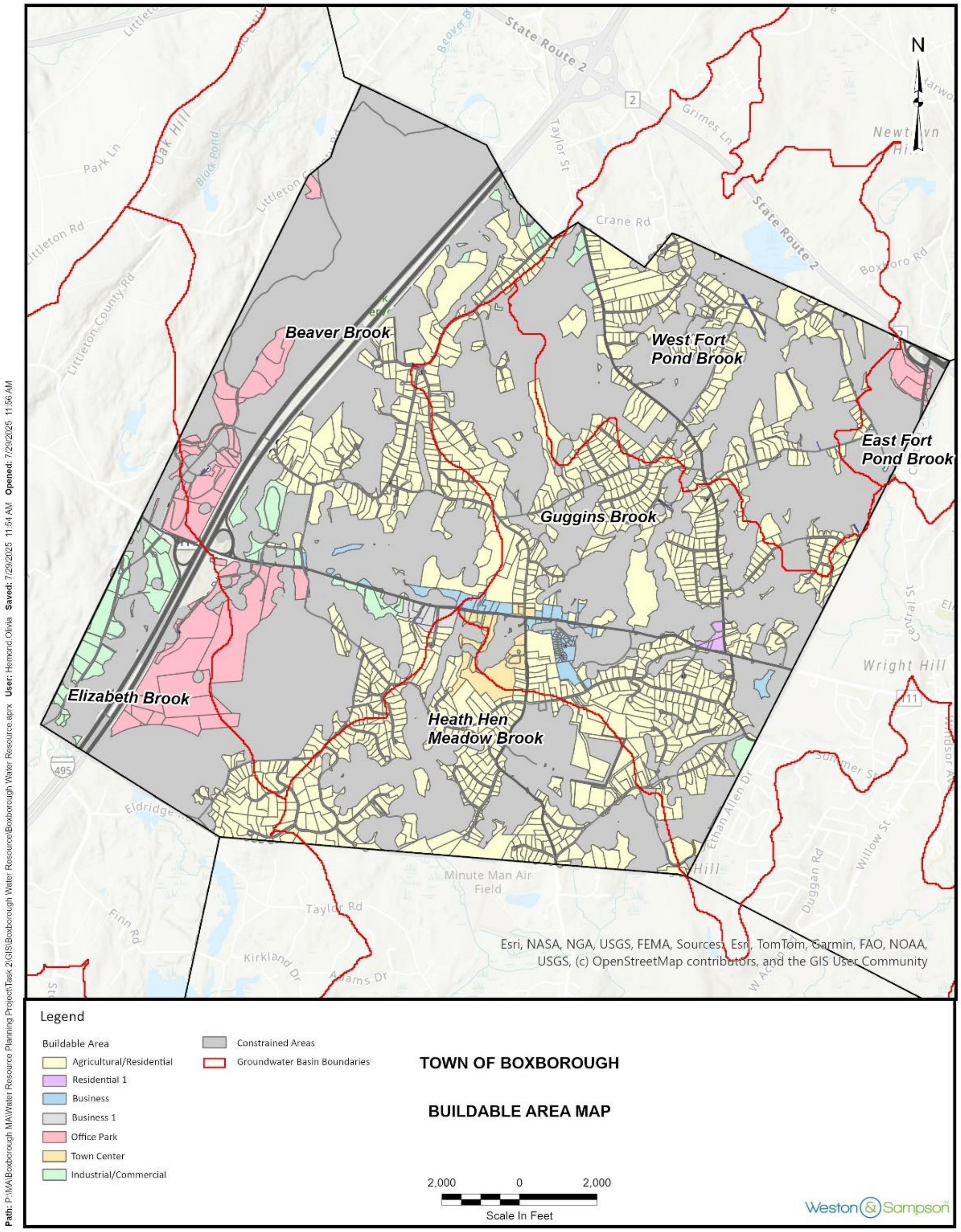

Figure 4.1 Buildable Area Map[49]

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49 Town of Boxborough, 2020. Zoning Districts.

4.3.3 Numeric Buildout

The numeric buildout process estimated how many new dwelling units could be built in Boxborough based on current zoning rules. Development in Boxborough is regulated by zoning district. Boxborough's zoning districts are summarized in Table 4.4.

Under the Numeric Buildout, it is estimated that ***327 new dwelling units*** *could be added based on zoning requirements. This does not account for existing building locations or setback requirements, which is covered in the Spatial Buildout.*

Table 4.4 Boxborough Zoning Districts[50]

District Name	Description
Agricultural/Residential	Residential and agricultural development permitted
Residential 1	Residential development permitted
Business	General commercial and retail uses permitted
Business 1	General commercial and retail uses permitted
Office Park	Professional office complexes
Town Center	Compact development with general commercial and retail uses
Industrial/Commercial	Industrial and commercial uses

Zoning requirements for residential development were applied to parcels outside of the constrained areas (listed in Section 4.3.2) to calculate the maximum number of dwelling units that could be added to each parcel. For this buildout, CommunityViz only accounted for by-right residential development and did not include any development that could be approved under potential variances or special permits. Variances and special permit requirements include Planning Board (PB) approval and Zoning Board of Appeals (ZBA) approval.

Under residential use zoning requirements, seen in Table 4.5, only Districts Agricultural/Residential and Residential 1 allow for residential use with no restrictions. Furthermore, these two districts only allow for single-family dwellings on a parcel and did not allow for anything larger without special permits.

[50] Town of Boxborough, 2023. Zoning Bylaw.

Table 4.5 Residential Uses[51]							
	Districts						
	Agricultural/ Residential	Residential 1	Business	Business 1	Office Park	Town Center	Industrial/ Commercial
Single-family dwelling	Y	Y	N	N	N	ZBA	N
Two-family dwelling	N	N	N	PB	N	ZBA	N
Conversion to two-family dwelling of dwelling in existence on 5/3/65	ZBA	ZBA	Y	PB	N	Y	ZBA
Multi-family dwelling	N	Y*	N	PB	N	N	N
Two-family dwelling, reserved exclusively for elderly occupancy	PB	N	N	PB	N	PB	N
Bed and Breakfast	ZBA	ZBA	N	N	N	ZBA	N
Trailer or mobile home	N	N	N	N	N	N	N
Dwelling unit incidental to principal commercial use	Y	Y	N	N	N	ZBA	N

*With restrictions; Y=Yes; N=No; PB=Planning Board permit required; ZBA=Zoning Board of Appeals approval required

Each zoning district in Boxborough has rules about how small a lot can be. These "minimum lot size" requirements help determine how many homes can be built on a piece of land. For example, the minimum lot size for District Agricultural/Residential is 60,000 square feet. If an undeveloped parcel was 120,000 square feet, it could theoretically yield two dwelling units, assuming no other constraints.

Table 4.6 shows the minimum lot size requirements for each zoning district. CommunityViz applied the appropriate minimum lot size zoning parameter to calculate the theoretical maximum development capacity for each parcel. The system accounted for existing development by subtracting existing buildings from the calculation.

[51] Town of Boxborough, 2023. Zoning Bylaw.

Table 4.6 Lot Size Requirements[52]	
District	Minimum Lot Area (sq.ft.)
Agricultural/ Residential	60,000
Residential 1	80,000
Business	40,000
Business 1	40,000
Office Park	160,000
Town Center	40,000
Industrial/ Commercial	80,000

4.3.4 Spatial Buildout

After establishing theoretical maximums in the numeric buildout, the analysis advanced to a more detailed "Spatial Buildout". This second stage evaluated whether the theoretically allowed development could fit within each parcel when accounting for dimensional regulations like setbacks, and minimum distances between structures. This two-step approach provides both quantitative development projections and verification that these projections could be physically accommodated within the landscape while complying with the existing zoning and setback requirements. The setback assumptions are listed in Table 4.7.

Table 4.7 Building Setbacks[49]					
District	Minimum Lot Frontage (ft.)	Minimum Lot Width (ft.)	Minimum Front Setback (ft.)	Minimum Side Setback (ft.)	Minimum Rear Setback (ft.)
Agriculture/ Residential	150	100	40	30	40
Residential 1	150	125	40	30	40
Business	100	100	50	30	40
Business 1	100	100	50	30	40
Office Park	200	125	50	50	50
Town Center	100	100	25	20	20
Industrial/ Commercial	200	125	50	50	50

[52] Town of Boxborough, 2023. Zoning Bylaw.

The building locations identified through the spatial buildout analysis were placed on a map, shown in in Figure 4.2. In total, the buildout estimated that 263 new dwelling units could be added across town under the existing zoning and setback requirements.

*It is estimated that **263 new dwelling units** could be added across town under the existing building locations, zoning, and setback requirements.*

4.3.5 Impacts on Water Resources

Expanded residential development within a groundwater basin can have significant impacts on both the quantity and quality of water resources. As new homes are added, each with its own well, the cumulative demand on the aquifer increases. Over time, this can lower the water table, particularly in areas where natural recharge is limited or where impervious surfaces from development reduce the amount of rainwater soaking back into the ground. This imbalance can result in reduced well yields or well failures during periods of drought.

In addition to water quantity concerns, the increased number of septic systems can lead to elevated nutrient and contaminant loading in the groundwater. While individual systems are designed to treat wastewater on-site, a high concentration of septic systems within a basin can result in cumulative impacts that may threaten drinking water quality. These risks are especially acute in areas with shallow groundwater or highly permeable soils.

To better understand how this growth may impact Boxborough's water resources, the results of the Buildout Analysis were analyzed within the context of Boxborough's six groundwater basins (Section 2.6.3). Understanding the geographic distribution of future development will determine where water demand could increase most sharply.

Heath Hen Meadow Brook groundwater basin has the greatest increase in buildings per square mile

Table 4.8 summarizes the potential number of new dwelling units that could be added within each groundwater basin based on the results of the spatial buildout. Guggins Brook groundwater basin, which covers 24% of the town's land area and has the greatest number of existing buildings (729), has the greatest theoretical increase in development at 79 potential units. Heath Hen Meadow Brook, while smaller in size and currently contains 304 buildings, also shows relatively high potential development with 66 additional units. These areas are shown in Figure 4.2.

Table 4.8 Buildout by Groundwater Basin						
Groundwater Basins	Square Miles Within Boxborough	% of Total	Number of Existing Buildings	Number of Potential Dwelling Units	Percent Increase	Increase in Number of Buildings per Square Mile
Beaver Brook	3.5	33.6%	413	61	15%	17
Guggins Brook	2.5	23.8%	729	79	11%	32
Heath Hen Meadow Brook	1.4	13.3%	304	66	22%	47
East Fort Pond Brook	0.2	1.9%	12	1	8%	5
West Fort Pond Brook	1.8	17.6%	318	52	16%	29
Elizabeth Brook	1.0	9.8%	106	4	4%	4
Total	**10.4**	**100.0%**	**1,882**	**263**	**14%**	**25**

The Drinking Water Assessment (Section 5) and Septic System Assessment (Section 6) provide greater detail about the impact that the estimated additional population could have on the town's groundwater resources.

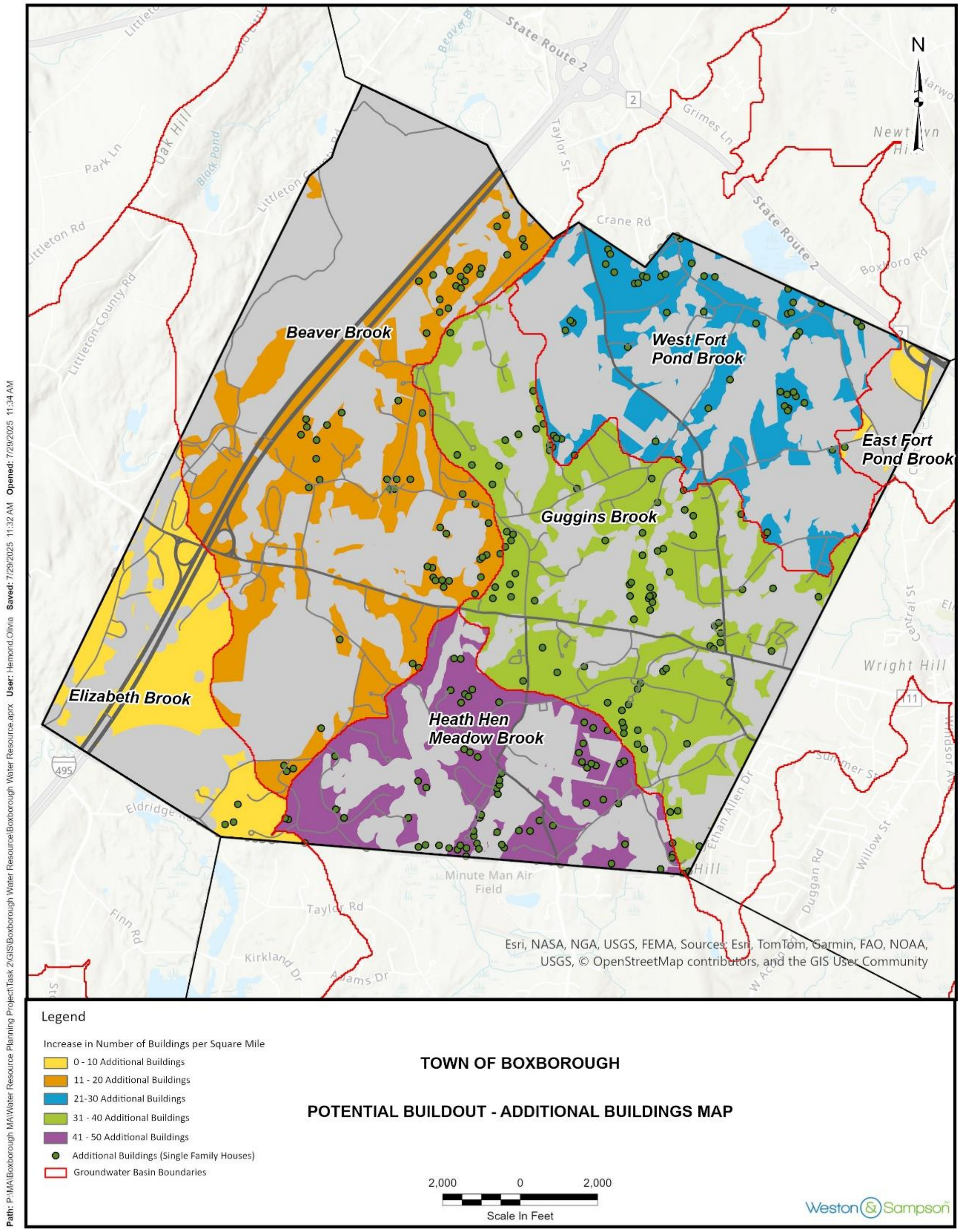

Figure 4.2. Potential Buildout – Additional Buildings Map

5.0 DRINKING WATER ASSESSMENT

As Boxborough does not have a centralized public water system for drinking water supply, all residents, businesses, and public facilities rely on groundwater from private wells and a network of small, privately-owned public water systems for their drinking water. This decentralized system requires an in-depth understanding of local groundwater availability, protection, and use. A high-level drinking water assessment is a first step in understanding the limitations on Boxborough's groundwater resources and offers a foundation for informed planning and groundwater protection.

***Water quantity** refers to the volume or amount of water available for various needs. The following section addresses **Boxborough's water quantity**.*

5.1 Water Supply

Potable drinking water supplies in Boxborough come primarily from groundwater wells located within the town. There are 24 privately-owned public water supply systems serving housing developments and businesses in the town, which are sourced from 17 community groundwater wells and 29 non-community groundwater wells (see Figure 5.1). Currently, there is one interconnection between Boxborough and Littleton, where the Littleton Water Department provides water to Central Street and the Meenmore Condominiums on Leonard Road, which houses 96 units. There is also an industrial park on Summer Road that receives water from an interconnection with the Acton Water District. All other drinking water supplies in the town come from private wells.

Community vs. Non-Community Water Systems

MassDEP defines a community water system as a public water system that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents. Community water systems typically serve neighborhoods. A non-community water system is a public water system that is not a community water system, and is categorized as either non-transient non-community, or transient non-community. Non-transient non-community wells regularly serve water to at least 25 of the same people for at least 6 months per year.

5.2 Wellhead Protection Areas

Boxborough's water resources are primarily supported by two main aquifer types: till/bedrock aquifers and sand and gravel aquifers (Figure 2.6). Till and bedrock aquifers offer several advantages, including resilience during moderate drought conditions due to their depth and natural filtration capabilities that can reduce certain surface contaminants. However, these aquifers typically yield lower water volumes, often sufficient only for individual household wells, and may contain naturally occurring minerals like iron, manganese, and occasionally radon or arsenic that require treatment. In contrast, Boxborough's sand and gravel aquifers provide significantly higher yield potential suitable for public water supplies, faster recharge rates during precipitation events, and generally good water quality with less mineral content. The drawbacks of these sand and gravel formations include higher vulnerability to surface contamination due to their porous nature, and greater susceptibility to depletion during extended drought periods.

Groundwater is primarily recharged by precipitation. Groundwater quality is affected by the bedrock and overburden material it flows through as well as land use. As land use changes and impervious cover increases, the amount of precipitation that enters the ground to replenish groundwater will change significantly. Arsenic and other contaminants found in groundwater may be naturally occurring, while other contaminants may be introduced to groundwater through agricultural, septic systems, stormwater runoff, and other human activities. As development has increased, it has become more important to protect groundwater resources from contamination.

In 1986, the US EPA amended the Safe Water Drinking Act to include Wellhead Protection Areas (WPAs). A wellhead is the physical structure of the well above ground. The WPA is the area around the wellhead where land use activities have the potential to affect the quality of water that flows into the well. The amount of land involved in a WPA is determined by a variety of factors such as the way the land rises or falls, the amount of water being pumped, the type of aquifer, the type of soil surrounding the well, and the direction and speed that groundwater travels. All these factors help to determine how long it takes water to move underground to the well itself and how much land around the wellhead should be protected. Boxborough has two MassDEP-approved WPA (Zone II) and multiple interim WPAs (IWPA). In Boxborough, 46 public water supply wells have IWPAs, and of those, four are also located within the MassDEP-approved WPA (Zone II), as shown in Figure 5.1. Boxborough's PWS wells are also summarized in Appendix A.

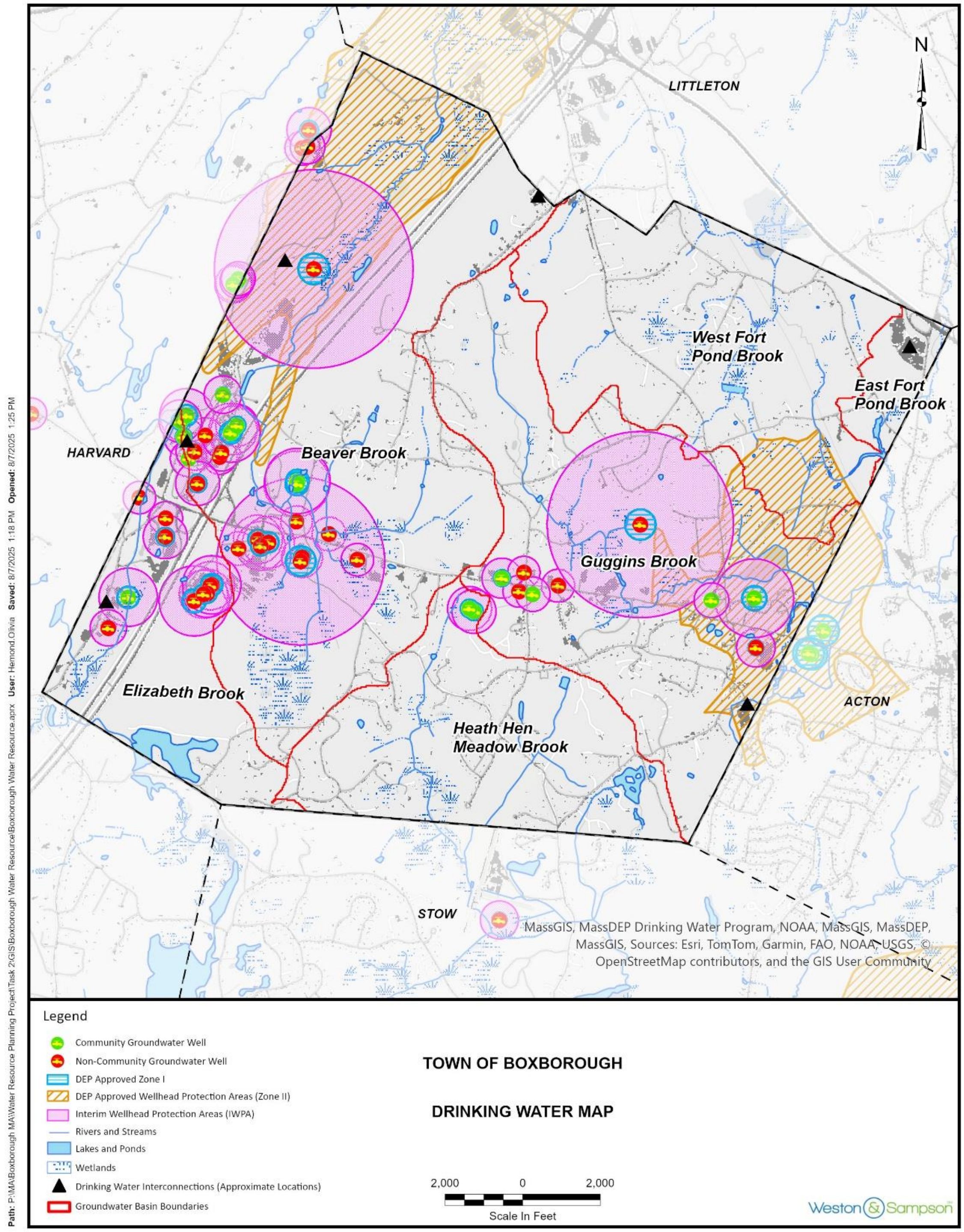

Figure 5.1. Current Drinking Water Map[53,54]

[53] MassGIS, 2025. Public Water Supplies.
[54] MassGIS, 2025. MassDEP Wellhead Protection Areas (Zone II, Zone I, IWPA).

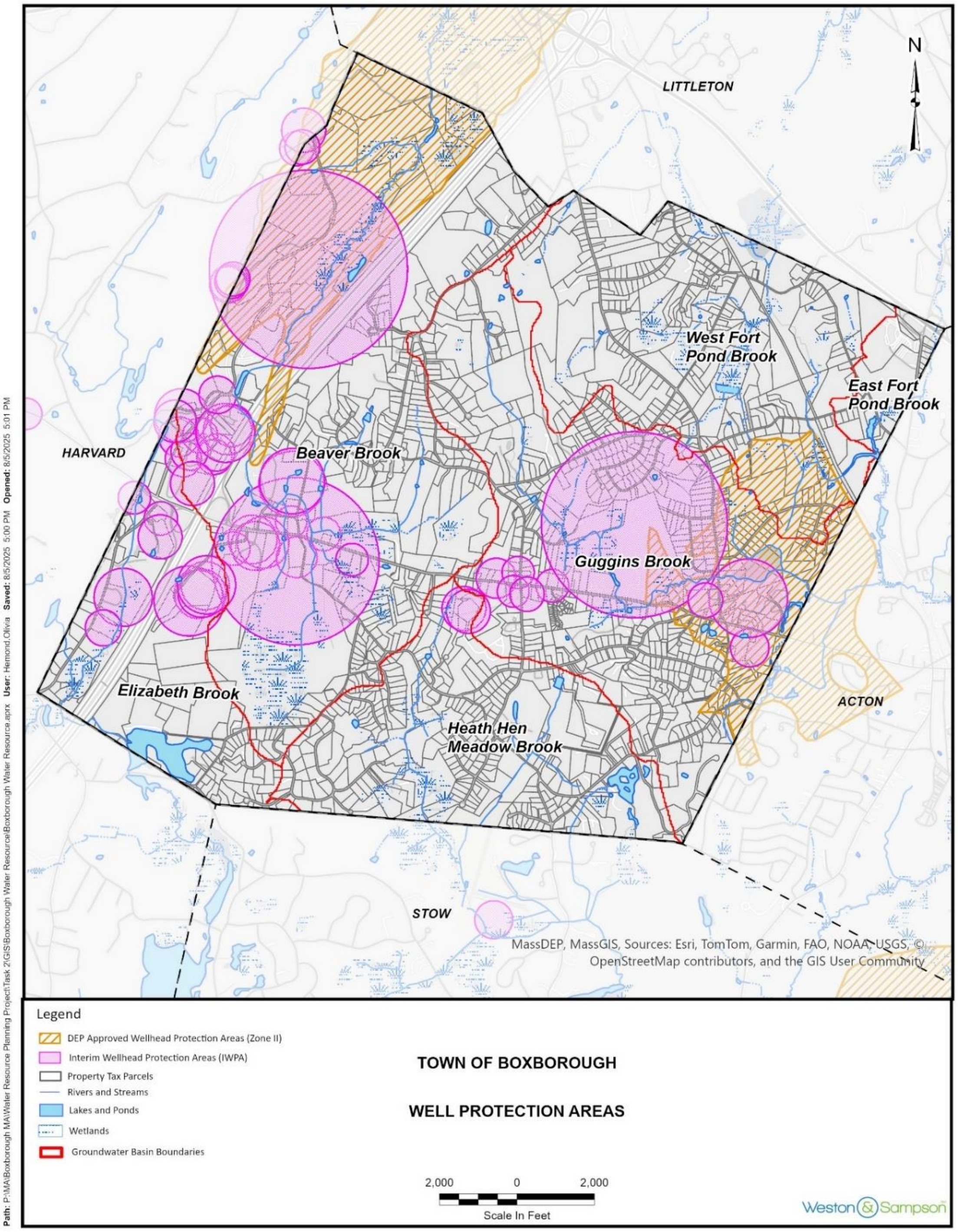

Figure 5.2. Well Protection Areas Map[55]

[55] MassGIS, 2025. MassDEP Wellhead Protection Areas (Zone II, Zone I, IWPA).

5.3 Current Drinking Water Demand

Boxborough's drinking water is primarily supplied by groundwater wells within the town. As described in Section 5.1, there are some privately-owned community wells and some interconnections with adjacent towns that supply water to town buildings, commercial properties and condominiums. The remainder of the town's drinking water is supplied by individual private drinking water wells serving residential properties.

5.3.1 Estimated Current Residential Drinking Water Demand

Town-Level Estimates: As described in detail in Section 4, Boxborough has a population of 5,506 people based on the US census data from April 1, 2020.[56] To estimate current drinking water usage for residential properties, the MassDEP standard assumption of 65 gallons per person per day (GPCD) was used. This 65 GPCD standard assumption includes both indoor residential uses such as drinking, cooking, bathing, and laundry, as well as outdoor uses such as lawn irrigation. Note that the actual usage may be higher or lower, and these numbers are used for planning purposes only.

To calculate Average Daily Demand, the following formula is used:

Average Daily Demand (gallons) = Number of people × 65 gallons/person/day

Based on the Census-provided population of 5,506 people, the average daily demand for Boxborough is estimated at 357,890 gallons per day (GPD) or 0.36 million gallons per day (MGD). **This is equal to approximately 131 million gallons per year (MGY)** (Table 5.1).

Table 5.1 Current Estimated Residential Drinking Water Usage			
Source	Number of Households	Estimated Population	Estimated Usage (MGY)
United States Census Bureau, 2020	--	5,506	131
Tax Parcel Calculations	2,225	5,498	130.4

*The population calculation using **the Property Tax Parcel** data was conducted to quantify the number of households and estimated population in each groundwater basin. The **US Census** data is only available on a townwide scale and does not allow for spatial analysis of the population.*

[56] US Census Bureau, 2020. Decennial Census.

> *The Guggins Brook groundwater basin has the greatest annual demand of approximately* ***48.5 MGY.***

Basin-Level Estimates*:* U.S. Census data is only available on a townwide scale and not by groundwater basin. Basin-specific water usage estimates used parcel-level data and average household demographics. Population distribution across groundwater basins was estimated by analyzing the spatial distribution of residential parcels within each basin boundary and applying the town's average household size (Section 4.3). According to the US Census Bureau, the average household population in Boxborough is 2.47 people per household.[57] This approach estimates relatively uniform household size density across basins.

The analysis utilizes MassGIS Property Tax Parcel data[58] and Town Assessor's Data to identify residential properties within each groundwater basin. Of the 1,761 parcels within Boxborough, 1,360 parcels are listed with residential area in the GIS data, some of which contained single family homes while others contained multi-family homes and condominiums. Thirty parcels within the Town have more than one dwelling unit on the parcel, and for these parcels, the total number of units was accounted for in this calculation as shown in Table 5.2. While 1,360 parcels were estimated from the GIS data, the 30 parcels with more than one dwelling unit brought the total number of units to 2,225.

For each basin, the number of households was multiplied by the average household size to estimate population, which was then applied to the 65 GPCD standard to calculate drinking water usage. Population estimates were rounded up to the nearest whole number. Note that this methodology assumes uniform household occupancy rates across all basins and does not account for variations in actual household sizes, seasonal occupancy patterns, or differences in water consumption behavior between households and basins. Based on this analysis, residential use was estimated at approximately 130 MGY with the highest demand in the Guggins Brook basin (Table 5.2).

Table 5.2 Current Estimated Residential Groundwater Demand by Basin

Groundwater Basin	Number of Households	Estimated Population	Estimated Water Demand (GPD)	Estimated Water Demand (MGD)	Estimated Water Demand (MGY)
Beaver Brook	712	1,759	114,335	0.11	41.7
Guggins Brook	827	2,043	132,795	0.13	48.5
Heath Hen Meadow Brook	259	640	41,600	0.04	15.2
East Fort Pond Brook	10	25	1,625	0.002	0.6
West Fort Pond Brook	240	593	38,545	0.04	14.1
Elizabeth Brook	177	438	28,470	0.03	10.4
Total	2,225	5,498	357,370	0.35	130.4

[57] US Census Bureau, 2023. QuickFacts, Boxborough town, Middlesex County, Massachusetts.
[58] MassGIS, 2024. Property Tax Parcels.

5.3.2 *Estimated Current Commercial Drinking Water Demand*

Commercial development in Boxborough is concentrated primarily in the western portion of the town, with significant activity along the Route 495 corridor and Massachusetts Avenue. The town's zoning designated several areas for commercial use, including business districts, commercial/industrial zones, office parks, and the town center. These zones represent the primary commercial water users within the municipal water system and constitute an important component of overall water demand projections.

This analysis employed a methodology based on MassGIS parcel data to estimate commercial water usage. The total area of commercial development has been calculated from current parcel records, encompassing all properties within the business district, commercial/industrial, office park, and town center zoning classifications. Commercial buildings cover 2,166,175 square feet of Boxborough's area.

To calculate Commercial Demand, the following formula is used:

$$\text{Average Daily Demand (gallons)} = \text{Building Footprint (ft}^2) \times 75 \text{ gpd/1000 ft}^2$$

Water usage for commercial areas is estimated using a consumption rate of 75 gallons per day per 1,000 square feet of commercial space (75 gpd/1000 sf). This rate, established in the CDM Water Resources Analysis Study[59] and within the range found in a Commercial Buildings Energy Consumption Survey[60], reflects typical commercial water usage patterns for mixed commercial uses including office buildings, retail establishments, and light industrial facilities. Note that the actual usage may be higher or lower and water usage between different types of commercial development can vary drastically. These numbers are used for planning purposes only. Applying the equation above, the commercial water usage was estimated to be 164,464 gpd in Boxborough, or 59.3 MGY (Table 5.3).

Table 5.3 Estimated Commercial Groundwater Usage by Basin

Groundwater Basin	Commercial Building Area (sq.ft.)	Estimated Commercial Water Demand (GPD)	Estimated Commercial Water Demand (MGY)
Beaver Brook	856,892	64,267	23.5
Guggins Brook	486,606	36,496	13.3
Heath Hen Meadow Brook	0	0	0
East Fort Pond Brook	336,596	27,245	9.2
West Fort Pond Brook	40,881	3,066	1.1
Elizabeth Brook	445,200	33,390	12.2
Total	**2,166,175**	**164,464**	**59.3**

59 CDM, 2002. Water Resources Analysis Study.
60 U.S. Energy Information Administration, 2012. Commercial Buildings Energy Consumption Survey. https://www.eia.gov/consumption/commercial/reports/2012/water/

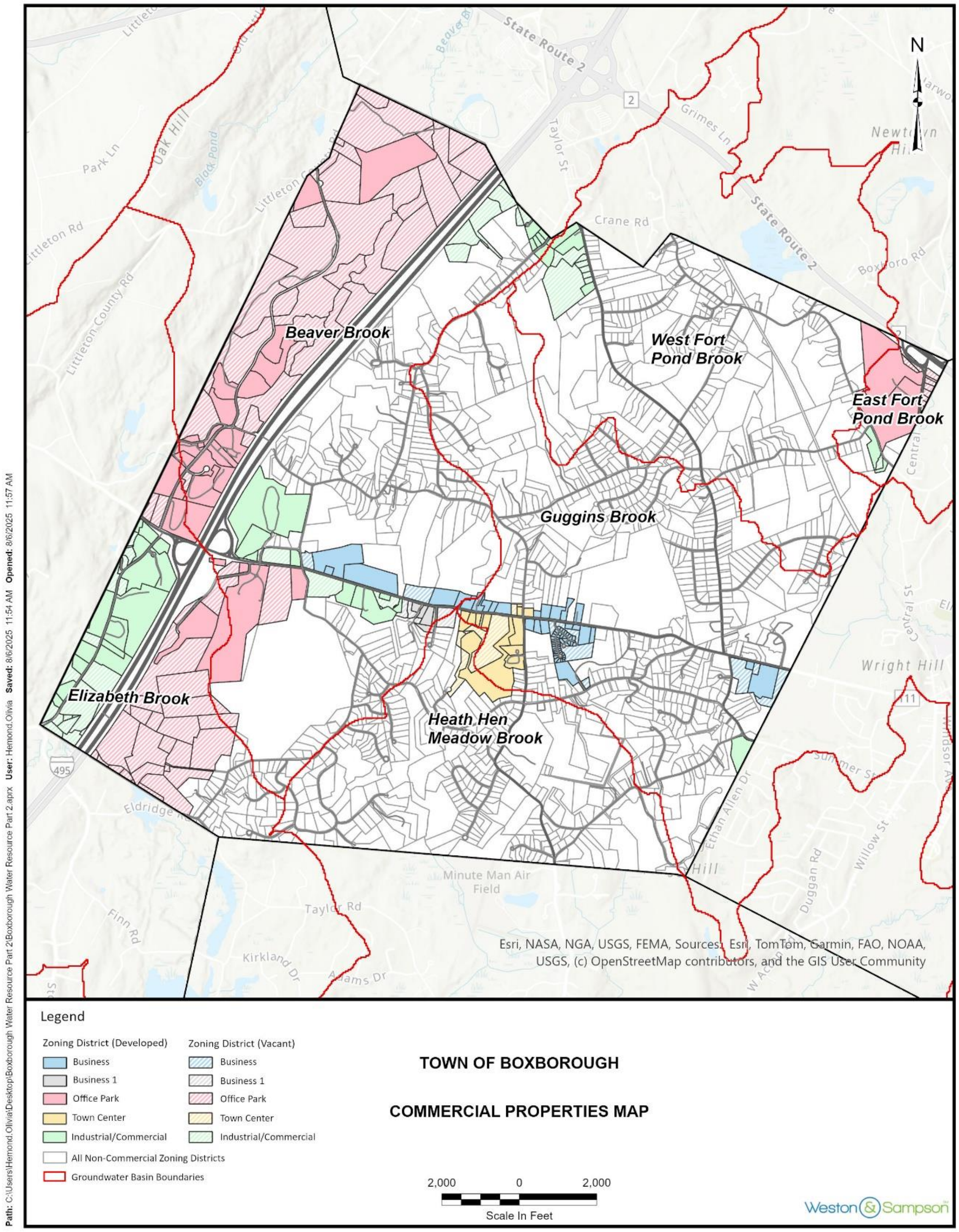

Figure 5.3. Commercial Properties Map[61,62]

[61] Town of Boxborough, 2020. Zoning Districts.
[62] MassGIS, 2024. Property Tax Parcels.

5.3.3 Total Current Estimated Drinking Water Demand

The total current estimated drinking water demand for Boxborough represents the combined residential and commercial water usage across all groundwater basins within the town. The demand estimates are organized by groundwater basin in Table 5.4 and shown in Figure 5.4.

Table 5.4 Total Current Estimated Drinking Water Demand by Basin			
Groundwater Basin	Estimated Residential Demand (MGY)	Estimated Commercial Demand (MGY)	Total Estimated Demand (MGY)
Beaver Brook	41.7	23.5	65.2
Guggins Brook	48.5	13.3	61.8
Heath Hen Meadow Brook	15.2	0	15.2
East Fort Pond Brook	0.6	9.2	9.8
West Fort Pond Brook	14.1	1.1	15.2
Elizabeth Brook	10.4	12.2	22.6
Total	**130.4**	**59.3**	**189.8**

It should be noted that these estimates have limitations. Residential demand calculations rely on population estimates and standard per-capita usage rates, while commercial demand is estimated using building square footage and literature-based consumption rates rather than actual metered data. Additionally, the analysis does not account for seasonal variations, peak demand periods, or specific operational characteristics of individual commercial establishments. These planning-level estimates are based on established literature values and industry standards, providing a reasonable approximation of current water usage for system planning purposes. The estimates could be further refined through detailed metering studies, seasonal demand analysis, and site-specific commercial usage assessments.

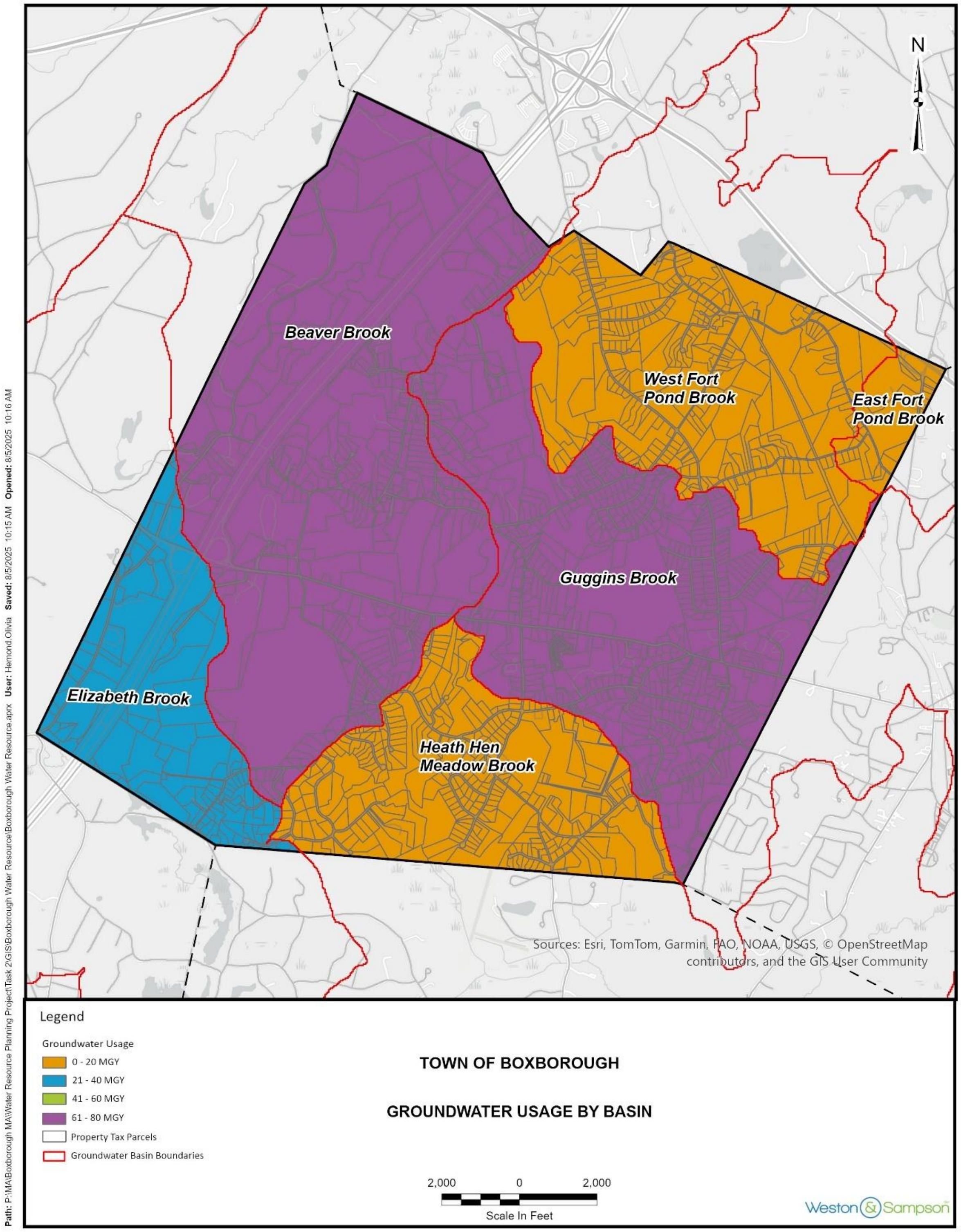

Figure 5.4. Groundwater Demand by Basin Map

5.4 Future Drinking Water Demand

Assessing the future demand for drinking water is an important exercise for towns to plan for future demand on water resources as the population grows. Future water demands will be affected by various factors including population growth, commercial/industrial development, weather patterns, and others. Future drinking water demand estimates in this section are only done for residential properties, as there is no accurate way to estimate future commercial development in Boxborough, as was done for the residential maximum buildout exercise. Using GIS, it was found that there are 135 undeveloped commercial parcels covering 1,024 acres in Boxborough which could be developed in the future.

5.4.1 Future Residential Demand

***US Census data** rather than Tax Parcel Data was used in this analysis. The population used for the future drinking water demand calculation is based on number of homes and an average number of people per household.*

Town-Level Estimates: Future residential water demand estimates are based on the population analysis and buildout scenarios presented in Section 4. According to census data from 2019-2023, homes in Boxborough have an average of 2.47 people per household. The following table summarizes the key demographic parameters and resulting population projections used to estimate future residential water usage.

Table 5.5 Future Population and Housing Estimates			
Parameter	Current	Future Buildout	Increase
Population	5,506	6,156	650
Housing Units	2,225	2,488	263

Future residential water demand projections are calculated using the MassDEP standard assumption of 65 gallons per capita per day (GPCD) applied to different population scenarios. Table 5.6 summarizes the projected water usage under various growth scenarios.

Table 5.6 Future Residential Water Demand Projections				
Scenario	Population	Water Demand (MGD)	Water Demand (MGY)	Percent Increase from Current
Current	5,506	0.35	130.4	-
Buildout	6,156	0.4	146	11%
UMDI 2050 Projection	6,996	0.45	166	25%

The buildout scenario represents development under current zoning regulations, while the UMDI 2050 projection reflects demographic trends and regional growth patterns. Both scenarios indicate moderate increases in residential water demand, with the more conservative buildout scenario showing an 11% increase and the UMDI projection indicating a 25% increase over current usage levels.

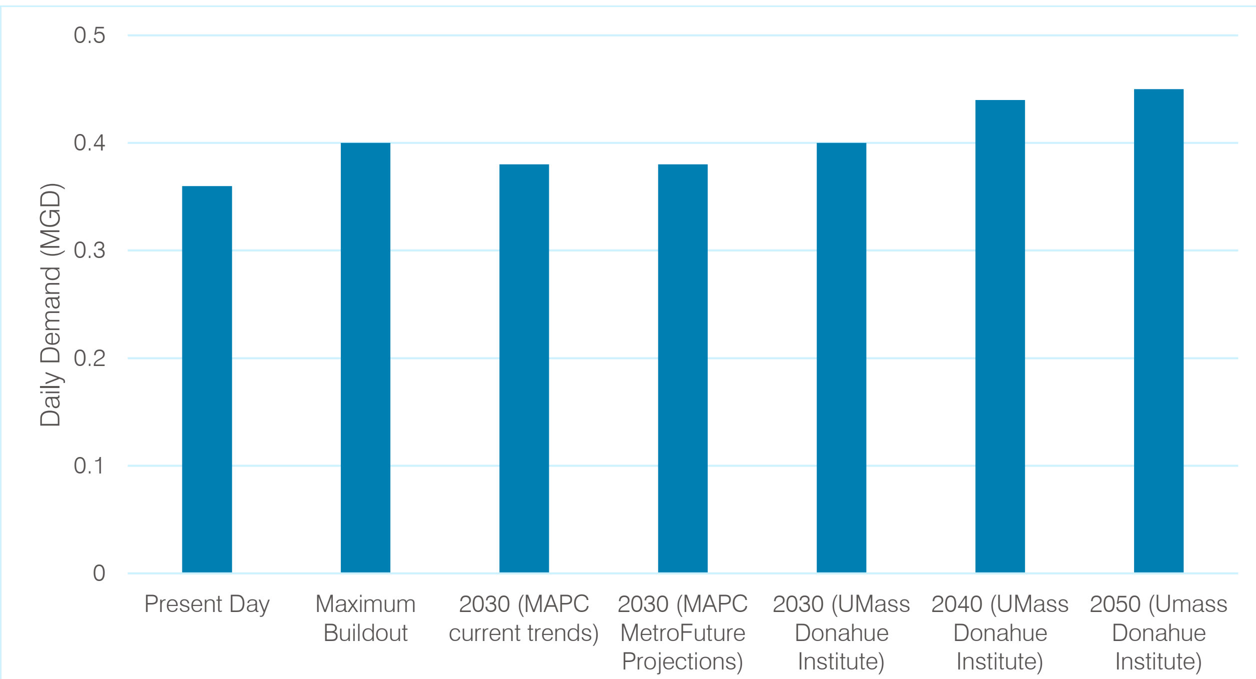

Figure 5.5. Estimate Future Average Day Demands

Basin Level-Estimates: Future drinking water demand by groundwater basin was estimated by projecting population growth based on potential residential development capacity identified in the buildout analysis. The estimated future population was calculated by taking the existing baseline population within each basin (see Table 5.2) and adding the projected population from potential new residential development. For each future dwelling unit identified in the buildout analysis, an assumption of 2.47 people per household was applied, consistent with Boxborough's current average household size as reported by the US Census Bureau. Population estimates were rounded up to the nearest whole number. These future population estimates were then multiplied by the standard assumed usage rate of 65 GPCD to estimate projected drinking water demand for each groundwater basin under full residential buildout conditions. The estimated water usage by basin is summarized in Table 5.7 below.

***Future drinking water demand** by basin was calculated based on number of dwellings (homes) and average people per household, consistent with the calculations in the **Buildout Analysis**.*

Table 5.7 Future Estimated Residential Groundwater Demand by Basin

Groundwater Basin	Number of Future Dwelling Units (Current plus Predicted)	Estimated Population	Estimated Water Demand (GPD)	Estimated Water Demand (MGD)	Estimated Water Demand (MGY)
Beaver Brook	773	1,910	124,150	0.12	45
Guggins Brook	906	2,238	145,470	0.15	53
Heath Hen Meadow Brook	325	803	52,195	0.05	19
East Fort Pond Brook	11	28	1,820	0.002	1
West Fort Pond Brook	292	722	46,930	0.05	17
Elizabeth Brook	181	448	29,120	0.03	11
Total	**2,488**	**6,146**	**399,685**	**0.4**	**146**

Three approaches were used to estimate future demand: the basin-specific calculation based on existing and projected dwelling units from the buildout, the UMass Donahue Institute's 2050 population projections, and the maximum buildout scenario combined with average household population. The resulting water demand in MGY of the three approaches can be seen below in Table 5.8.

Table 5.8 Future Demand Estimation Approaches		
Basin-Specific Calculation	2050 UMass Donahue Institute	Maximum Buildout Scenario
146 MGY	166 MGY	146 MGY

Due to the high number of existing and potential dwelling units in Guggins Brook groundwater basin, this basin is anticipated to maintain the highest water usage across all scenarios, increasing 10% from 48.5 MGY (current demand) to 53.1 MGY (future demand).

5.4.2 Future Commercial Water Usage

Analysis of current zoning and parcel data indicates that there are 135 undeveloped commercial properties in Boxborough covering an area of 1,024 acres. These parcels represent potential future commercial water demand in the town. The undeveloped commercial land is mainly distributed across areas of the town zoned as commercial/industrial, business, and office park, with only five properties zoned as town center. The majority of the vacant commercial parcels are located in Beaver Brook and Elizabeth Brook groundwater basins.

Future commercial drinking water demand was calculated by ***maximizing commercial buildout*** *according to building size zoning regulations on all undeveloped commercial lots.*

Commercial water use projections for undeveloped parcels presents challenges due to the methodology's dependence on building square footage other than land area. Without specific development plans, it is difficult to accurately project the increase in water usage due to development of these currently vacant parcels. For this analysis, a "worst-case" scenario was used to determine maximum potential water usage for undeveloped parcels. Note that this is just one way to determine future commercial water usage and is in no way reflective of development plans in the town.

All undeveloped parcels were assigned a maximum building size based on zoning restrictions. All commercial districts have a maximum percent coverage by buildings, structures, and impervious surfaces:

- Business Districts: 50%
- Office Park and Industrial/Commercial: 30%
- Town Center: 35%

By applying the zoned maximum percent coverage (assuming all coverage is building area, to reach the "worse-case" results) and the commercial demand calculation below, average daily demand in gallons can be calculated for future commercial water usage.

$$\textbf{Average Daily Demand (gallons)} = \textbf{Building Footprint (ft}^2\textbf{)} \times \textbf{75 gpd/1000 ft}^2$$

Through this analysis, it was determined that the total possible building area across all currently undeveloped commercial properties was equal to 13,643,508 square feet. By applying the above calculations, it was found that the average daily demand due to maximized commercial development could be as high as 1,036,763 gallons. The demand is broken down by basin in Table 5.9 below.

Table 5.9 Future Estimated Commercial Groundwater Demand by Basin (Maximized)				
Groundwater Basin	Number of Vacant Lots	Maximum Commercial Building Area (sq.ft.)	Estimated Commercial Water Demand (GPD)	Estimated Commercial Water Demand (MGY)
Beaver Brook	55	8,298,067	622,355	251
Guggins Brook	9	866,784	65,009	37
Heath Hen Meadow Brook	4	209,856	15,739	8
East Fort Pond Brook	11	131,508	9,863	13
West Fort Pond Brook	7	454,704	34,103	14
Elizabeth Brook	49	3,682,589	289,694	118
Total	**135**	**13,643,508**	**1,036,763**	**441**

5.4.3 *Total Future Demand*

The total future water usage for Boxborough combines current commercial demand with projected residential growth under various development scenarios. The projections account for residential growth based on buildout potential and demographic trends, while commercial projections are limited by the challenges of estimating usage for undeveloped parcels without specific development plans. Future residential usage accounts for both low (basin-specific) and high (UMDI 2050) projections. Future commercial usage accounts for both low (no future commercial development) and high (maximum commercial buildout). Current and future demand is summarized in Table 5.10.

Table 5.10 Total Current and Future Groundwater Demand				
Water Demand	Current Demand (MGY)	Future Demand – Low (MGY)	Future Demand – High (MGY)	Projected Percent Increase (Range)
Residential	130	146	166	12% - 27%
Commercial	59	59	441	0% - 648%
Total Usage	**189**	**205**	**607**	**8% - 221%**

While residential water demand projections can be calculated using established demographic data and consumption rates, commercial projections present uncertainties. As detailed in Section 5.4.2, Boxborough has 135 undeveloped commercial properties covering 1,024 acres, primarily located in the Beaver Brook groundwater basin. These parcels represent development potential that could significantly increase commercial water demand, but quantifying this impact requires assumptions about building density, footprint, and commercial use types that are not currently available, and therefore the future estimates reflect current conditions plus maximum commercial buildout on all vacant commercial lots. Table 5.11 summarizes the total future estimate drinking water demand by basin, adding together future residential and future commercial demand by basin. "Low" future residential demand and "high" future commercial demand were used in this summary as those are the two scenarios with detailed basin analyses.

Table 5.11 Total Estimated Future Drinking Water Demand by Basin

Groundwater Basin	Estimated Future Residential Demand (MGY)	Estimated Future Commercial Demand (MGY)	Total Estimated Future Demand (MGY)
Beaver Brook	45	251	296
Guggins Brook	53	37	90
Heath Hen Meadow Brook	19	8	27
East Fort Pond Brook	1	13	14
West Fort Pond Brook	17	14	31
Elizabeth Brook	11	118	129
Total	146	441	587

5.5 Evaluation of Recharge Rate by Groundwater Basins

This section outlines the methodology, assumptions, and results of a literature review and desktop analysis used to estimate groundwater recharge rates for different surficial deposits within the six groundwater basins (based on the Massachusetts Water Indicator (MWI) subbasins) in Boxborough.

Groundwater recharge rates are calculated for the entire groundwater basin rather than prorated based on the percentage of basin area within Boxborough's municipal boundaries. This approach recognizes that groundwater basins function as integrated hydrologic systems where recharge occurring throughout the basin contributes to overall aquifer storage and availability. Groundwater flows across municipal boundaries following natural hydraulic gradients, meaning that recharge occurring upgradient in adjacent communities contributes to the water available for extraction from wells within Boxborough. Conversely, recharge within Boxborough may contribute to groundwater availability in downgradient areas. Due to this reasoning, analysis is required at both the basin-wide and town-wide scales.

As shown in Table 5.12 and Figure 5.6, 27% of the total groundwater basin area lie within Boxborough's municipal boundaries.

Table 5.12 Groundwater Basins in the Boxborough Area

Groundwater Basin	Total Area of Basin (mi^2)	Percentage of Groundwater Basin in Boxborough	Basin Area in Boxborough (mi^2)
Beaver Brook	13.5	15%	3.5
Guggins Brook	6.1	65%	2.5
Heath Hen Meadow Brook	5.6	41%	1.4
East Fort Pond Brook	3.7	5%	0.2
West Fort Pond Brook	2.8	65%	1.8
Elizabeth Brook	6.8	25%	1.0
Total	38.5	27%	10.4

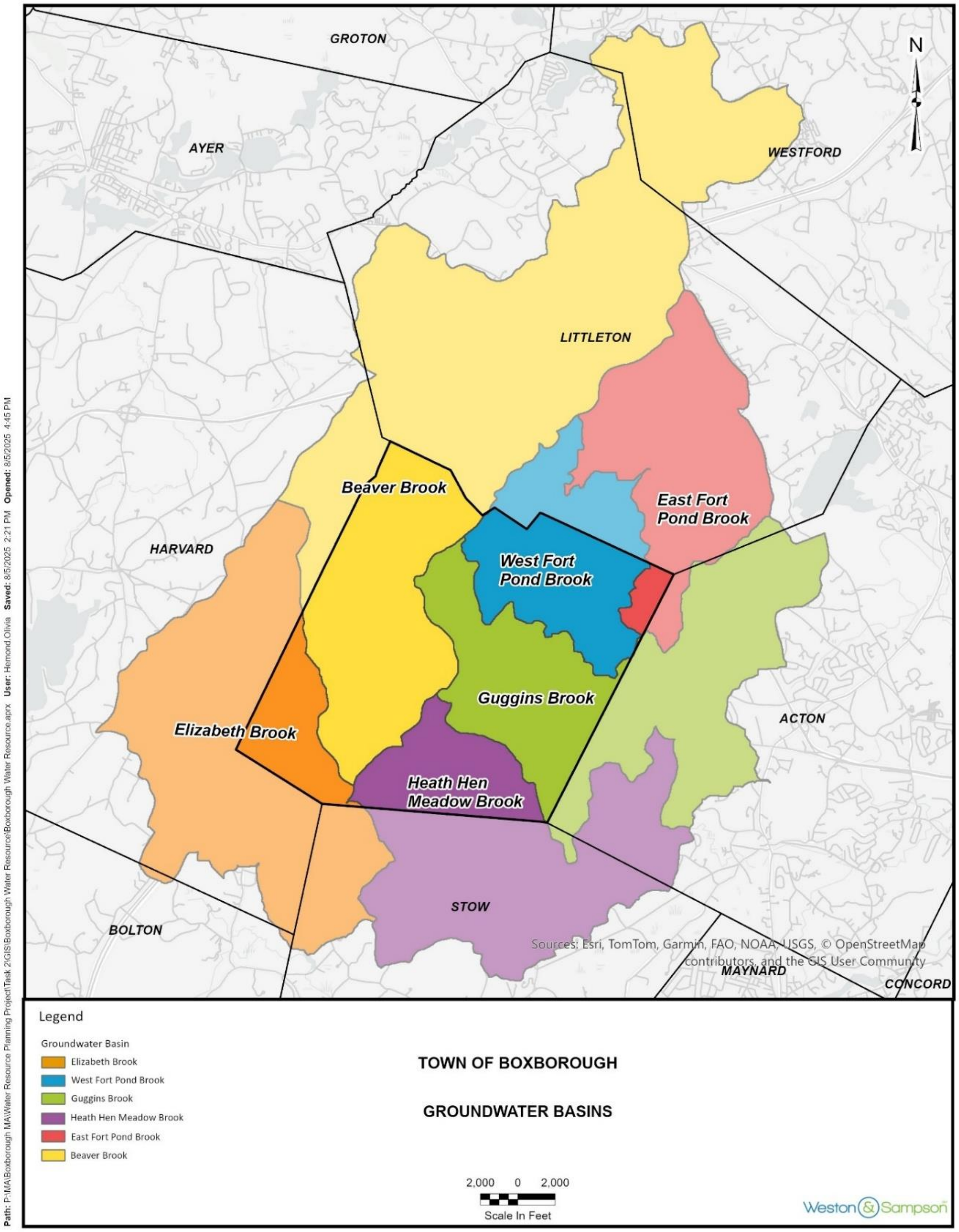

Figure 5.6. Groundwater Basins Map[63]

[63] MassDEP, 2025. Sustainable Water Management Initiative (SWMI) Technical Resources.

5.5.1 Methodology

To estimate the recharge rates for surficial deposits in the Boxborough area, these rates were estimated on a basin scale through a GIS-based analysis combining regional surficial geologic mapping, groundwater basins, and published recharge data. The process involved data selection, geologic classification, and the assignment of recharge rates based on literature and professional experience in similar settings.

Surficial deposits were obtained from the MassGIS Data: USGS 1:24,000 Surficial Geology (July 2022) dataset. This statewide geodatabase, developed by the U.S. Geological Survey, provides 1:24,000-scale mapping of surface materials across Massachusetts and was used to identify the dominant hydrogeologic units within the study area (Figure 2.6). Six groundwater basin boundaries (basin ID 12054, 12055, 12066, 12067, 12072, and 13054) were obtained from the MassDEP Sustainable Water Management Initiative (SWMI) Massachusetts Water Indicators (MWI) dataset, as described in Section 2.6.3. These boundaries were used to define hydrologic units for recharge rate assignment and to support potential watershed-level water balance assessments.

Three surficial deposit types were prioritized based on their prevalence in the region and their hydrologic influence: till, swamp deposits, and stratified glacial deposits (coarse material). Within the identified groundwater basins, exposed bedrock and other deposit types were assumed to exhibit similar recharge behavior to till and were therefore treated as functionally equivalent for the purposes of this analysis.

Recharge estimates were compiled from the following published literature sources:

- DeSimone, L.A., 2004, Simulation of ground-water flow and evaluation of water-management alternatives in the Assabet River Basin, eastern Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004-5114, 133 p
- Nielsen, M.G., and Westenbroek, S.M., 2019, Groundwater recharge estimates for Maine using a Soil-Water-Balance model—25-year average, range, and uncertainty, 1991 to 2015: U.S. Geological Survey Scientific Investigations Report 2019–5125, 56 p., https://doi.org/10.3133/sir20195125.
- Olimpio, J. C., & De Lima, V. (1984). Ground-water resources of the Mattapoisett River Valley, Plymouth County, Massachusetts (Water-Resources Investigations Report 84–4043). U.S. Geological Survey. https://doi.org/10.3133/wri844043

These sources are applicable due to their similar geologic settings and hydrologic soil properties. Rates were reviewed for geologic and hydrologic similarity and used to establish ranges for each deposit type in the study area. While both till and stratified glacial deposits had a range of available values, swamp deposit recharge rates were unable to be located within available literature. As a result, recharge characteristics of till are applied to the swamp deposits identified in the MassGIS USGS Surficial Geology shapefile. This decision is supported by the stratigraphic relationship in the MassGIS Surficial Geology dataset where till underlies the swamp deposits, thereby influencing their hydrologic behavior. Swamp deposits typically exhibit low recharge potential due to high evapotranspiration losses and low hydraulic conductivity, which aligns with the low permeability generally associated with till. Given these similarities, treating swamp deposits as having till-like recharge properties is a conservative and appropriate assumption for this preliminary assessment. Table 5.13 presents the final recharge rate assignments applied to the surficial geology polygons within the groundwater basins.

Table 5.13 Surficial Geology Estimated Recharge Rates (in/year)	
Surface Deposit Type	Estimated Recharge Rate (in/year)
Till and Swamp Deposits	7.5 – 22.5
Glacial Stratified Deposits (coarse)	17.5 – 28.2

It is important to note that these deposits show wide variability depending on local sediment sorting in each literature's study region (Assabet River Basin, Mattapoisett, and several aquifers in Maine). Where multiple sources were available, priority was given to local, model-calibrated results (i.e. DeSimone, 2004 and Nielsen and Westenbroek, 2019). Using ArcGIS Pro, the surficial geology shapefile was intersected with groundwater basin boundaries. Each unit was attributed with its corresponding recharge rate range, allowing for groundwater basin-level recharge estimates to be developed for drinking water availability assessments. For the purposes of this analysis, recharge is applied uniformly within each classified surficial deposit type. Appendix B presents statistics for each groundwater basin.

5.5.2 Results

Basin-Level Groundwater Recharge and Usage

Based on the analysis described above, the recharge rates for the six groundwater basins were estimated to range from 6,780 to 15,996 MGY (Table 5.14). On a basin scale, the Beaver Brook groundwater basin was estimated to have the highest estimated recharge volume (2,670 to 5,778 MGY), while West Fort Pond Brook groundwater basin was estimated to have the lowest volume (394 to 1,111 MGY).

> *Beaver Brook groundwater basin has the highest estimated recharge volume ranging from* ***2,670 to 5,776 MGY.***

Table 5.14 Recharge Rates and Estimated Withdrawals by Groundwater Basin			
Groundwater Basin	Groundwater Basin Area (mi^2)	Recharge Rates (MGY)	Groundwater Withdrawals from WMA Tool (MGY)
Beaver Brook	13.5	2670 to 5778	664.7
Guggins Brook	6.1	1104 to 2538	176.7
Heathen Hen Meadow Brook	5.6	967 to 2326	52.2
East Fort Pond Brook	3.7	511 to 1457	5.1
West Fort Pond Brook	2.8	394 to 1111	24.1
Elizabeth Brook	6.8	1134 to 2786	56.6
Total	38.5	6,780 to 15,996	979.4

To evaluate the relationship between groundwater usage and natural recharge rates within the full boundary of each groundwater basin, subbasin data was obtained from the MassDEP Water Management Act Permitting Tool (WMA Tool).[64] The WMA Permitting Tool estimates groundwater withdrawals for each basin based on average August pumping data from 2000–2004 for public water supply wells and commercial wells, while private well volumes are derived from U.S. Census data. The tool provides these withdrawal rates in million gallons per day (MGD). To estimate annual volumes, these daily August withdrawal rates were multiplied by 365 days, assuming August daily usage remains constant throughout the entire year. Because water demands typically peak in the summer months (June, July, and August) and decline in the winter, this approach results in a conservative annual estimate that likely overestimates actual groundwater withdrawals. As shown in Table 5.14, the total estimated groundwater withdrawal for this area is 979 MGY.

Town-Level Groundwater Usage

*The natural **recharge rates within Boxborough's six groundwater basins are likely sufficient** to meet current and projected drinking water quantity demands under current practices whereby most properties are served by their own private wells.*

As shown in Table 5.10, Boxborough occupies approximately 27% of the total groundwater basin area in this region. Total current and future estimate drinking water withdrawals within the limits of Boxborough were estimated in Section 5.3.3 and 5.4.3 (shown in Table 5.4 and 5.11). These numbers can be compared to the MWI groundwater withdrawals to better understand how groundwater withdrawals and recharge can affect Boxborough's drinking water supply.

It should be noted that the portion of basin area within town boundaries does not directly correlate to the portion of recharge occurring within those boundaries. Recharge rates depend on site-specific factors including soil conditions, land cover, and topography. Accurate recharge calculations for areas within Boxborough require field data collection and hydrogeological analysis rather than proportional estimates based on geographic area alone. Therefore, Table 5.15 summarizes groundwater withdrawals for the entire groundwater basin and for the portion of the basin within Boxborough, and the recharge rates are summarized only for the entire groundwater basin.

[64] MassDEP, 2025. Sustainable Water Management Initiative (SWMI) Technical Resources. https://www.mass.gov/guides/sustainable-water-management-initiative-swmi-technical-resources

Table 5.15 Estimated Groundwater Withdrawals and Recharge					
Groundwater Basin	August Groundwater Withdrawals for the Entire Groundwater Basin (MGY)	Percentage of Groundwater Basin in Boxborough	Current Estimated Drinking Water Demand in Boxborough (MGY)	Future Estimated Drinking Water Demand in Boxborough (MGY)	Recharge Rates for the Entire Groundwater Basin (MGY)
Beaver Brook	664.7	15%	65	296	2670 to 5778
Guggins Brook	176.7	65%	62	90	1104 to 2538
Heath Hen Meadow Brook	52.2	41%	15	27	967 to 2326
East Fort Pond Brook	5.1	5%	10	14	511 to 1457
West Fort Pond Brook	24.1	65%	15	31	394 to 1111
Elizabeth Brook	56.6	25%	23	129	1134 to 2786
Total	**979.4**	**27%**	**190**	**587**	**6,780 to 15,996**

Note that the recharge for the entire basin, 6,780 to 15,996 MGY, is not the quantity of water available to Boxborough, which is significantly less than that. Based on this analysis, groundwater *quantity* appears to be sufficient for current and future drinking water needs, under current practices whereby most properties are served by their own private wells. However, further analysis of groundwater *quality* is needed to evaluate whether clean drinking water is available for all. Furthermore, if Boxborough had to develop a municipal water system, it is not clear whether a well(s) of sufficient capacity, and meeting the State's requirements, could be developed to access the water.

Other water users, including future agricultural and institutional sections, were not included in the demand estimates. Residential and commercial demand was based on standard rates. Additionally, the use of August withdrawals from the WMA Tool is a conservative approach to estimating annual withdrawals. To fully capture water withdrawal rates, metered data would need to be collected over time on a townwide scale. This analysis does not address water quality, infrastructure constraints, or ecological flow requirements, which may influence the ultimate availability and sustainability of groundwater resources.

5.6 Drinking Water Supply Alternatives

The following section presents a set of proposed and developing drinking water supply alternatives aimed at addressing long-standing water quality challenges in Boxborough and the surrounding region. These efforts focus primarily on mitigating contamination from per- and polyfluoroalkyl substances (PFAS) and deicing chemicals, which have impacted several public and private drinking water wells in the area. The Town of Littleton, through the Littleton Electric Light & Water Departments, is advancing the development of new infrastructure that could also benefit Boxborough's residents and businesses by providing access to a clean and reliable public water supply.

5.6.1 Trumbull Well (previously Taylor Street Well)

Littleton Electric Light & Water Departments (LELWD) is in the process of developing a new groundwater supply well in Littleton (previously proposed Taylor Street Well, now called Trumbull Well) to add to its water supply sources. It is located near the intersection of Route 495 and Route 2 (153 Taylor Street). It is designed to be a 36" x 24" gravel packed well with a depth of 50 feet. The construction will include pipe installation from the well station to the Whitcomb Avenue Water Treatment Plant, where the well will feed for treatment.

The Trumbull Well will be connected to the new 3 MGD water treatment plant (WTP) at 15 Whitcomb Avenue funded under DWSRF-6906 to treat PFAS found in their existing raw water sources. The existing sources include the Spectacle Pond Well (2158000-04G) and the Whitcomb Ave Wells (215800-02G, -08G). Construction of the proposed raw water main will connect the proposed Taylor Street well to the WTP. The treated sources will then be pumped into the finished water main to serve the existing distribution system within Littleton in addition to the proposed finish water main to be extended into Boxborough. The extension would begin in the Merrimack basin (at the Littleton / Boxborough town line) and extend into the SuAsCo basin, serving the impacted PWSs and other benefitting parcels in the Town of Boxborough. The maximum daily transfer volume for this extension from the Merrimack basin to the SuAsCo basin would be 60,000 GPD.

5.6.2 Proposed Littleton-Boxborough Connector

A finished water main was proposed to be constructed from the existing Littleton water main at Nancy's Way in Littleton (near the Boxborough Town Line), progressing south along Beaver Brook Road and Swanson Road (Merrimack Basin) and terminating at 330 Codman Hill Road in Boxborough, Massachusetts (SuAsCo Basin). Several existing public drinking water supply wells in Boxborough[65] within the Merrimack basin, which include PWS ID's 2037007- 01G, 2037007-02G, 2037007-03G, 2037017-01G, 2037017-02G, 2037017-03G, 2037018-01G, 2037018-02G, 2037020-01G, 2037020-02G, 2037022-01G, 2037024-01G, 2037024-02G, 2037026-01G, 2037030-02G, 2037033-01G, 2037034-01G, 2037036-01G and 2037036-02G as well as the SuAsCo basin, which include PWS ID's 2037021-01G, 2037002-02G, 2037019-01G, 2037023-01G, 2037001-01G and 2037035-01G, have been impacted by deicing chemicals and Per- and polyfluoroalkyl substances (PFAS) contamination. Boxborough's impacted public drinking water supplies would be able to connect to the Littleton water system to resolve these serious water quality challenges in this community.

5.6.3 Additional Proposed Alternatives

Drinking water alternatives, including those currently under construction and previously proposed alternatives, have focused on the western side of Boxborough. This is due to the documented groundwater quality issues impacting private drinking water wells serving residents and businesses in the area. Table 5.16 below provides a summary of additional drinking water alternatives that have been identified, proposed, or assessed over the years. Their approximate locations of these alternatives are shown in Figure 5.7, and the alternative numbers are noted in the legend of that figure.

[65] MassDEP, 2025. Public Water Supplier Document Search.

Table 5.16 Proposed Drinking Water Alternatives					
Number	Proposed Alternative	Description	Location(s) (Groundwater Basin)	Date of Report	Data Source
1a	New Water Distribution System Alternative 1 – Independent System	Develop an independent, self-sufficient water distribution system.	Western Boxborough along 495 corridor (Beaver Brook, Elizabeth Brook, and a small portion of Guggins Brook and West Fort Pond Brook)	April 2008	Water Distribution System Feasibility Study
1b	New Water Distribution System Alternative 2 – Regional System Starting West of I-495	Boxborough would enter into an agreement with Littleton to develop a regional water system that would serve the low service area on the west side of I-495.	Western Boxborough along 495 corridor (Beaver Brook, Elizabeth Brook, and a small portion of Guggins Brook and West Fort Pond Brook)	April 2008	Water Distribution System Feasibility Study
1c	New Water Distribution System Alternative 3 – Regional System Starting East of I-495	Boxborough would enter into an agreement with Littleton to develop a regional water system that would serve the high pressure zone on the east side of I-495. This alternative was identified as most feasible of the three evaluated in 2008.	Western Boxborough along 495 corridor (Beaver Brook, Elizabeth Brook, and a small portion of Guggins Brook and West Fort Pond Brook)	April 2008	Water Distribution System Feasibility Study
2	Water Resources Analysis Study	Fourteen zones were potentially favorable areas for bedrock well development.	Heath Hen Meadow Brook, Guggins Brook, Elizabeth Brook, Beaver Brook	December 2002	Water Resources Analysis Study
3	Options to Improve Drinking Water Quality in Western Boxborough	Collaboration with the Town of Littleton to drill a new well and extend their water system into Boxborough was identified as most feasible.	Western Boxborough (Beaver Brook, Elizabeth Brook)	April 2019	Options to Improve Drinking Water Quality in Western Boxborough

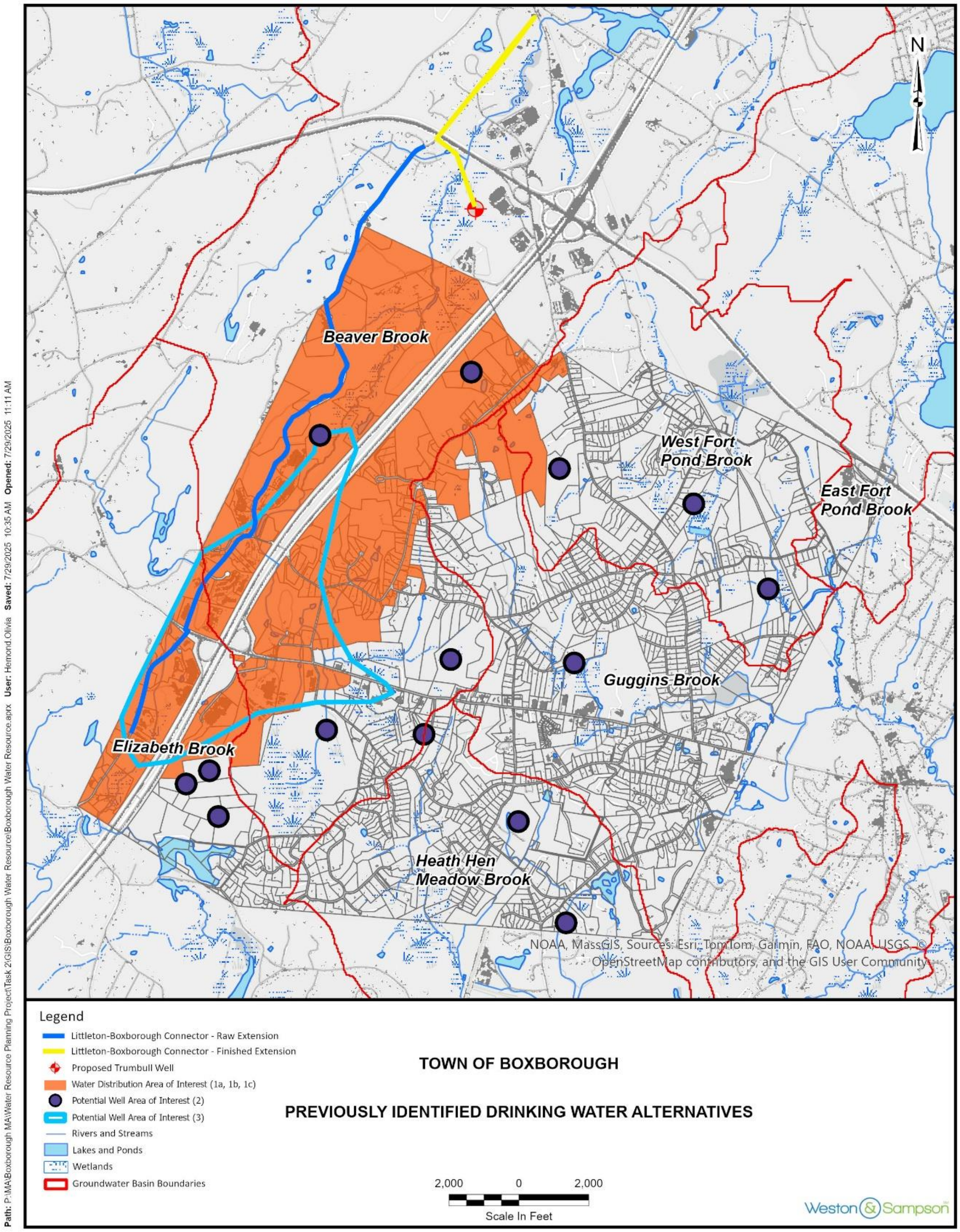

Figure 5.7. Proposed Drinking Water Alternatives Map

6.0 WASTEWATER ASSESSMENT

Boxborough relies entirely on onsite wastewater disposal such as septic systems for residential wastewater treatment. Proper septic system management is critical to protecting the quality of the town's groundwater resources. Septic system failures or malfunction can directly threaten public health and water quality as pollutants may enter the groundwater system. This section evaluates the town's septic systems to assess current conditions and identify future demand.

GIS Analysis** identified 1,357 properties in Boxborough that rely on **private septic systems.

6.1 Conventional Septic Systems

The most common type of septic system is conventional, while others are innovative/alternative (I/A) systems and cesspools. Traditional systems, mainly found in rural areas where public sewer systems are unavailable, include a septic tank, distribution box, and soil absorption system (SAS), as seen in Figure 6.1. This tank can separate solids and liquids while treating the SAS, and then the wastewater is distributed to the ground through perforated pipes typically filled with gravel or sand. The effluent is released into the soil for natural filtration and treatment.

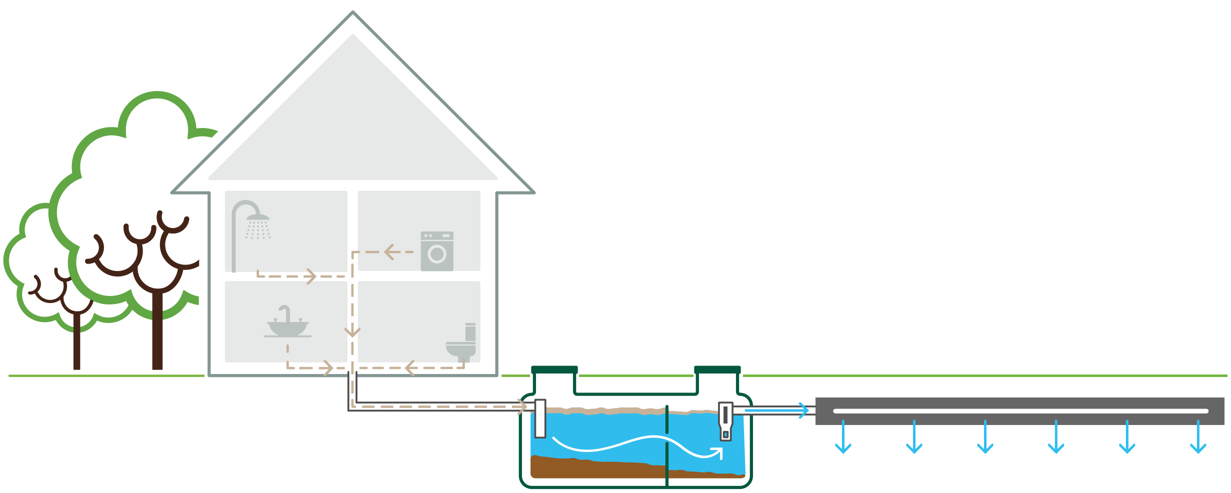

Figure 6.1 Septic System Schematic[66]

Septic systems require only periodic pump-outs, as they contain no mechanical parts and can function without electricity. The functionality of conventional systems is straightforward. As wastewater flows from the home into the septic tank, solids settle at the bottom, forming sludge; oils and grease float to the top as scum; and liquid effluent exits through an outlet pipe. The effluent enters the drain field, where it

[66] Premier Tech, 2025. Wastewater.

percolates through soil layers. Microbes in the soil remove contaminants like pathogens and nutrients before the treated water reaches groundwater.[54]

6.1.1 Limitations to Conventional Septic System Treatment

Conventional septic systems are ideal for properties with sufficient space, suitable soil conditions, and low water tables. However, alternative systems may be necessary for challenging sites or higher treatment needs. Conventional septic systems have several disadvantages, including their reliance on permeable soil, making them unsuitable for areas with impermeable soils or high-water tables. They require a large area for the drain field and produce lower-quality treated wastewater compared to aerobic systems. Additionally, replacing the system can be labor-intensive, involving significant excavation that may disrupt landscaping.

6.2 Wastewater Management in Boxborough

Boxborough relies primarily on individual septic systems for wastewater management, as the town does not have a centralized municipal sewer system. Most of the properties in Boxborough utilize conventional Title 5 septic systems, with the remaining properties served by alternative private wastewater treatment solutions and smaller privately owned wastewater treatment facilities. Larger commercial sites with groundwater discharge permits include the Campanelli campus (100-500 Beaver Brook Road), the Boxborough Regency (242 Adams Place), 1414 Mass Avenue, and 80/90 Central Street. These facilities also serve larger condominium developments such as Harvard Ridge (Swanson Road), Codman Hill (Codman Hill Road), and Brook Village (Swanson Court). These types of facilities operate under groundwater discharge permits issued by the Massachusetts Department of Environmental Protection (MassDEP). In addition to these larger systems, Boxborough also has smaller, privately owned and operated wastewater treatment facilities serving entities like the Applewood Village condominiums and several individual commercial properties. These smaller facilities are permitted and regulated by the local Board of Health.

Parcel data was assessed in GIS to determine the number and location of properties with residential development. Any property with residential development was assumed to have a septic system, although the size of the system will vary depending on the type of residential development. In total, it was estimated that there are 1,357 parcels that use septic systems for residential wastewater management.

6.2.1 Current Septic System Demand

Current septic system wastewater flows in Boxborough were estimated using Massachusetts Title 5 design standards, which establish minimum design flows based on residential bedroom counts rather than occupancy or actual water usage patterns. For residential properties, septic system design flows are calculated using the standard rate of 110 gallons per bedroom per day, as established by Massachusetts Title 5 regulations.[67] This design flow rate accounts for typical water usage patterns in residential settings. This rate is for planning purposes only, and the actual rate may vary. The total design flow for each property is calculated as:

[67] MassDEP. 2023. 310 CMR 15.000: Septic Systems ("Title 5").

Daily Design Flow (gallons) = Number of Bedrooms × 110 gallons/bedroom/day

Based on town assessor data and accounting for the Applewood Condominium having private wastewater treatment, Boxborough contains an estimated total of 5,889 bedrooms across all residential properties. Using the Title 5 design standard, this translates to an estimated total septic system design flow of approximately 647,790 gallons per day (5,889 bedrooms × 110 gallons/bedroom/day) for the town. Since the assessor's data is available by parcel, it was possible to summarize the septic flow by basin, shown in Table 6.1 below.

Table 6.1 Estimated Septic Flow by Basin

Groundwater Basin	Number of Bedrooms	Design Flow (GPD)	Design Flow (MGD)	Design Flow (MGY)
Beaver Brook	1,542	169,620	0.17	61.9
Guggins Brook	2,141	235,510	0.24	86.0
Heath Hen Meadow Brook	975	107,250	0.11	39.1
East Fort Pond Brook	16	1,760	0.002	0.6
West Fort Pond Brook	833	91,630	0.09	33.4
Elizabeth Brook	382	42,020	0.04	15.3
Total	5,889	647,790	0.65	236.4

*Guggins Brook has the **highest septic system flow** at 86 million gallons per year*

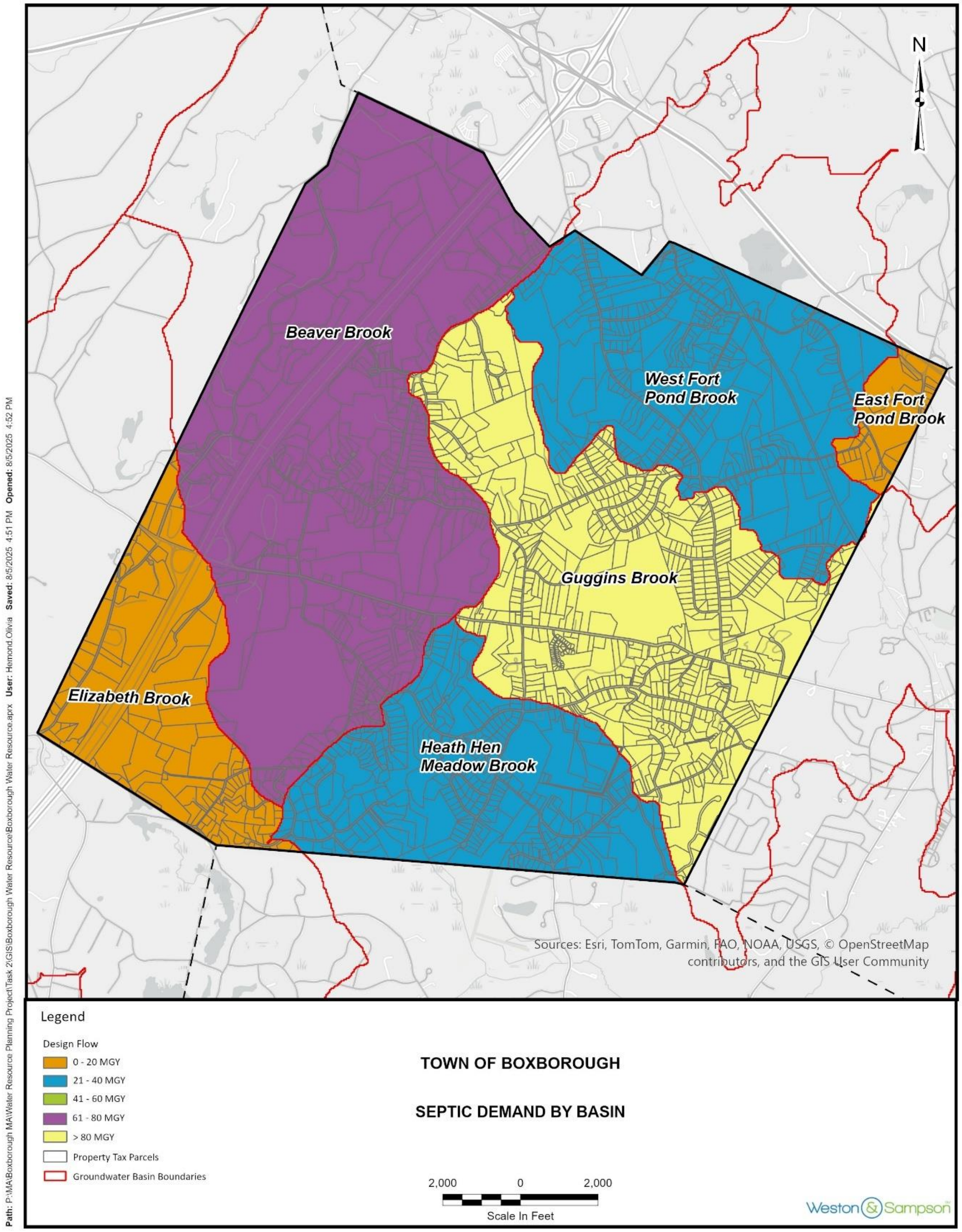

Figure 6.2. Septic Flow by Basin

6.3 Future Septic System Demand

To plan for Boxborough's future wastewater management needs, an analysis was completed to estimate potential septic system loading based on established design flow standards, projected development patterns, and the buildout completed and described in Section 4.1. The Massachusetts Title 5 septic regulation and industry best practices provides the foundation for this assessment. Since the Title 5 standard calculates demand based on number of bedrooms rather than population, the calculations in this section differ from the future drinking water demand in Section 5.5.

*Future septic system demand under **maximum buildout conditions** would **increase 17%** over current usage*

Future septic system demand was calculated by combining existing residential wastewater loads with projected additional demand from potential new development identified in the buildout analysis. The baseline septic system demand was established using the current number of bedrooms from town assessor data, as summarized in Table 6.1 of Section 6.2.1. To estimate the additional septic system loading from future development, the number of additional dwelling units projected in the buildout analysis was multiplied by the average number of bedrooms per household in Boxborough. Analysis of the town assessor data revealed that the average number of bedrooms per household is three bedrooms, calculated by taking the average number of bedrooms among all buildings with bedrooms recorded in the Boxborough assessor database.

The total future septic system demand for each groundwater basin was calculated by applying the Title 5 standard of 110 gallons per bedroom per day to both existing and projected bedroom counts. For existing development, the actual bedroom counts from assessor data were used, while for future development, each projected dwelling unit was assigned three bedrooms based on the town average. The number of bedrooms for existing and future development were combined and the total number of bedrooms by groundwater basin, as well as the future design flow, are summarized in Table 6.2 below.

Table 6.2 Estimated Future Septic Flow by Basin

Groundwater Basin	Number of Bedrooms	Design Flow (GPD)	Design Flow (MGD)	Design Flow (MGY)	Percent Change
Beaver Brook	1,725	189,750	0.19	69.3	12%
Guggins Brook	2,378	261,580	0.26	95.5	11%
Heath Hen Meadow Brook	1,173	129,030	0.13	47.1	21%
East Fort Pond Brook	19	2,090	0.002	0.8	33%
West Fort Pond Brook	989	108,790	0.12	40.1	20%
Elizabeth Brook	394	43,340	0.04	15.8	4%
Total	**6,678**	**734,580**	**0.73**	**268.1**	**17%**

6.4 Environmental Risk Assessment

An environmental risk assessment was performed on all residential developed properties to identify areas with elevated risk for septic system malfunction or failure based on soil constraints, including filtering capacity, flooding, depth to bedrock, depth to saturated zone, slope, and restricted permeability. Additional environmental considerations such as wetland proximity, stream buffer zones, and flooding potential were also incorporated into the analysis. Properties were categorized within a tiered structure based on their proximity to a combination of these environmental considerations. The risk assessment also considered potential for drinking water contamination based on the proximity to public wells.

168 properties are at high risk
for drinking water contamination based on either proximity to public wells, or septic system malfunction or failure due to soil and environmental conditions.

Properties with existing residential development as of the fiscal year 2024 assessors' parcel mapping dataset[68] were accepted as properties utilizing septic systems within Boxborough. These properties were mapped, and the following parameters were examined to determine areas within the watershed that may present challenges for septic systems.

1. Septic Tank Absorption Rating (NRCS)

The Natural Resources Conservation Service Soils Data layer in GIS supplies a Septic Tank Absorption Rating for properties within the watershed based on these soil and environmental parameters (as characterized by NRCS) that may constrain the effectiveness of traditional septic systems. The NRCS evaluates soil suitability using the following rating system:

Table 6.3 Septic Tank Absorption Rating Categories[69]

Category	Definition
Not Limited	Soils possess highly favorable features for the specified use, with good performance and minimal maintenance expected.
Slightly Limited	Soils have favorable features with minor limitations that can be easily overcome. Good performance and low maintenance are expected.
Somewhat Limited	Soils have moderately favorable features, and limitations can be overcome with special planning, design, or installation procedures. Fair performance and moderate maintenance are expected.
Very Limited	Soils have unfavorable features, and limitations are generally difficult and expensive to correct, requiring major soil reclamation, special field design, or intensive maintenance. Poor performance and high maintenance are expected.

[68] Town of Boxborough, 2025. MassGIS: Property Tax Parcels.
[69] NRCS, 2004. Septic Tank Absorption Ratings.

- **Filtration capability**: The saturated hydraulic conductivity of soil, designated as KSat, represents a crucial physical attribute that affects the soil's capacity to hold and transmit water. The soil layer with the highest Ksat determines the leaching and seepage potential (or filtration capability) of the soil profile. When this measurement is elevated, fluid movement through the soil occurs too readily, potentially causing leaching and seepage that could lead to environmental, health, and performance issues.
- **Flood susceptibility**: Flooding can mobilize waste materials and transport them to surface waters, resulting in contamination. Flood-prone areas also present limitations for construction, recreational use, and proper operation of sanitary facilities on these soils.
- **Water accumulation**: Standing water on the soil surface for specified durations, known as ponding, indicates soil conditions that restrict most land use applications. Analysis considers both the duration and frequency of such ponding events.
- **Proximity to bedrock**: Shallow depth to bedrock impedes the installation, construction, and proper functioning of septic absorption fields and related applications. These shallow soil profiles have reduced absorption capacity and insufficient biologically active zones for proper wastewater treatment, potentially creating environmental and public health concerns when used for effluent filtration.
- **Terrain gradient**: Septic absorption fields must not be positioned near cuts or on steep inclines, as wastewater may migrate laterally through the slope before adequate treatment occurs. Additionally, improperly placed septic systems can destabilize vulnerable slopes.
- **Water table depth**: Soils with minimal separation between the surface and water table may become saturated during precipitation events and drain poorly. These conditions increase the potential for groundwater contamination, presenting health and environmental hazards.
- **Downward percolation**: The bottom soil layer's KSat value determines the soil's leaching and seepage characteristics. Elevated values in this parameter allow unrestricted fluid transmission through the soil and underlying materials, potentially causing leaching and seepage that raise environmental, health, and performance concerns.
- **Limited permeability**: The soil horizon with the lowest KSat value controls water movement through the entire soil profile. When this measurement is low, fluid transmission into and through the soil is hampered, potentially causing runoff, reduced infiltration, and pollutant percolation that may create environmental, health, and performance issues.
- **Excessive gradient**: For unrated "rock outcrop" soil classifications, a maximum risk value of five was manually designated based on their extreme unsuitability for septic systems. For unrated "urban land" soil types, risk factors were assigned based on adjacent rated soils, typically adopting the highest nearby score (excluding water bodies). This conservative approach reflects the heightened consequences of wastewater failures near populated areas.

2. Wetland and Surface Water Proximity

The MassDEP Hydrography dataset[70] and the MassDEP Wetlands dataset[71] identifies all surface water and wetland features within the town. All septic systems positioned within 100 feet of wetlands or surface water bodies were identified in the analysis.

3. Flood Zones

Flood zones are geographic areas that the Federal Emergency Management Agency (FEMA) has categorized according to varying flood risk levels. Each designation reflects the expected severity or type of flooding for that area. This analysis identified Boxborough regions with the highest flooding potential as determined by FEMA. These areas, designated as Flood Zone A, face a 1% annual chance of flooding and a 26% chance of flooding during a standard 30-year mortgage period. Land susceptibility to flooding increases the probability of septic system failure or effluent transfer to nearby water bodies or wetlands.

4. MassDEP Wellhead Protection Area Zone I

MassDEP Wellhead Protection Area Zone I refers to the protective radius around a public water supply well or wellfield. This area is designed to safeguard the water source from potential contamination. Any properties that overlap a MassDEP Zone I are automatically categorized as a Tier 1 property, described below.

These soil characteristics and environmental factors were integrated with municipal property data through a GIS analysis, with each property assigned to a specific "Tier" or septic system category as outlined in Table 6.4. Properties were considered to be within a tier if any part of the parcel intersected with the data for that tier. Actual locations of septic systems were not included in this analysis, therefore the results do not necessarily indicate whether a septic system is within these boundaries.

As shown in Table 6.4 and Figure 6.3, there are 1,761 parcels in Boxborough, of which 1,357 have residential area listed in tax parcel data, which are assumed to rely on private septic systems. In total, 168 of these properties are considered "Tier 1" properties. These properties are most at risk for drinking water contamination based on either proximity to public wells, or septic system malfunction or failure due to soil and environmental conditions. An additional 491 properties are considered "Tier 2", which are properties that are at a lesser risk and are located in limited soils and within 100 feet of a water body. Tier 3 properties are those not meeting criteria for Tier 1 or Tier 2 classifications.

[70] MassDEP, 2019. MassGIS Data: MassDEP Hydrography.
[71] MassDEP, 2017. MassGIS Data: MassDEP Wetlands.

Table 6.4 Environmental Risk Assessment		
Category	Category Description	Number of Properties
Total Properties	Total Number of Properties in Boxborough	1,761
Estimated Properties with Septic Systems	Total properties with residential area listed in the MassGIS Tax Parcel Data	1,357
Tier 1	Properties situated within DEP Zone I; properties situated on limited soils, within the 1% FEMA Flood Zone, and located within the 100-foot buffer of a water body or wetland.	164
Tier 2	Properties situated on limited soils and located within the 100-foot buffer of a water body or wetland.	491
Tier 3	Properties not meeting criteria for Tier 1 or Tier 2 classifications.	701

6.5 Septic System Inventory

A septic system inventory was conducted to gather more information about septic systems in Boxborough. Title 5 inspection records were provided by the Nashoba Associated Board of Health (NABH), which maintains all septic system inspection records for the Town of Boxborough. The NABH serves as the regional health authority for multiple communities in the area and maintains detailed records of septic system installations, inspections, and compliance status in accordance with Massachusetts Title 5 regulations governing onsite wastewater treatment systems. More information on the Title 5 septic systems is provided in Section 7, Review of State and Local Regulations.

The inventory focused on Tier 1 septic systems, as these systems are located in areas of highest environmental risk, as described in Section 6.2. The inventory for Tier 1 septic systems includes system locations, ages, types, inspection dates, distance to well, and compliance status, when available. Of the 168 Tier 1 properties, Title 5 information was available for 73 septic systems. The inspection information reviewed for this inventory was the most recent inspection data for each property. Inspections were not available for all 168 properties as Title 5 inspections are primarily completed during property transfers or renovations that impact the septic system capacity. See Table 6.5 for the results of reviewing the available Title 5 information for Tier 1 properties.

Table 6.5 Tier 1 Septic System Assessment		
Pass (With or Without Conditions)	Fail	Total
64	9	73

Nine septic systems received an inspection result of "D – Fail". No additional inspections have been completed for these locations showing that the concern was rectified. Failures date from 2002 to 2022. Systems failed for a variety of reasons, including rotting or broken tank or distribution box, leaking, and leach pit located within the groundwater.

Table 6.6 provides a summary of additional inventory information for the 73 Tier 1 section systems. The detailed inspection data and system specifications collected during this inventory process can be found in Appendix C.

Table 6.6 Tier 1 Septic System Inspection Summary

Inspection Parameter	Range	Number of Systems
Age	Under 10 years old	0
	10-20 years old	13
	Greater than 20 years old	60
Date of Last Inspection	2015-2025	29
	2005-2014	33
	1995-2004	11
Distance to Well	Less than 10 feet	1
	10-39 feet	25
	40-99 feet	10
	100 feet or greater	22
	Unknown	15

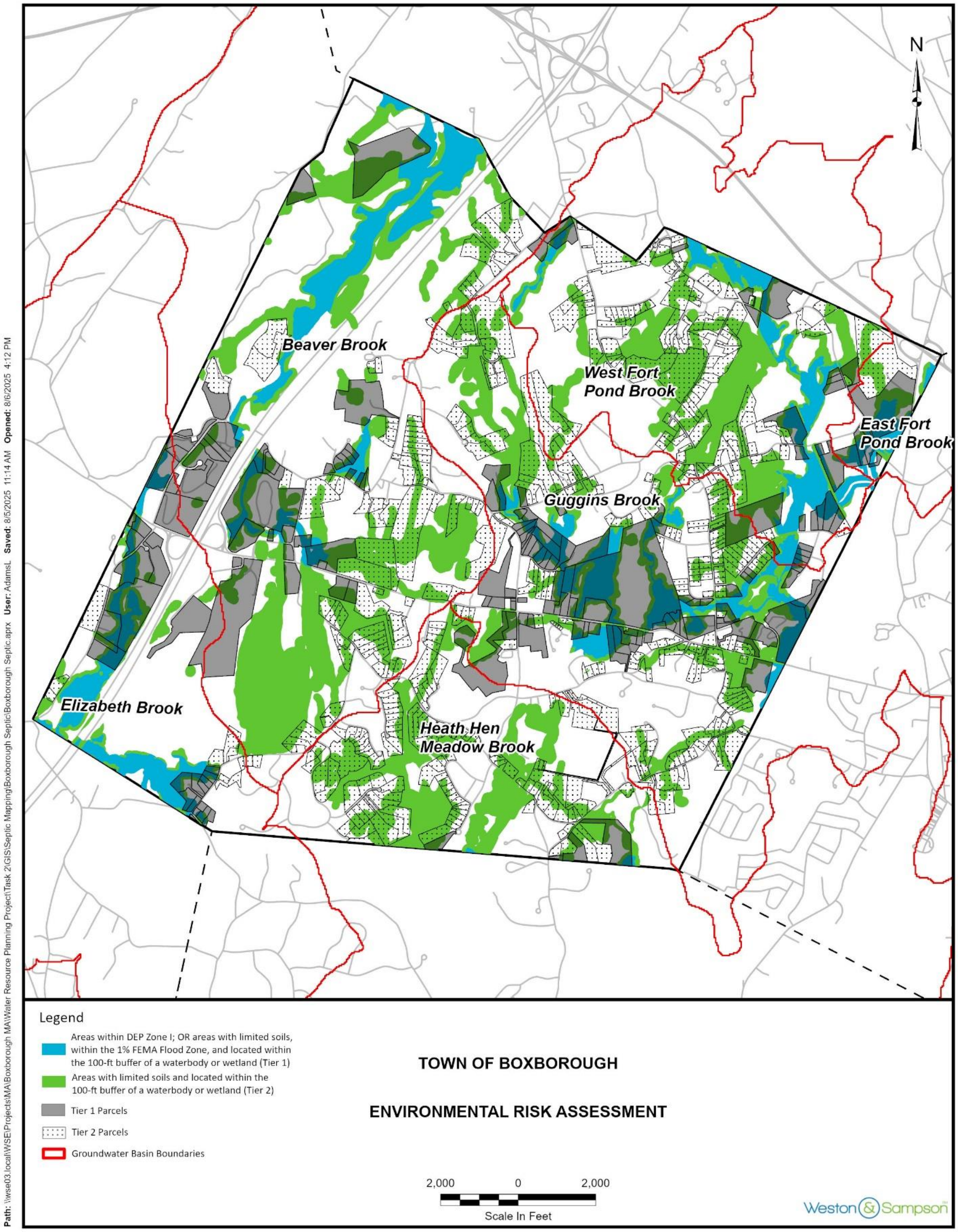

Figure 6.3. Environmental Risk Assessment Map

7.0 REVIEW OF STATE AND LOCAL REGULATIONS

In Massachusetts, water resources are governed by a complex framework of state and local regulations that oversee wastewater disposal, drinking water, and land use practices that affect aquifer recharge and water contamination risks. This section provides a review of the Commonwealth of Massachusetts's regulatory structure as it pertains to septic systems, drinking water supplies, and groundwater protection. It also includes an analysis of local regulations adopted by the Town of Boxborough with additional information from nearby communities such as Harvard and Stow.

7.1 Commonwealth of Massachusetts Regulations

7.1.1 Septic System Regulations

Septic systems are regulated by the Commonwealth of Massachusetts under Massachusetts General Laws (MGL) and the Code of Massachusetts Regulations (CMR). Specifically, MGL c. 21A, § 13 addresses the state environmental code and its adoption, including the preparation of sewage disposal systems and enforcement of the code. Additionally, 310 CMR 15.000 established minimum standards for the location, construction, and maintenance of on-site sewage disposal systems (septic systems) through a program known as Title 5.

The Massachusetts Title 5 Septic System Program, implemented in 1985 and continuously updated, governs the proper siting, construction, and maintenance of onsite wastewater disposal systems (septic systems) to protect public health and the environment. Title 5 regulations are administered locally by BOHs, with technical oversight and support from MassDEP. This framework operates under MGL, ensuring compliance with environmental and public health standards for wastewater and septic systems. Title 5 is enforced by local BOHs where duties lie in issuing permits, conducting inspections, and addressing violations. The key aspects of Title 5 include the following:

- **Inspection**: Title 5 inspections verify septic system compliance during property transfers or renovations. Local BOHs oversee these evaluations to prevent groundwater contamination.
- **Certification**: Passing inspection results in certification, valid for two to three years, confirming system functionality. Conditional passes require timely repairs.
- **Upgrade and Repair Requirements**: Failing systems must be upgraded within two years, with stricter standards in nitrogen-sensitive areas. Local BOHs enforce these timelines.
- **Maintenance**: Regular maintenance, including pumping and checks, is crucial for compliance. Educational resources guide proper care.
- **Alternative Treatment**: Innovative/Alternative systems enhance nutrient removal in sensitive areas, requiring MassDEP approval and specialized maintenance.

Title 5 also provides some guidance for those properties served by private drinking water wells. Specifically, it requires a water well analysis for fecal coliform, ammonia nitrogen, and nitrate nitrogen for those wells that are located greater than 50-feet but less than 100-feet to septic systems. In no case, under Title 5, are private wells allowed within 50-feet of a septic system.

7.1.2 Drinking Water Regulations

The Massachusetts Department of Environmental Protection (MassDEP) is granted general responsibility for protecting public drinking water supplies within the Commonwealth under Chapter 111 of the Massachusetts General Laws. Specifically, Section 159 gives MassDEP oversight of all inland and underground water. Section 160 authorizes MassDEP to make rules and regulations to prevent pollution and ensure sanitary protection of these waters. Additionally, Section 5G allows MassDEP to require treatment facilities necessary for safe water supply delivery. MassDEP also regulates drillers under Chapter 21G, requiring annual certification and reports after well completion. The Department also oversees wetland protection under Chapter 131, Section 40, to safeguard groundwater supplies.

MassDEP has a comprehensive Drinking Water Program (DWP) for public water systems to ensure that public water systems provide safe and potable drinking water. The MassDEP DWP does not regulate private wells. They do provide informational materials for private well owners. Resources provided are only informational to educate well owners about proper practices for safe water.

While MassDEP does not regulate private wells, they do provide information and guidance to local Boards of Health (BOHs), well drillers, and well owners in the Private Well Guidelines. These guidelines define private water supplies, assist well drillers with construction standards, and provide useful information for well owners.

There are some existing state regulations that are applicable to private wells. These include:

- 310 CMR 46.00 "Certification of Well Drillers and Filing of Well Completion Reports" mandates that well drillers must be certified annually by MassDEP. This regulation also requires drillers to submit a report detailing well construction within 30 days. Failure to comply with these requirements may result in penalties, including the revocation of a driller's certification.
- Under 310 CMR 27.00 "Underground Injection Control" it is illegal to use private wells, test holes, or other dry borings as receptables for hazardous waste or other containments.
- 310 CMR 15.000 "Septic Systems" established minimum standards for the location, construction, and maintenance of on-site sewage disposal systems (septic systems) through a program known as Title 5, including set-back distances for private wells from septic systems.
- MassDEP recommends regular water quality testing for private wells, though this is not legally required. Public water suppliers must test their water through MassDEP certified laboratories under 310 CMR 22.00 "Drinking Water" and 310 CMR 42.00 "Certification and Operation of Environmental Analysis Laboratories" and while private well owners are not subject to these requirements, these regulations include water quality standards that can be used to interpret results of tests performed on private well water samples.
- The Massachusetts Department of Agricultural Resources, through its Pesticide Board, established regulations under 333 CMR 11.00 "Rights of Way Management" to protect private drinking wells from contamination from herbicides. Private wells that are located within one hundred feet of a right-of-way are required to be marked and recorded before herbicide application. Additionally, no herbicide may be applied within fifty feet of a private well, and applications between fifty and one hundred feet must follow specific procedures to minimize contamination risks.

- The Massachusetts Department of Public Health (DPH) also plays a key role in regulating drinking water through **MGL Chapter 111, Section 127A**. Under this law, property owners must provide safe drinking water from either a public water system or an approved private source.

Local BOHs are responsible for private wells, but local regulations are varied, often outdated, or nonexistent. BOHs can take action to enforce regulations, including ordering compliance with regulations, or taking other actions deemed appropriate by the respective BOH.

7.2 Town of Boxborough Local Regulations

7.2.1 Septic System Regulations

The Town of Boxborough adopted the Subsurface Disposal of Sewage regulations on October 18, 2000. A draft revision of these regulations was completed in January 2025; the following section is based on the revised draft of these regulations. The Subsurface Disposal of Sewage regulations establish comprehensive requirements for the siting, design, construction, and maintenance of on-site wastewater systems in accordance with Massachusetts Title 5 (310 CMR 15.000). These regulations are administered by the Boxborough Board of Health in collaboration with Nashoba Associated Boards of Health. The key provisions of the regulation include:

- **Permitting and Inspection**: All system installations, repairs, and lot inspections require a permit and applicable fees. Nashoba BOH conducts field testing, plan reviews, and construction inspections prior to issuance of a Certification of Compliance.
- **System Siting and Design**: Disposal systems must be located entirely within the lot they serve. Shared systems across property lines are not allowed. Minimum soil depth for new construction is five feet. Setback distances from property lines, wells, and wetlands are strictly enforced.
- **Hydrogeologic Studies**: For lots under subdivision exemptions, the Board of Health may require a hydrogeologic analysis to evaluate collective impacts on groundwater quality.
- **Construction Standards**: Detailed specifications oversee leaching area sizing, perimeter drain design, separation from high groundwater, and use of retaining walls (which are restricted in new construction).
- **Maintenance and Repairs**: Septic tanks should be pumped at least every three years and more frequently for multifamily or commercials facilities. Repairs must be reported within seven days of system failure and brought into full compliance (passing) within six months.
- **Variances**: The Board of Health may grant variances where enforcement of these regulations would cause manifest injustice, provided the applicant can demonstrate that public health and environmental protection would not be compromised.
- **Enforcement**: The Nashoba Board of Health is authorized to revoke any approvals or certificates of compliance if they are found to be based on incomplete or inaccurate information.

7.2.2 Drinking Water Regulations

The Town of Boxborough's Well Regulations, amended on March 25, 2004, aim to protect public health and groundwater quality through strict oversight of private well construction, maintenance, and decommissioning. Authorized by MGL Chapter 111, Section 31, these regulations provide comprehensive requirements for the siting, installation, and destruction of private and irrigation wells within the Town. The key provisions of the Well Regulations include the following:

- Permitting and Oversight: All well construction or destruction activities require prior approval through a permitting process administered by the Nashoba Associated Boards of Health. The permitting process includes submission of detailed site plans and identification of contamination sources within a 400-foot radius of the well.
- Construction Standards: Wells must comply with U.S. EPA guidelines as outlined in the Manual of Individual Water Supply Systems. Specific distances from potential contamination sources such as septic systems, landfills, or wetlands are mandated to minimize groundwater contamination risk.
- Water Quality and Sampling: New wells are required to undergo water sampling for bacteria and potentially a chemical analysis. Only water that meets the standard of zero total coliform per 100 mL can be approved for potable use. Sampling must be conducted by certificated laboratories and coordinated with the Nashoba Board of Health.
- Well Abandonment: Abandoned wells are defined as wells that go unused for over a year and are not intended to be used again for supplying water. Abandoned wells must be properly sealed and reported. Destruction involves removing all infrastructure and restoring the land to its original grade to prevent safety hazards and aquifer contamination.
- Variances: The Board of Health may grant variances when strict enforcement would result in manifest justice, provided that public health and environmental protections remain uncompromised.

The Town of Boxborough Zoning Bylaw established the Aquifer Protection District (APD) to safeguard the town's groundwater resources. This overlay district is designed to preserve the quality and availability of groundwater by regulation land use practices that could adversely affect aquifer recharge areas. The key provisions include:

- Purpose: The APD aims to protect public health and safety by maintaining the purity and viability of the town's groundwater supply.
- Overlay District: The APD is superimposed over existing zoning districts, meaning that land within the APD is subject to both the underlying zoning regulations and additional requirements of the APD.
- District Boundaries: The boundaries of the APD are delineated on a map prepared for the Town of Boxborough, which identified significant aquifer areas. The Planning Board can commission a hydrogeological study to determine the precise location and extent of the aquifer or recharge area.

- **Special Permits**: The Zoning Board of Appeals serves as the Special Permit Granting Authority for the APD.
- **Use Regulations**: Certain activities are prohibited within the APD to prevent contamination of groundwater. These include but are not limited to:
  - Use of sodium salts, except on public highways in minimum amounts necessary for safety.
  - Storage of road salt or other de-icing chemicals, unless properly housed to prevent leaching.
  - Dumping of snow brought in from outside the APD.
  - Industrial uses that discharge processed wastewater on-site, except for the treatment of sanitary waste.
  - Use of septic tank additives, except for sulfuric acid or other biodegradable treatment performed by a licensed professional and supervised by the BOH.
  - Subsurface disposal of liquid or leachable waste other than sanitary waste.

These regulations are intended to prevent activities that could lead to the contamination of the town's groundwater resources.

Local BOHs are authorized, under MGL Chapter 111, Section 31 and 122, to oversee activities impacting groundwater quality. The Boxborough Board of Health adopted the Groundwater Protection Regulation on March 31, 2021, in response to growing concerns about the potential for contamination and hazardous materials and other pollutants. The regulation's primary goal is to protect both public and private drinking water supplies by establishing clear rules for activities taking place within designated groundwater protection areas.

The Groundwater Protection Regulation applies to facilities within Zone II and Interim Wellhead Protection Areas in Boxborough, as delineated in Figure 5.1 in this report. These zones represent critical areas that contribute water to shared wells and other drinking water sources. Activities within these areas are subject to enhanced scrutiny due to the increased risk they pose to groundwater quality.

To support effective enforcement, the regulation defines key terms and sets expectations for how materials with potential environmental impacts must be handled. For example, there are restrictions for the storage and disposal of hazardous substances with strict guidelines for any new or existing facility operating within a protected zone. Some activity areas such as automobile graveyards or on-site disposal of industrial waste sites may be prohibited from groundwater use entirely due to their high contamination risk.

All proposed developments or activities within the groundwater protection zones must undergo review and approval by the Boxborough BOH. This review process ensures that each activity aligns with the town's commitment to long-term groundwater safety and public health.

Surrounding towns Harvard and Stow have specific private well guidelines relating to testing requirements for property transfers. The Town of Harvard adopted private well water sampling and quality testing requirements for the sale of property in 2018 originally and most recently updated in

2023.[72] Harvard's regulations apply to private drinking wells located on properties being sold or where wells are newly constructed or rehabilitated. The Town of Stow Board of Health recommends that prior to selling, conveying, or transferring title to real property, the private well serving that property should be sampled and tested.[73] Both Harvard and Stow recommend sampling be conducted by a certified laboratory or authorized professional.

[72] Town of Harvard, 2023. Private Well Water Sampling and Quality Testing Requirements for the Sale of Property.
[73] Town of Stow, 2024. Private Well Regulations.

8.0 SUMMARY AND RECOMMENDATIONS

8.1 Recommendations

Based on this analysis, groundwater *quantity* appears to be sufficient for current and future drinking water needs, under current practices whereby most properties are served by their own private wells. However, further analysis of groundwater *quality* is needed to evaluate whether clean drinking water is available for all. Furthermore, if Boxborough had to develop a municipal water system, it is not clear whether a well(s) of sufficient capacity, and meeting the State's requirements, could be developed to access the water. The following recommendations may enhance Boxborough's water resource management and planning capabilities.

1. Develop educational materials for homeowners discussing septic system maintenance and drinking water well sampling.
2. Develop a townwide drinking water sampling program to assess the water quality of private wells.
3. Add to the septic system inventory by reviewing town files and Title 5 inspection information for all properties.
4. Expand this study beyond Boxborough's town boundaries to include more accurate withdrawal assessments for the entire groundwater basins.
5. Identify additional properties to be placed under protection for water supply purposes.
6. Evaluate the Town's firefighting needs.
7. Continue to discuss regional water supply options with neighboring towns, including an interconnection with the Massachusetts Water Resources Authority (MWRA).
8. Follow up with further evaluations recommended in this report, including additional work needed to address the water-related Actions in the Town's Master Plan.

8.2 Implementation Framework

Implementation requires coordination between town departments, particularly the Water Resources Committee, Board of Health, Planning Board, and Conservation Commission, as well as entities outside of Boxborough's boundaries such as the Nashoba Associated Board of Health and the neighboring communities of Littleton and Ayer. Technical expertise will be required for future modeling and the development of targeted sampling programs.

Budget planning should phase work across multiple fiscal years to manage costs while maintaining project momentum. Grant opportunities through state agencies and regional planning organizations may offset municipal expenses, particularly for regional basin analysis benefiting multiple communities.

Early coordination with state regulators will verify that data collection methodologies meet regulatory standards and support future permitting activities. Data collection often requires cooperation from private property owners and commercial entities. Community engagement will assist with data collection phases that rely on private property access and commercial property owner cooperation.

8.3 Potential Funding Sources

The identification of funding sources is preliminary and may vary depending on numerous factors. The Town of Boxborough has access to a variety of funding sources to support drinking water infrastructure improvements, particularly considering PFAS contamination and the absence of a municipal water system. Key funding opportunities include:

1. Massachusetts State Revolving Fund (SRF)

   Administered by the Massachusetts Clean Water Trust and MassDEP, the SRF offers low-interest loans and grants for water infrastructure projects. Boxborough has previously benefited from SRF funding through the Littleton Water Department's line extension initiative.

2. Emerging Contaminants in Small or Disadvantaged Communities (EC-SDC) Grant

   This federal grant program addresses contaminants such as PFAS in small or disadvantaged communities. Boxborough's Codman Hill Condominium Association received $930,000 through this program to connect with the Littleton Electric Light and Water Department.

3. Community Development Block Grant (CDBG) Program

   Managed by the Massachusetts Department of Housing and Community Development, CDBG funds support infrastructure projects that benefit low- and moderate-income residents, including drinking water improvements.

4. USDA Rural Development Water and Waste Disposal Loan and Grant Program

   This program provides long-term, low-interest loans and grants to rural communities (population under 10,000) for drinking water system development, including sourcing, treatment, storage, and distribution.

5. EPA Drinking Water State Revolving Fund (DWSRF)

   A federal-state partnership that funds infrastructure projects to help public water systems comply with the Safe Drinking Water Act. Administered by MassDEP, eligible projects include treatment facilities, distribution systems, and system consolidation.

6. Asset Management Planning Grant Program

   This Massachusetts program supports municipalities in creating and implementing asset management plans for water systems, including inventory development, risk analysis, and financial planning.

7. Section 319 and Section 604(b) Grants

   Funded under the Clean Water Act, these grants support water quality planning and implementation projects, including watershed planning and pollutant source identification.

8. Local and Legislative Appropriations

APPENDIX A

Boxborough's Public Water Supply Wells

MassDEP Public Water Supply Sources, filtered to Boxborough (48 results)

Source ID	Site Name	City/Town	DEP Region	Latitude	Longitude	Type	Zone II Number
2037007-01G	ROCK WELL 1 SWANSON (NORTH)	BOXBOROUGH	2	42.49	-71.54	GW	0
2037026-01G	BOXBORO GREEN PLAZA	BOXBOROUGH	2	42.49	-71.53	TNC	0
2037031-01G	BOXBOROUGH COMMONS (629 MASS AVE)	BOXBOROUGH	2	42.48	-71.51	TNC	0
2037002-03G	LEVERETT HOUSE WELL	BOXBOROUGH	2	42.49	-71.55	GW	0
2037008-05G	BOXBOROUGH REGENCY	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037002-05G	WINTHROP HOUSE WELL	BOXBOROUGH	2	42.5	-71.54	GW	0
2037030-02G	MASS. AVE. GULF	BOXBOROUGH	2	42.48	-71.54	TNC	0
2037007-02G	ROCK WELL 2 SWANSON (SOUTH)	BOXBOROUGH	2	42.49	-71.54	GW	0
2037020-01G	1300 MASS AVE	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037033-01G	NATIONAL TECHNICAL SYSTEMS	BOXBOROUGH	2	42.48	-71.53	NTNC	0
2037001-01G	ROCK WELL #1	BOXBOROUGH	2	42.48	-71.55	GW	0
2037021-01G	60 AND 70 CODMAN HILL RD	BOXBOROUGH	2	42.49	-71.55	NTNC	0
2037002-02G	ELIOT HOUSE WELL	BOXBOROUGH	2	42.49	-71.55	GW	0
2037027-01G	61 STOW RD. BLDG./THE MARKETPLACE	BOXBOROUGH	2	42.48	-71.51	NTNC	0
2037002-01G	DUNSTER HOUSE WELL	BOXBOROUGH	2	42.49	-71.55	GW	0
2037020-02G	1300 MASS AVE	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037012-01G	NASHOBA VALLEY OLYMPIA INC.	BOXBOROUGH	2	42.48	-71.49	TNC	0
2037025-02G	COSGROVE REALTY	BOXBOROUGH	2	42.51	-71.54	NTNC	0
2037017-01G	1414 MASS AVE BOXBOROUGH	BOXBOROUGH	2	42.49	-71.54	NTNC	0
2037037-02G	THE TAYLOR SCHOOL	BOXBOROUGH	2	42.49	-71.54	NTNC	0
2037038-01G	WELL 1	BOXBOROUGH	2	42.48	-71.52	GW	0
2037038-03G	WELL 3	BOXBOROUGH	2	42.48	-71.52	GW	0
2037019-01G	BOXBOROUGH EXECUTIVE OFFICE CENTER	BOXBOROUGH	2	42.49	-71.55	NTNC	0
2037007-03G	ROCK WELL 3 SPENCER	BOXBOROUGH	2	42.49	-71.54	GW	0
2037024-01G	155 SWANSON RD SYNQOR	BOXBOROUGH	2	42.49	-71.54	NTNC	0
2037028-01G	UNITED CHURCH OF CHRIST/DAYCARE	BOXBOROUGH	2	42.48	-71.51	NTNC	0
2037023-01G	330 CODMAN HILL ROAD	BOXBOROUGH	2	42.48	-71.55	NTNC	0
2037018-01G	159 SWANSON RD SETRA SYSTEMS INC	BOXBOROUGH	2	42.49	-71.54	NTNC	0
2037008-04G	BOXBOROUGH REGENCY	BOXBOROUGH	2	42.48	-71.55	NTNC	0
2037022-01G	85 SWANSON RD LLC	BOXBOROUGH	2	42.49	-71.55	NTNC	0
2037009-01G	ROCK WELL 1	BOXBOROUGH	2	42.48	-71.52	GW	0
2037014-02G	WELL # 2	BOXBOROUGH	2	42.48	-71.5	GW	0
2037018-02G	159 SWANSON RD SETRA SYSTEMS INC	BOXBOROUGH	2	42.49	-71.54	NTNC	0
2037002-04G	LOWELL AND DUDLEY HOUSES WELL	BOXBOROUGH	2	42.49	-71.55	GW	0
2037008-01G	BOXBOROUGH REGENCY	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037024-02G	155 SWANSON RD SYNQOR	BOXBOROUGH	2	42.49	-71.55	NTNC	0
2037036-02G	WELL 2	BOXBOROUGH	2	42.49	-71.54	GW	0
2037010-02G	BOXBOROUGH MUNICIPAL BUILDINGS	BOXBOROUGH	2	42.49	-71.5	NTNC	0
2037034-01G	CAMPANELLI DEVELOPMENT	BOXBOROUGH	2	42.5	-71.53	NTNC	0
2037025-01G	COSGROVE REALTY	BOXBOROUGH	2	42.51	-71.54	NTNC	0
2037013-02G	ROCK WELL # 2	BOXBOROUGH	2	42.48	-71.49	GW	0
2037006-01G	BEDROCK WELL # 1	BOXBOROUGH	2	42.48	-71.51	GW	0
2037008-03G	BOXBOROUGH REGENCY	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037036-01G	WELL 1	BOXBOROUGH	2	42.49	-71.54	GW	0
2037008-02G	BOXBOROUGH REGENCY	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037017-03G	1414 MASS AVE BOXBOROUGH	BOXBOROUGH	2	42.49	-71.54	NTNC	0
2037017-02G	1414 MASS AVE BOXBOROUGH	BOXBOROUGH	2	42.48	-71.54	NTNC	0
2037035-01G	BRIGHT HORIZONS DAYCARE	BOXBOROUGH	2	42.49	-71.55	NTNC	0

APPENDIX B

Groundwater Basin Recharge Rates

Groundwater Basin Estimated Recharge Rates per Surficial Geologic Unit								
Groundwater Basin	Surficial Geologic Unit	Area (mi^2)	Min Recharge Rate (in/yr)	Max Recharge Rate (in/yr)	Min Recharge Volume (MGY)	Max Recharge Volume (MGY)	Total Min Recharge (MGY)	Total Max Recharge (MGY)
Beaver Brook	Glacial Stratified Deposits (coarse)	5.24	17.5	28	1595	2552	2670	5778
	Swamp Deposits	2.06	7.5	22.5	269	808		
	Thin Till	5.21	7.5	22.5	679	2036		
	Thick Till	0.98	7.5	22.5	127	382		
Guggins Brook	Glacial Stratified Deposits (coarse)	1.81	17.5	28	552	883	1104	2538
	Swamp Deposits	0.84	7.5	22.5	110	329		
	Thin Till	2.94	7.5	22.5	384	1151		
	Thick Till	0.45	7.5	22.5	58	175		
Heath Hen Meadow Brook	Glacial Stratified Deposits (coarse)	1.35	17.5	28	412	659	967	2326
	Swamp Deposits	0.98	7.5	22.5	128	385		
	Thin Till	2.68	7.5	22.5	350	1049		
	Thick Till	0.60	7.5	22.5	78	233		
East Fort Pond Brook	Glacial Stratified Deposits (coarse)	0.18	17.5	28.2	54	87	511	1457
	Swamp Deposits	0.43	7.5	22.5	56	169		
	Thin Till	2.40	7.5	22.5	313	940		
	Thick Till	0.67	7.5	22.5	87	262		
West Fort Pond Brook	Glacial Stratified Deposits (coarse)	0.17	17.5	28	51	82	394	1111
	Swamp Deposits	0.45	7.5	22.5	59	177		
	Thin Till	2.10	7.5	22.5	273	820		
	Thick Till	0.08	7.5	22.5	11	32		

Groundwater Basin Estimated Recharge Rates per Surficial Geologic Unit								
Groundwater Basin	Surficial Geologic Unit	Area (mi²)	Min Recharge Rate (in/yr)	Max Recharge Rate (in/yr)	Min Recharge Volume (MGY)	Max Recharge Volume (MGY)	Total Min Recharge (MGY)	Total Max Recharge (MGY)
Elizabeth Brook	Glacial Stratified Deposits (coarse)	1.45	17.5	28	440	704	1134	2786
	Swamp Deposits	0.70	7.5	22.5	91	274		
	Thin Till	4.42	7.5	22.5	577	1730		
	Thick Till	0.20	7.5	22.5	26	77		
Total		**38.5**					**6,780**	**15,996**

APPENDIX C

Tier 1 Septic System Inspections

Street Name	Date Installed	System Type	System Size	Depth below grade	Number of Bedrooms	Date of Inspection	Inspection Results (A-E)	System Failures	Large System (Y/N)	Additional Notes	Distance to Well (ft)	Depth to Groundwater
Middle Rd	1995	Septic tank, distribution box, SAS	1000 gallons	18 in, riser 4 in	3	8/20/2024	B - Conditionally Passes	N	N	Distribution box is rotted	60 ft	13 ft
Guggins Ln	1973	Septic tank, distribution box, SAS	1000 gallons	Sewer - 14 in Tank - 4 in	4	8/3/2012	A - Pass	N	N	Septic has no signs of failure, clean and dry	>10 ft	6 ft
Guggins Ln	2005	Septic tank, distribution box, SAS	1500 gallons	Sewer - 22 in Tank - 1 ft	4	11/6/2009	A - Pass	N	N	System appears to be functioning properly without leakage. Tank to be pumped annually	50 ft	64 in
Inches Brook Ln	12/22/1993	Septic tank, distribution box, SAS	1000 gallons	Sewer - 2 ft Tank - 2 ft	4	7/1/2010	A - Pass	N	N	This report only describes conditions at the time of inspection and under the conditions of use at that time. This inspection does not address how the system will perform in the future under the same or different conditions of use. No signs of leakage in the system.	Unknown	6 ft
Whitcomb Rd	1995	Septic tank, distribution box, SAS	1000 gallons	Sewer - 20 in Tank - To grade	4	12/3/2004	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly.	>25 ft	10 ft
Middle Rd	10/15/1980	Septic tank, distribution box, SAS	1500 gallons	Sewer - 1 ft Tank - 8 in	4	8/3/2022	D - Fail	Y	N	Baffles on tank working properly, tank showed no signs of leakage. Tank was flooded at time of inspection. Sewer has no evidence of leakage. Clogged SAS leading to discharge or ponding of effluent on the surface of the ground.	100 ft	54 in
Prescott Rd	2000	Septic tank, distribution box, SAS	1500 gallons	Sewer - 19 in Tank - 10 in	4	9/8/2003	A - Pass	N	N	At the time of inspection, all system components appeared to be in good working order. System passes Title 5.	33+ ft	2.5 ft
Joseph Rd	1994	Septic tank, distribution box, SAS	1000 gallons	Sewer - Below cellar floor Tank - 65 in	4	10/25/2012	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly.	15 ft	> 8 ft
Joseph Rd	2008	Septic tank, distribution box, SAS	1500 gallons	Sewer - 1 ft Tank - 1 ft below grade with covers at grade	4	5/16/2019	A - Pass	N	N	System appears to be functioning properly at this time under its current usage.	100 ft	4 ft
Barteau Ln	9/20/2009	Septic tank, distribution box, SAS	1500 gallons	Sewer - 2 ft Tank - 19 in with a rise on outlet to 3" of grade.	4	3/2/2023	A - Pass	N	N	System appears to be functioning properly at this time under its current usage. Yearly pumping and cleaning of effluent filter on outlet tee recommended.	25 ft	24-33 in
Reed Farm Rd	1990	Septic tank, distribution box, SAS	1000 gallons	Sewer - 16 in Tank - 8 in	4	4/10/2025	B - Conditionally Passes	N	N	D-box is rotted and needs replacing.	25+ ft	6 ft
Eldridge Rd	Jun-88	Septic tank, distribution box, SAS	1000 gallons	Sewer - 24 in Tank - 12 in	4	4/17/2001	A - Pass	N	N	No evidence of leakage.	80+ ft	9 ft
Old Harvard Rd	1972	Septic tank, distribution box, SAS	1000 gallons	Sewer - 24" Tank - 18"	4	6/11/2002	D - Fail	Y	N	Recommend installing new septic system no leakage at tank	Unknown	26 ft
Old Harvard Rd	8/12/2003	Septic tank, distribution box, SAS	1500 gallons	Sewer - 20" Tank - 7" at inlet 9" at outlet	4	4/5/2021	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	100+ feet	45 feet

Street Name	Date Installed	System Type	System Size	Depth below grade	Number of Bedrooms	Date of Inspection	Inspection Results (A-E)	System Failures	Large System (Y/N)	Additional Notes	Distance to Well (ft)	Depth to Groundwater
Old Harvard Rd	1971	Septic tank, distribution box, SAS	1000 gallons	Sewer - 11" Tank - 12"	4	5/24/2018	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	108 feet	Unknown
Old Harvard Rd	1971	Septic tank, distribution box, SAS	1000 gallons	Sewer - 30" Tank - 10"	3	2/28/2007	B - Conditionally Passes	N	N	Distribution box in need of replacing	Unknown	8+ ft
Old Harvard Rd	1972	Septic tank and one leaching pit	Unknown	Sewer - 22" Tank - 13"	4	11/26/2003	D - Fail	Y	N	Leach pit is in the ground water, system needs an inlet baffle	Unknown	7 ft
Stow Road	1999	Shared System	4000 gallons	Sewer - 61" Tank - 2.6'	8	12/7/2023	A - Pass	N	N	Yearly service recommended	Unknown	4 ft
Old Harvard Rd	1971	Septic tank, distribution box, SAS	1000 gallons	Sewer - 50" Tank - 24"	4	4/12/2019	D - Fail	Y	N	An existing 1000 gallon septic tank that is cracked, a dbox that is broken in several pieces, and a leach bed that has been dug up for some reason top layer excavated, only broken orangeburg piping laying there	Unknown	8+ ft
Kendall Rd	1965	Septic tank, distribution box, SAS	Unknown	Sewer - 20" Tank - 10"	3	5/14/2012	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	Unknown	5 ft
Codman Hill Rd	1980	Septic tank, distribution box, SAS	1000 gallons	Sewer - 26" Tank - 16"	ommercial office	5/16/2005	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	25+ ft	6'3"
Massachusetts Ave	2000	Septic tank, distribution box, SAS	1500 gallons	Sewer - 30" Tank - 10"	3	10/2/2014	A - Pass	N	N	Tank is in good condition. Recommended yearly pumping.	28'	7'
Liberty Square Road	1997	Septic tank, distribution box, SAS	4000 gallons	Sewer - 20" Tank - 16"	20	4/20/2022	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	500+ ft	6'
Macintosh Ln	2002	Septic tank, distribution box, SAS	Unknown	Sewer - to grade Tank - to grade	50	6/10/2014	A - Pass	N	N	All appears in good working order	Unknown	10 ft
Hughes Ln	2006	Septic tank, distribution box, SAS	1500 gallons	Sewer - 18" Tank - 3"	5	5/21/2018	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	25+ ft	30"
Massachusetts Ave	1989	Septic tank, distribution box, SAS	1000 gallons	Sewer - 5" Tank - 2"	3	3/7/2016	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	30+ ft	6'6"
Russet Ln, 1A	2005	Shared System	6 3,000 gallon tanks 1 2000 gallon secondary tank	Sewer - 36" Tank - 26"	60	3/21/2022	A - Pass	N	N	All system components working properly. Cleaning and water jetting of all sewer inverts onsite recommended.	10' +	13'4"
Sara's Way	2010	Septic tank, distribution box, SAS	1500 gallons	Sewer - 16" Tank - 10"	4	1/40/2020	A - Pass	N	N	All appears in good working order	100'+	53"
Massachusetts Ave	1960-1965	Septic tank, distribution box, SAS	Unknown	Sewer - 14" Tank - 5"	4	9/8/2010	A - Pass	N	N	All appears in good working order	20'	Greater than 5 ft
Massachusetts Ave	Unknown	Septic tank, SAS	Unknown	Unknown	3	3/29/2002	D - Fail	Y	N	Clogged SAS couching static liquid level to be high	Unknown	Unknown
Hughes Ln	2005	Septic tank, distribution box, SAS	Unknown	Sewer - 1" Tank - 7"	4	5/22/2022	B - Conditionally Passes	N	N	Distribution box is rotted and needs replacement	25'+	39"
Guggins Ln	1974	Septic tank, distribution box, SAS	Unknown	Sewer - 22" Tank - 30"	4	6/8/2018	A - Pass	N	N	No signs of leakage in the system. System is functioning and flowing correctly under its current usage.	100+'	5'
Massachusetts Ave	Unknown	Single Cesspool	Unknown	Sewer - 1'	3	2/2/2005	A - Pass	N	N	System was working properly	65'	20'+

Street Name	Date Installed	System Type	System Size	Depth below grade	Number of Bedrooms	Date of Inspection	Inspection Results (A-E)	System Failures	Large System (Y/N)	Additional Notes	Distance to Well (ft)	Depth to Groundwater
Massachusetts Ave	1963	Septic tank, distribution box, SAS	500 gallons	Sewer - 8" Tank - 4"	Office	4/11/2022	A - Pass	N	N	No evidence of failure	135'	84"
Massachusetts Ave	1998	Septic tank, distribution box, SAS	1500 gallons	Sewer - 16" Tank - 6"	Office	10/10/2007	A - Pass	N	N	No evidence of failure	20'	4'
Middle Rd	1984	Septic tank, distribution box, SAS	1000 gallons	Sewer - 16" Tank - 6"	3	11/18/2019	B - Conditionally Passes	N	N	D-box is rotted and needs replacing.	15'	4+'
Cobleigh Rd	1978	Septic tank, distribution box, leaching field	1000 gallons	Sewer - 2'6" Tank - 12"	4	5/7/2010	A - Pass	N	N	System was working properly	100+'	5 ft
Liberty Square Road	1995	Septic tank, distribution box, SAS	1000 gallons	Sewer - 29" Tank - 18"	4	5/9/2013	B - Conditionally Passes	N	N	D-box is rotted and needs replacing.	50'+	4'+
Blanchard Rd	1991	Septic tank, distribution box, SAS	1000 gallons	Sewer - 2 ft Tank - 5"	4	4/16/2019	A - Pass	N	N	System was working properly	4"	5 ft
Massachusetts Ave	1982, D-box replaced 1997	Septic tank, distribution box, SAS	1000 gallons	Sewer - 4 ft Tank - 42"	Office	9/21/2010	A - Pass	N	N	System was working properly with no sign of leakage	100'	3.5' from bottom of septic system
Liberty Square Road	2005	Septic tank, distribution box, SAS	1000 gallons	Sewer - 34" Tank - 24"	3	8/31/2002	A - Pass	N	N	System was working properly with no sign of leakage	15-20'	6'+
Codman Hill Rd	1987	Septic tank, distribution box, SAS	12,000 gallons, 4,000 gallons, and 2,500 gal grease	Sewer - 2' and 4' Tank - 2'-3' with covers to grade	Office	7/20/2008	A - Pass	N	N	System was working properly with no sign of leakage	Unknown	10+'
Boxmill Road	1975	Septic tank, distribution box, SAS	1000 gallons	Sewer - 77" Tank - 66"	4	10/2/2000	A - Pass	N	N	System was working properly with no sign of leakage	Unknown	>5'
Liberty Square Road	2005	Septic tank, distribution box, SAS	Unknown	Sewer - 12" Tank - 9"	4	8/23/2012	A - Pass	N	N	System was working properly with no sign of leakage	80'	4'
Box Mill Road	1994	Septic tank, distribution box, SAS	1000 gallons	Sewer - 29" Tank - 2'	4	8/31/2013	B - Conditionally Passes	N	N	Distribution box is corroded and needs to be replaced	100+'	>7'8"
Middle Rd	1979	Septic tank, SAS	1500 gal	Sewer - 29" Tank - 2'	4	5/23/2005	A - Pass	N	N	System was working properly with no sign of leakage. Annual pumping is recommended	134'	6'6"
Middle Rd	1970	Septic tank, distribution box, SAS	1000 gallons	Sewer - 20" Tank - 10'	4	9/25/2001	A - Pass	N	N	System was working properly with no sign of leakage	100+'	54"
Reed Farm Rd	1994	Septic tank, distribution box, SAS	1000 gallons	Sewer - 6" Tank - 12'	4	8/20/2003	A - Pass	N	N	System was working properly with no sign of leakage	Unknown	4+'
Joseph Rd	1996	Septic tank, distribution box, SAS	1000 gallons	Sewer - 16" Tank - 6'	4	7/9/2007	A - Pass	N	N	System was working properly with no sign of leakage	Unknown	4.5'
Liberty Square Road	1972	Septic tank, distribution box, SAS	1000 gallons	Sewer - 1.6 ft Tank - 1.1 ft	4	5/24/2012	B - Conditionally Passes	N	N	Outlet baffle on tank has a hole and should be replaced with an outlet tee. Distribution box needs to be replaced.	Unknown	5.5'
Joseph Rd	1996	Septic tank, distribution box, SAS	1000 gallons	Sewer - 72" Tank - 36" at inlet and 27" at outlet	4	6/28/2013	B - Conditionally Passes	N	N	Distribution box is rotted and needs replacement	50+'	11'+
Depot Rd	1968	Septic tank, distribution box, SAS	1000 gallons	Sewer - 1.3' Tank - 0.8'	4	4/6/2011	B - Conditionally Passes	N	N	Distribution box is corroded and needs to be replaced	Unknown	4+'
Old Orchard Lane	1984	Septic tank, distribution box, SAS	1000 gallons	Sewer - 16" Tank - 6"	4	4/4/2006	A - Pass	N	N	System was working properly with no sign of leakage	25+'	10'
Hill Road	1997	Septic tank, distribution box, SAS	1500 gallons	Sewer - 20" Tank - 10"	4	4/4/2005	A - Pass	N	N	System was working properly with no sign of leakage	30'	4'

Boxborough Title 5 Inspections
Tier 1 Septic Systems

Street Name	Date Installed	System Type	System Size	Depth below grade	Number of Bedrooms	Date of Inspection	Inspection Results (A-E)	System Failures	Large System (Y/N)	Additional Notes	Distance to Well (ft)	Depth to Groundwater
Hill Road	2005	Septic tank, distribution box, SAS	1500 gallons	Sewer - 4" Tank - 12" with a manhole on center cover to 8" of grade	4	8/28/2013	A - Pass	N	N	System was working properly with no sign of leakage	50+'	18"
Sargent Road	1963	Septic tank, distribution box, SAS	900 gallons	Sewer - 12" Tank - 18"	3	6/20/2008	D - Fail	Y	N	Backup of sewage into facility and static liquid level in the distribution box above outlet	100+'	2'
Depot Rd	1976	Septic tank, distribution box, SAS	1000 gallons	Sewer - 8" Tank - 12"	3	4/15/2013	D - Fail	Y	N	Box is level and distribution outlets are not equal. Box is rotted.	100+'	5.5'
Prescott Rd	1967	Septic tank, distribution box, SAS	1000 gallons	Sewer - 20" Tank - 14"	3	5/23/2016	B - Conditionally Passes	N	N	Distribution box is heavily deteriorated and leaking	20'	5'
Barteau Ln	2002	Septic tank, distribution box, SAS	1500 gallons	Sewer - 6" Tank - 6"	4	11/8/2013	A - Pass	N	N	No evidence of any problems on this day of inspection	100+'	6+'
Liberty Square Road	1972	Septic tank, distribution box, SAS	1000 gallons	Sewer - 30" Tank - 24"	4	9/17/2015	D - Fail	Y	N	Distribution is falling apart	24'	4'
Whitcomb Rd	1997	Tank and galleries	1500 gallons	Sewer - 5' Tank - 4.5'	3	8/14/2017	A - Pass	N	N	System was working properly with no sign of leakage	100+'	2+'
Whitcomb Rd	1993	Septic tank, SAS	1250 gallons	Sewer - 14" Tank - 9"	4	2/19/2004	A - Pass	N	N	System was working properly with no sign of leakage	40'	12'
Sargent Road	1976	Septic tank, distribution box, SAS	1000 gallons	Sewer - 9" Tank - 2"	4	8/3/2012	B - Conditionally Passes	N	N	D-box is deteriorated, unlevel, and showing signs of leakage.	20'	4+'
Littlefield Road	2009	Septic tank, distribution box, SAS	1500 gallons	Sewer - at grade Tank - at grade	4	7/6/2015	A - Pass	N	N	It was working ok and in ok condition on this day of inspection, recommendation for pumping is every two years	100+'	48"
Picnic St	1957	Septic tank, distribution box, SAS	750 gallons	Sewer - 16" Tank - 8"	4	10/10/2019	A - Pass	N	N	System appears to be functioning properly at this time	100'	6+'
Picnic St	1998	Septic tank, distribution box, SAS	1500 gallons	Sewer - 13" Tank -4"	4	5/20/2019	B - Conditionally Passes	N	N	Distribution box needs replacing	100+'	4+'
Liberty Square Road	1970	Septic tank, distribution box, SAS	1500 gallons	Sewer - 36" Tank -26"	3	12/22/2014	B - Conditionally Passes	N	N	Septic tank is badly deteriorated and not structurally sound. The distribution box is deteriorated and needs to be reaplaced.	22'	46"
School House Lane	1999	Septic tank, distribution box, SAS	1500 gallons	Sewer - 24" Tank -10"	4	2/9/2018	B - Conditionally Passes	N	N	Distribution box needs replacing	25+'	32"
Davidson Road	2010	Septic tank, distribution box, SAS	1000 gallons	Sewer - 24" Tank -12"	4	3/14/2025	A - Pass	N	N	Effluent filter should be cleaned every 6 months	25+'	4'
Liberty Square Road	1999	Septic tank, distribution box, SAS	1500 gallons	Sewer - 24" Tank -12"	4	3/26/2015	A - Pass	N	N	System appears to be in good condition. There is no sign of hydraulic failure	60'	120"
Davidson Road	1965	Septic tank, distribution box, SAS	Unknown	Sewer - 24" Tank -12"	4	9/4/2020	D - Fail	Y	N	Tank is rotted at water line and leaking out from side of tank	100+'	6-8'
Tokatawan Spring Ln	1999	Septic tank, distribution box, SAS	1500 gallons	Sewer - 16" Tank -10"	4	5/27/2014	A - Pass	N	N	System appears to be functioning properly at this time	100+'	3'
Hill Road	1965	Septic Tank with Leach Pit	Unknown	Sewer - 10" Tank -34"	2	9/13/2010	A - Pass	N	N	System appears to be functioning properly at this time	20'	4'

APPENDIX D

Townwide Water Balance Model

Development of a Townwide Water Balance Model

A water balance model is a powerful tool used by hydrologists, planners, and environmental engineers to understand how water moves through a specific area, ranging from a small watershed to an entire region. Water balance models account for the inputs, outputs, and changes in store of water across a landscape over time. By developing a water balance model, it can help communities make informed decisions about water supply, land use, development, and environmental protection.

Simply, a water balance model quantifies the difference between the amount of water entering a system and the amount of water leaving the system. The model considers natural processes like precipitation and evapotranspiration, as well as human activities such as water withdrawals and wastewater discharges. The figure below shows typical inflows and outflows of a water balance model and how they interact with each other.

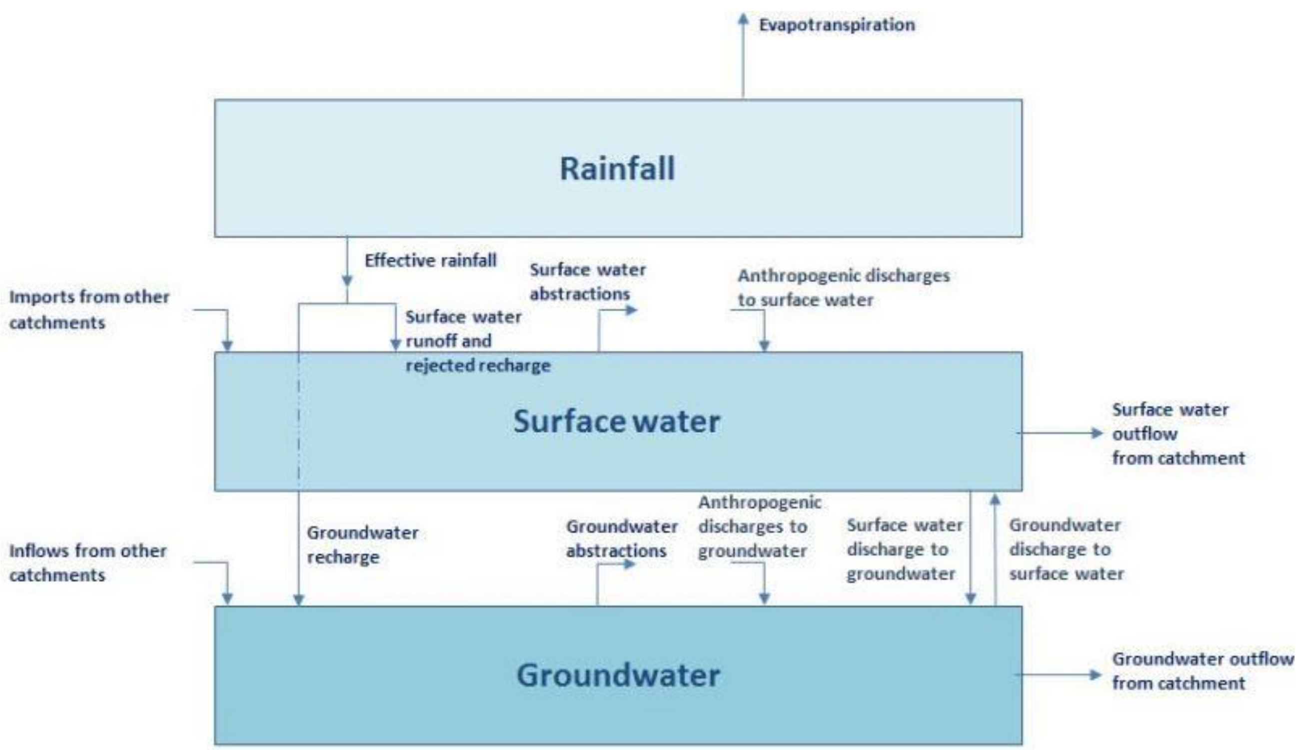

Figure 5.3. Components of Water Balance Model[1]

The goal of a water balance model is to have a comprehensive understanding of how water is gained, lost, and stored in a given area. Developing a townwide water balance model requires a comprehensive approach that integrates hydrologic, hydrogeologic, and water use data. A townwide water balance model is not just a technical exercise but a decision support tool that can help communities understand how their water systems function and how to manage them sustainably. Though developing a full water balance is beyond the scope of this report, a summary of the basic steps required to build a water balance model are discussed below and include:

[1] Water Balance, 2025. Geological Survey: Components of the Water Balance Assessment.

- Step 1: Data Collection: Gather all necessary data.
- Step 2: Understanding Inflows and Outflows: Determine all inflows and outflows.
- Step 3: Conceptual Model Development: Determine system representation and boundary conditions.
- Step 4: Numerical Modeling: Develop a quantitative model.
- Step 5: Water Balance Computation: Calculate water balance and run scenarios.

A detailed description of each step is provided below.

Step 1: Data Collection

The first step in developing a water balance model is data collection of extensive hydrologic, hydrogeologic, and water use data. Where available, existing data can be used. Additional data collection may also be required. Data can include the following:

- Precipitation and Evapotranspiration: Long-term climate records and national weather service gauge data are used to measure the water entering the system (precipitation) and water lost to the atmosphere (evapotranspiration).
- Surface Water and Groundwater Interactions: Understanding how aquifers, streams, and wetlands are connected is crucial. These relationships influence streamflow patterns and water quality.
- Aquifer Characteristics: Data on recharge rates, aquifer storage capacity, and hydraulic conductivity help describe how groundwater behaves in the system.
    - *For context, East Fort Pond Brook recharge rate ranges from 511 MGY to 1457 MGY (see Table 5.2 in Section 5.7 for detailed analysis on groundwater basin recharge rates)*
- Water Withdrawals and Discharges: Identifying all sources of water withdrawals—both public and private—and mapping wastewater discharges provide a picture of human impacts on the water system.
- Water Transfers: Any water imported into or exported out of the area must be included to ensure balance.
- Land Use: Land development affects runoff patterns and water demand, so understanding

Step 2: Understanding Inflows and Outflows

current and planned land uses is important.

After all necessary data has been collected, it is important to define all inflows (inputs) and outflows (outputs) and understand what they are and how they impact the water cycle.

- Inflows:

- Precipitation: Rainfall and snowfall that add water to the system.[2]
- Inflow Streams: Water entering the area via rivers and tributaries.[3]
- Runoff: Surface water that doesn't infiltrate the ground and flows to lower areas.[4]
- Wastewater Discharges: Treated effluent that is released back into the environment.

- Outflows:
  - Evaporation and Evapotranspiration: Sum of water lost to the atmosphere.[5, 6]
  - Groundwater Recharge: Water percolating into and replenishing aquifers.[7, 8]
  - Outflow Streams: Water leaving the area via streams or seepage to groundwater.
  - Water Supply Wells: Human withdrawals for public and private use.

Step 3: Conceptual Model Development

This step involves building a conceptual representation of the local hydrologic system:

- System Representation: Define key elements such as recharge areas, flow paths, aquifers, and discharge zones.
- Boundary Conditions: Define the spatial extent of the model and the boundary condition that influence water movement.

Step 4: Numerical Modeling

Once the conceptual model is complete, a quantitative model is developed using the following:

- Model Selection: Software such as MODFLOW may be used to simulate groundwater flow and interactions with surface water.
- Calibration and Validation: The model is adjusted using observed data to improve accuracy and then validated with independent datasets to ensure reliability.
- Scenario Analysis: Different management or environmental scenarios (e.g. increased withdrawals, urbanization, climate change) are simulated to evaluate potential impacts

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[2] National Geographic, 2025. Precipitation.
[3] USGS, 2019. Streamflow and the Water Cycle.
[4] National Geographic, 2025. Runoff.
[5] USGS, 2019. Evaporation and the Water Cycle.
[6] USGS, 2018. Evapotranspiration and the Water Cycle.
[7] USGS, 2018. Groundwater Decline and Depletion.
[8] ScienceDirect, 2022. Encyclopedia of Inland Waters.

Step 5: Water Balance Computation

Once the numerical model has been developed, all inflows, outflows, and changes in storage are accounted for, you will have a comprehensive understanding of the water dynamics within the system being modeled.

- Inflow and Outflow Quantification: Calculate all components of the water balance.
- Temporal and Spatial Analysis: The model can evaluate changes over different seasons, years, or geographic zones, identifying areas of concern like water deficits or unsustainable withdrawals.

The cost to develop a townwide water balance model can vary significantly based on the complexity of the town's water system, level of detail required in the model, and the data available.

APPENDIX E

PFAS Article

Environmental Science Processes & Impacts

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An overview of the uses of per- and polyfluoroalkyl substances (PFAS)†

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Per- and polyfluoroalkyl substances (PFAS) are of concern because of their high persistence (or that of their degradation products) and their impacts on human and environmental health that are known or can be deduced from some well-studied PFAS. Currently, many different PFAS (on the order of several thousands) are used in a wide range of applications, and there is no comprehensive source of information on the many individual substances and their functions in different applications. Here we provide a broad overview of many use categories where PFAS have been employed and for which function; we also specify which PFAS have been used and discuss the magnitude of the uses. Despite being non-exhaustive, our study clearly demonstrates that PFAS are used in almost all industry branches and many consumer products. In total, more than 200 use categories and subcategories are identified for more than 1400 individual PFAS. In addition to well-known categories such as textile impregnation, fire-fighting foam, and electroplating, the identified use categories also include many categories not described in the scientific literature, including PFAS in ammunition, climbing ropes, guitar strings, artificial turf, and soil remediation. We further discuss several use categories that may be prioritised for finding PFAS-free alternatives. Besides the detailed description of use categories, the present study also provides a list of the identified PFAS per use category, including their exact masses for future analytical studies aiming to identify additional PFAS.

Environmental significance

Per- and polyfluoroalkyl substances (PFAS) are a large group of more than 4700 substances that are used in a wide range of technical applications and consumer products. Releases of PFAS to the environment have caused large-scale contamination in many countries. For an effective management of PFAS, an overview of the use areas of PFAS, the functions of PFAS in these uses, and the chemical identity of the PFAS actually used is needed. Here we present a systematic description of more than 200 uses of PFAS and the individual substances associated with each of them (over 1400 PFAS in total). This large list of PFAS and their uses is intended to support the identification of essential and non-essential uses of PFAS.

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1 Introduction

Per- and polyfluoroalkyl substances (PFAS) are a class of thousands of substances[1,2] that have been produced since the 1940s and used in a broad range of consumer products and industrial applications.[3] Based on concerns regarding the high persistence of PFAS[4] and the lack of knowledge on properties, uses, and toxicological profiles of many PFAS currently in use, it has been argued that the production and use of PFAS should be limited.[5] However, there are specific uses that make an immediate ban of all PFAS impractical. Some specific uses of PFAS may currently be essential to health, safety or the functioning of today's society for which alternatives so far do not exist. On the other hand, if some uses of PFAS are found to be non-essential, they could be eliminated without having to first find alternatives that provide an adequate function and performance. To determine which uses of PFAS are essential and which are not, the concept of "essential use," as defined under the Montreal Protocol, has recently been further developed for PFAS, including illustrative case studies for several major use categories of PFAS.[6]

PFAS are costly to produce (*e.g.* fluorosurfactants are 100–1000 times more expensive than conventional hydrocarbon surfactants per unit volume[7]) and therefore are often used where other substances cannot deliver the required performance,[1] or where PFAS can be used in a much smaller amount and with the same performance as a higher amount of a non-fluorinated chemical. Examples are uses that operate over wide temperature ranges or uses that require extremely stable and non-reactive substances. The C–F bonds in PFAS lead to very stable substances, a feature that also makes the terminal transformation products of PFAS very persistent in the environment. Furthermore, the perfluorocarbon moieties in PFAS are both hydrophobic and oleophobic, making many PFAS effective surfactants or surface protectors.[8] PFAS-based fluorosurfactants can lower the surface tension of water from about 72 mN m^{-1} (ref. 9) to less than 16 mN m^{-1}, which is half of what is attainable by hydrocarbon surfactants.[8,10] Likewise, the surfaces of fluorinated polymers have about half the surface tension compared to hydrocarbon surfaces. For instance, a close-packed, uniformly organized array of trifluoromethyl ($-CF_3$) groups creates a surface with a solid surface tension as low as 6 mN m^{-1}.[11]

Due to these and other desirable properties, PFAS are used in many different applications. A good overview of the range of uses of PFAS as surfactants and repellents is provided in the monograph by Kissa (2001).[3] It lists 39 use categories, mostly derived from patents, and describes the functions of PFAS in these use categories. However, the work by Kissa (2001) was published nearly 20 years ago, focused on fluorosurfactants and repellents, and it is not clear which of these uses are still relevant today. In addition to Kissa (2001),[3] there are a few other monographs and a number of peer-reviewed scientific articles and reports that have looked into the uses of PFAS.[8,12–22] While these articles and reports provide useful information, each of them focuses on the uses of a specific PFAS group (in specific use categories). This is also the case for the reviews from the Persistent Organic Pollutants Review Committee (POPRC), the focuses of which are on perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), their precursors, and the PFAS that may be or have been introduced as replacements for these PFAS.[23–29] The FluoroCouncil[30] has provided additional information on uses of PFAS. However, the information is rather generic with limited details about specific uses and substances. Hence, a comprehensive overview that summarizes major current uses is missing.

The present paper, together with the Appendix (Table 4) and the ESI,† aims to provide a broad, but not exhaustive, overview of the uses of PFAS and associated individual substances (note that a working definition of PFAS is used here to define the scope of PFAS considered in this study, which is provided in the Methods section below). The paper addresses the following points: (i) in which use categories have PFAS been employed and for which functions? (ii) Which PFAS have been – and are still – used in a certain category? (iii) What is the extent of the uses in certain parts of the world? Within the European Union (EU), there are discussions underway for restricting PFAS to those uses that are essential,[31] and extensive information on many PFAS uses will be needed in this context. The present work also aims to support this process by showing in which specific applications PFAS are used, and in which functions, as a first step toward differentiating essential and non-essential uses of PFAS.

2 Methods

2.1 Which PFAS are addressed?

A first clear definition of PFAS was provided by Buck *et al.* (2011).[1] They defined PFAS as aliphatic substances containing the moiety $-C_nF_{2n+1}$ within their structure, where n is at least 1. The OECD/UNEP Global PFC Group noted that many substances containing other perfluorocarbon moieties (*e.g.* $-C_nF_{2n}-$) were not commonly recognized as PFAS according to Buck *et al.* (2011), *e.g.* perfluorodicarboxylic acids.[2] Considering their structural similarities to commonly recognized PFAS with the $-C_nF_{2n+1}$ moiety, the OECD/UNEP Global PFC Group proposed to also include substances that contain the moiety $-C_nF_{2n}-$ ($n \geq 1$) as PFAS.[2] However, the exact definition is still under discussion. The present study is in line with the OECD proposal in several, but not all, respects. In contrast to the definition by Buck *et al.* (2011), the present study also includes (i) substances where a perfluorocarbon chain is connected with functional groups on both ends, (ii) aromatic substances that have perfluoroalkyl moieties on the side chains, and (iii) fluorinated cycloaliphatic substances.

More specifically, the present study focuses on polymeric PFAS with the $-CF_2-$ moiety and non-polymeric PFAS with the $-CF_2-CF_2-$ moiety. It does not include non-polymeric substances that only contain a $-CF_3$ or $-CF_2-$ moiety, with the exception of perfluoroalkylethers and per- and polyfluoroalkylether-based substances. For these two PFAS groups, substances with a $-CF_2OCF_2-$ or $-CF_2OCFHCF_2-$ moiety are also included.

2.2 Literature sources

The present inventory was started with the risk profiles and risk management evaluations for PFOA, PFOS, PFHxS and their related compounds to obtain an overview of uses of these chemicals.[23–29] Reports and books that address fluorosurfactants and fluoropolymers in general were also included.[3,8,12,16,20,21,32–43] Literature specific to certain use categories was retrieved for more information either on the substances used, or to understand why PFAS are, or were, necessary for a given use. All specific references are cited in the ESI-1.†

In addition, databases, patents, information from PFAS manufacturers and scientific studies that measured PFAS in products were examined. These additional sources are described in more detail in the following subsections. The searches were not exhaustive in any of the sources described, and there are still many more reports, scientific studies, patents, safety data sheets and databases with information on the uses of PFAS than the ones cited here or in the ESI-1.†

The information in the Tables in the ESI-1† from these sources was marked according to its original source. Information from patents (cited in a book, article or report) was marked with "P", information on PFAS analytically detected in products with "D", and information on uses or information without additional reference with "U" for "use", or "U*" for "current use" (which is defined as a use with public record(s) of use from the last 4 years, *i.e.* 2017 or later).

2.2.1 Chemical data reporting under the US Toxic Substances Control Act. Manufacturers and importers that produced chemicals in amounts exceeding 25 000 pounds (11.34 metric tons, t, per year) at a site in the United States (US) between 2012 and 2015 were obliged to report to the US Environmental Protection Agency (US EPA) in 2016 (data for 2016 to 2019 will be reported in 2020). The data reported in 2016 included for each reported substance: the name, Chemical Abstracts Service (CAS) registry number and product categories for consumer and commercial uses and sectors, as well as function categories for industrial processing and use. The masses (tonnages) used and exported also had to be reported; however, they are in most cases confidential business information (CBI). The reported data were filtered according to chemical names containing the word "fluoro". Non-polymeric substances that did not contain the $-CF_2CF_2-$ moiety and polymeric substances that did not contain the $-CF_2-$ moiety subsequently were removed. This left 39 entries where a specific PFAS was applied in a consumer or commercial use, and around 120 entries where a specific PFAS was applied in an industrial processing or use. The entries are labelled with "U" for "use" in the Tables in the ESI-1 and ESI-3.†

2.2.2 Data from the SPIN database of Denmark, Finland, Norway and Sweden. The Substances in Preparations in Nordic Countries (SPIN) database contains information on substances from the product registries of Denmark, Finland, Norway and Sweden.[44] There are several cases in which substances do not need to be registered. For example, Denmark, Finland, Norway and Sweden exempt products that come under legislation on foodstuffs and medicinal products from mandatory declaration. Furthermore, the duty to declare products to the product registers does not apply to cosmetic products and there is in principle no requirement to declare solid processed articles to any of the registers. There is also a general exemption from the duty to declare chemicals in Sweden, Finland and Norway, if the quantity produced or imported is less than 0.1 t per year (in Finland no exact amount is given). Of the Nordic countries, only Denmark and Norway require information on all constituents for most products for which declaration is mandatory. In Sweden, substances that are not classified as dangerous and that make up less than 5 per cent of a product may be omitted from the declaration. In Finland, information on the composition of products is registered from the safety data sheets. Complete information on the exact composition is consequently not necessarily given.

The data that we used in the present study were extracted for us from the SPIN database by an employee of the Swedish Chemicals Agency (KEMI) and the data included only non-confidential information. However, there is also a substantial amount of confidential information in the SPIN database. This is visible when the substances are accessed *via* the web interface of the SPIN database.[44] It was also pointed out to us that not all substances have available use data due to confidentiality.

The database includes four large data sets with information on uses. Two of the data sets ("UC62" and "National use categories") contain information on specific use categories, while the other two ("Industrial NACE" and "Industry National") contain information on sectors of uses. In addition to the use categories and sectors of uses, the data sets also contain information on the quantities of a chemical used in a certain use category or sectors of uses if the reported mass exceeds 0.1 t. The available data cover the time period 2000 to 2017. The four data sets were merged and then (as with the TSCA Inventory data) filtered for chemicals containing the word "fluoro". Those non-polymeric substances that did not contain the $-CF_2CF_2-$ moiety and polymeric substances that did not contain the $-CF_2-$ moiety subsequently were removed. This left 950 entries. Entries with available data for 2017 were labelled as "current use" (U*) in the Tables in the ESI-1 and ESI-3,† all other entries with "U" for "use".

2.2.3 Patents. Another important source of information is the patent literature. Patents were searched for *via* SciFinder^n[45] (which is the newest version of SciFinder) and Google Patents.[46] The patent search in SciFinder^n was mostly conducted *via* keywords and the constraint that the patent must contain a substance with the $-CF_2-CF_2-$ moiety. This can be done in SciFinder^n by using the "draw" function. Google Patents was mainly used to search for a full patent text (*via* the patent number) when SciFinder^n only provided the abstract of the patent. The advantage of SciFinder^n (which belongs to CAS) is that experts manually curate the substances described in the patents and provide CAS numbers. All substances identified in the patent are visible in SciFinder^n together with the patent. Through the patents it was possible to determine in which applications PFAS may be used. While it is not possible to determine whether licenses for a patent have been obtained, the status of the patent (*e.g.* active, withdrawn, expired, not yet granted) can be determined. Active patents become expensive for their owners over the years. Representatives from CAS informed us that it is very likely that a patent is still in use if it is still paid for after 10 to 15 years.[47] After 20 years, a patent expires, which means that the invention can be used by others free of cost. Note that many patents cover not just a specific substance, but rather a basic structure to which different functional groups can be attached. The SciFinder^n experts assign CAS numbers to those substances whose existence has been proven by the registrants. Such a proof can be a physical method or the description in a patent document example or claim. Still, it is not always clear which substances are actually used in practice. Patents were found for many uses, and the patented substances are included in the Table in the ESI-1,† labelled with "P" for "patent".

2.2.4 Information from companies that manufacture or sell PFAS. 3M, Chemours, DuPont, F2 Chemicals, Solvay, and other PFAS manufacturers describe on their webpages which products they make and what these can be used for. Separate factsheets are also available for some of the products, for example, for fluorocarbons from F2 Chemicals,[48] 3M™ Novec™ Engineered Fluids[49–52] or Vertrel™ fluids from Chemours.[53] The difficulty with this information is that it often does not specify which substances are contained in the products. Sometimes the safety data sheets provide information about the composition of the products, but in most cases they do not. Dozens of factsheets and safety data sheets were screened for the present study and the information on the PFAS they contained was extracted. However, it was not feasible, in a reasonable amount of time, to examine all factsheets and safety data sheets of the major PFAS manufacturers. The data included in the Table in the ESI-1† are labelled with "U" for "use".

2.2.5 Studies that measured PFAS in products. There are also numerous individual studies that analysed PFAS in products, for example in apparel,[54,55] building materials,[56] hydraulic fluids and engine oils,[57] impregnation sprays,[58,59] fire-fighting foams,[60–65] food packaging materials,[66,67] or various other consumer products.[33,68–75] These studies are important because they show in which products PFAS exist. However, in most studies only a handful of substances were analysed and even for these substances it is not clear whether they were used intentionally, impurities in the actual substances, or degradation products. The data included in the Tables in the ESI-1† are labelled with "D" for "detected analytically".

2.2.6 Market reports. A variety of non-verified commercial market reports exist for PFAS. Examples are the Fluorotelomer Market Report, Fluorochemicals Market Report or the Perfluoropolyether Market Report from Global Market Insights.[76–78] The information from these reports is not included in this study as these reports do not state their information sources and thus cannot be verified.

2.3 Nomenclature

In the present study, a distinction is made between use categories and subcategories. A use category can, but does not necessarily, have subcategories. An example of a use category for PFAS is sport articles; a subcategory under sport articles is tennis rackets.

A distinction is also made between use, function and property. The "use" is the area in which the substances are employed. This can either be the use category or the subcategory. The "function" is the task that the substances fulfil in the use, and the "properties" indicate why PFAS are able to fulfil this function. An example for a use would be chrome plating. In chrome plating, PFAS have the *function* to prevent the evaporation of hexavalent chromium(VI) vapour, because of the PFAS *properties* that lower the surface tension of the electrolyte solution and since the PFAS used are stable under strongly acidic and oxidizing conditions.[3]

In the present study, the term "individual PFAS" always refers to substances with a CAS number, irrespective of whether they are mixtures, polymers or single substances.

2.4 Classification of use categories

The use categories in the present study were developed and refined throughout the course of the project to have as few well-defined use categories as possible that were not too broad. Initially, the use categories as defined by Kissa (2001)[3] were employed, but they are very specific and thus broader categories were needed to cover the identified uses. Examples of use categories from Kissa (2001) which were assigned to broader categories are "moulding and mould release" (in the present study a subcategory under "production of plastic and rubber"), "oil wells" (in the present study a subcategory with a slightly different name under "oil & gas"), and "cement additives" (in the present study a subcategory under "building and construction"). In the course of the project, more use categories were defined as additional uses were added. The use categories in the present study were finally divided into "industrial branches" and "other use categories" to make a distinction between use categories that define broad industrial branches such as the "semiconductor industry" or the "energy sector", and use categories that are more specific such as "personal care products" or "sealants and adhesives". Note that some of the "other use categories" may be applied to several of the "industry branches". For example, "wire and cable insulations" may be applied in "aerospace", "biotechnology", "building and construction", "chemical industry" and others. A detailed overview of the use categories and their subcategories is provided in the Appendix (Table 4) of this paper.

Overall, the use categories defined in the present study are very similar to the categories of the SPIN database, although some categories of the SPIN database are more specific (and correspond to subcategories in the present study). Some of the categories in the SPIN database could not be assigned to any of the use categories in the present study because they were too general. Examples are "impregnation", "surface treatment", "anti-corrosion materials" or "manufacture of other transport equipment". Although the substances from these categories are not included in the present study, their quantities appear in Fig. 3 under "various".

2.5 What kind of information can be found where in this article?

The present study comes with an Appendix (Table 4) that lists the functions of the PFAS in the use categories and subcategories that we identified. In addition, we indicate which properties of the PFAS are important for the identified function. The Appendix thus contains the main results of the present study in a condensed form and is therefore part of the main paper and not part of the ESI.†

The ESI† of the present study is divided into three parts. ESI-1† is a comprehensive document with over 250 pages. It is available as a pdf, but can also be provided upon request as an MS Word document. ESI-1† is intended to be used as a reference document and contains a detailed description of all uses that were collected here as well as the PFAS employed in these categories with names, structural formulas and CAS numbers. Before reading sections of the ESI-1,† it is recommended to study the first two pages of the ESI-1,† where some of the specific features of the document are explained.

In addition, there is an MS Excel workbook (ESI-2†) that contains all PFAS that appear in ESI-1.† This workbook has a worksheet for each of the most common PFAS groups such as perfluoroalkyl acids (PFAA), perfluoroalkane sulfonyl fluoride (PASF)-based substances, or fluorotelomer-based substances and, thus, offers a good overview of the described PFAS. A list of what is included in the different worksheets is provided in the first worksheet. ESI-2† is primarily intended as a reference for readers who do not have access to SciFinder^n or other chemical databases or who just want to look up the name or structural formula for a specific CAS number. In addition to name, CAS number, and structural formula, ESI-2† also contains the identified uses of each PFAS. In contrast to ESI-1, ESI-2† assigns the uses to the PFAS (and not the PFAS to the uses).

The third part of the ESI-3† is also an Excel workbook that provides a separate worksheet for each use category. These worksheets list the PFAS from the ESI-1† with the names, CAS numbers, elemental compositions, and exact monoisotopic masses of the substances. Our intention is that the lists can be added to accurate mass spectrometry libraries and thus help to identify unknown PFAS more easily in the future. For this purpose, it would be helpful to connect the CAS numbers in the ESI-3† with *e.g.* the Norman SusDat ID of the NORMAN Substance Database[79] and perhaps to commercial mass spectrometry libraries in the future.

Table 1 Industry branches and other use categories where PFAS were or are employed. The numbers in parentheses indicate the number of subcategories. No parentheses indicate no subcategories

Industry branches	
Aerospace (7)	Mining (3)
Biotechnology (2)	Nuclear industry
Building and construction (5)	Oil & gas industry (7)
Chemical industry (8)	Pharmaceutical industry
Electroless plating	Photographic industry (2)
Electroplating (2)	Production of plastic and rubber (7)
Electronic industry (5)	Semiconductor industry (12)
Energy sector (10)	Textile production (2)
Food production industry	Watchmaking industry
Machinery and equipment	Wood industry (3)
Manufacture of metal products (6)	
Other use categories	
Aerosol propellants	Metallic and ceramic surfaces
Air conditioning	Music instruments (3)
Antifoaming agent	Optical devices (3)
Ammunition	Paper and packaging (2)
Apparel	Particle physics
Automotive (12)	Personal care products
Cleaning compositions (6)	Pesticides (2)
Coatings, paints and varnishes (3)	Pharmaceuticals (2)
Conservation of books and manuscripts	Pipes, pumps, fittings and liners
Cook- and bakingware	Plastic, rubber and resins (4)
Dispersions	Printing (4)
Electronic devices (7)	Refrigerant systems
Fingerprint development	Sealants and adhesives (2)
Fire-fighting foam (5)	Soldering (2)
Flame retardants	Soil remediation
Floor covering including carpets and floor polish (4)	Sport article (7)
Glass (3)	Stone, concrete and tile
Household applications	Textile and upholstery (2)
Laboratory supplies, equipment and instrumentation (4)	Tracing and tagging (5)
Leather (4)	Water and effluent treatment
Lubricants and greases (2)	Wire and cable insulation, gaskets and hoses
Medical utensils (14)	

3 Results

In the present study, more than 200 uses in 64 use categories were identified for more than 1400 individual PFAS. This means that the present study encompasses five times as many uses (counted as use categories plus subcategories) than included in Kissa (2001).[3] This shows that our present study goes much further than simply updating this previous work. The following subsections describe the identified use categories and substances, and show and discuss the most important use categories in terms of quantities used, based on the data of the SPIN database and the Chemical Data Reporting database under the TSCA.

3.1 In which use categories have PFAS been employed and for which function?

The Appendix to the present study sets forth the use categories identified and answers the question of why PFAS were employed for a specific use. The use categories identified in this study are divided into "industry branches" and "other use categories", as listed in Table 1. In total, 87 uses within the 21 industry branches and 123 uses within the 43 other use categories were identified. Among the use categories, medical utensils, the semiconductor industry, and the automotive industries have the largest numbers of subcategories. About 15% of the subcategories were identified by patents, and 5% by studies that measured PFAS in products (see ESI-3†). The remaining categories have been mentioned previously in other publications.

The identified uses include many uses not previously described in the scientific literature on PFAS. Some examples of those uses are PFAS in ammunition (ESI-1 Section 2.4†), climbing ropes (ESI-1 Section 2.38†), guitar strings (ESI-1 Section 2.24†), artificial turf (ESI-1 Section 1.17†), and soil remediation (ESI-1 Section 2.37†). Also, additional subcategories of PFAS in already described use categories such as in the semiconductor industry were identified. For example, in addition to the subcategories etching agents, anti-reflective coatings, or photoresists, PFAS may also be employed for wafer thinning (patent US20130201635 from 2013)[45] and as bonding ply in multilayer printed circuit boards (patent WO2003026371 from 2003) in the semiconductor industry.[45] In the energy sector, PFAS are known to be employed in solar collectors and photovoltaic cells, and in lithium-ion, vanadium redox, and zinc batteries. In addition, fluoropolymers are also used to coat the blades of windmills[13] and PFAS can be employed in the continuous separation of carbon dioxide in flue gases (patent CN106914122 from 2017)[45] and as heat transfer fluids in organic Rankine engines.[48] These examples all show that the uses of PFAS are much more extensive than so far reported in the scientific literature.

Altogether, we were able to identify almost 300 functions of PFAS (listed in the Appendix). Examples of those functions are foaming of drilling fluids, heat transfer in refrigerants, and film forming in AFFFs. The properties that led to the use of the PFAS are also identified. These include among others: ability to lower the aqueous surface tension, high hydrophobicity, high oleophobicity, non-flammability, high capacity to dissolve gases, high stability, extremely low reactivity, high dielectric breakdown strength, good heat conductivity, low refractive index, low dielectric constant, ability to generate strong acids, operation at a wide temperature range, low volatility in vacuum, and impenetrability to radiation. In the Appendix (Table 4), these properties are assigned to the specific uses (and functions).

3.2 Which PFAS have been – and are still – used in a certain category?

The ESI-1† to the present study describes or lists those PFAS that have been or are currently employed (or have been patented) for each individual use. In total we have found uses for more than 1400 individual PFAS. About one third of these PFAS are also listed in the OECD list.[2] This shows that many of the PFAS listed in the present study are on the market, and that many more PFAS that are not on the OECD list may be used or are already being used.

Due to the great variety of uses and the large number of PFAS, it is difficult to make generic statements here. Overall, it was found that the number of different PFAS identified for a certain use mostly depends on the properties required for that use. Some properties, or combinations of properties, are only found in specific groups of PFAS. For example, perfluorocarbons seem to be particularly well suited as vehicles for respiratory gas transport due to the high solubility of oxygen therein. Similarly, anionic PFAS (largely those with a sulfonic acid group) are used as additives in brake and hydraulic fluids due to their ability to alter the electrical potential of the metal surface and thus, protect the metal surface from corrosion through electrochemical oxidation. In contrast, there are also properties that are shared by many different groups of PFAS. Many PFAS are very stable and many can reduce the surface tension of aqueous solutions considerably, improving wetting and rinse-off. Therefore, a typical use in which many different types of PFAS have been or are used is in cleaning compositions. The patented, analytically detected and employed PFAS for this use include PFAAs, PASF-based substances, and fluorotelomer-based substances (see ESI-1 Section 2.6.1†). A similar variety of PFAS (87 substances in total) were identified in patents for photographic materials to control surface tension, electrostatic charge, friction, adhesion, and dirt repellency.

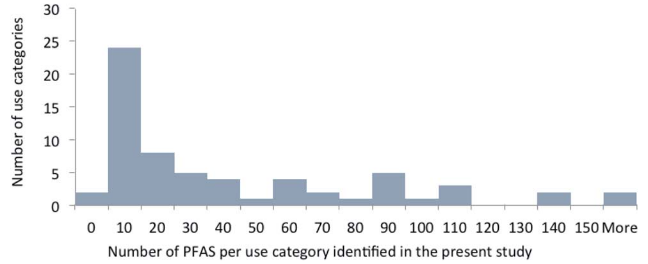

Fig. 1 Use categories grouped according to the number of PFAS identified. The use categories are those mentioned in Table 1 without distinction of subcategories. Identified PFAS included PFAS detected analytically in products, patented and employed PFAS. The data show *e.g.* that 26 use categories contain fewer than 20 PFAS and seven use categories contain more than 100 PFAS.

This array of different PFAS may be surprising, but it shows that some properties of PFAS are shared across many PFAS groups. The large number of patented PFAS for the same use raises the question of whether some of these substances offer better performance than others, or whether it does not really matter which PFAS are employed. The latter would indicate that manufacturers can invent new PFAS quite easily to avoid license fees for patents of other manufacturers.

For the majority of uses, however, far fewer PFAS were identified. Fig. 1 highlights the use categories grouped according to the number of PFAS identified. It should be noted that the number of PFAS reflects the number that we have identified in the present study, and not the number of substances on the market or available for a certain use. For half of the use categories, we have identified more than 20 PFAS, and for seven use categories more than 100 PFAS. The use categories with more than 100 identified PFAS are "photographic industry", "semiconductor industry", "coatings, paints and varnishes", "fire-fighting foams", "medical utensils", "personal care products", and "printing". There are also two categories where no specific substances were identified. These are "ammunition" and "nuclear industry".

The most frequently identified PFAS in our literature search are non-polymeric fluorotelomer-based substances, followed by non-polymeric PASF-based substances and PFAAs. Other identified non-polymeric substances are perfluoroalkyl phosphinic acids (PFPIA)-based substances, perfluoroalkyl carbonyl fluoride (PACF)-based substances, cyclic PFAS, aromatic substances with fluorinated side-chains, per- and polyfluoroalkyl ethers, hydrofluoroethers, and other non-polymers. Polymeric substances include fluoropolymers, side-chain fluorinated polymers, and perfluoropolyethers (see also ESI-2†). There is also a variety of substances in the groups themselves, especially among the non-polymeric fluorotelomer-based and PASF-based substances. For many of the substances, only one use (or patent for a use) was identified. For example, one use (or patent) was assigned to 375 fluorotelomer-based substances, two uses (or patents) to 46 fluorotelomer-based substances and three or more uses to 36 fluorotelomer-based substances. The reason why so many PFAS have only one identified use may be that not all the uses were identified for all PFAS. But it also seems that many patents contain "new" PFAS because they work just as well as the established ones.

In contrast to the many PFAS with only one assigned use, some PFAS have many uses. ESI-2† illustrates this point: of the 2400 links between individual PFAS and assigned uses, 16 PFAS have been assigned to 10 or more uses (see Table 2 and Fig. 2). The exact use counts are not important *per se*, because there may be more uses for these PFAS that have not been included in the present study, but they demonstrate that some PFAS are employed more frequently than others. It has to be noted that the three fluoropolymers in Table 2 are quite different from the other PFAS on the list, as they represent possibly dozens or hundreds of technical products with different grades and molecular sizes.

Of the 2400 links between individual PFAS and assigned uses, around 40% were obtained from patents, 26% from studies that detected PFAS in products, and 34% of the links were obtained from publications that reported actual uses.

3.3 What is the extent of the uses in certain areas of the world?

To prioritize PFAS uses in the search for alternatives, it is key to know for which uses PFAS were employed the most. Wang *et al.*[15,17,80] and Boucher *et al.* 2019 (ref. 14) published global emission inventories for C_4–C_{14} PFCAs and C_6–C_{10} PFSAs. For PFSAs and their precursors, the highest amounts were identified for the use in "apparel/carpet/textile", followed by "paper and packaging", "performance" and "after-market/consumers". There is also information on the quantities of individual fluoropolymers used.[40,81] However, a coherent data set with data covering a wide range of uses and at the same time a wide range of PFAS has not been available so far. The following two subsections will show the magnitude of the uses in the Nordic countries and the US based on the data from the SPIN database and the Chemical Data Reporting database under the TSCA, respectively. Data from REACH that would have covered more countries than the data from the SPIN database are not shown, because the tonnage bands in REACH refer to the substances and not to use categories. Accordingly, only in those cases where a substance has only one use would it have been possible to obtain useful information for this study, which would have created a lot of uncertainty in the data.

3.3.1 Data from the SPIN database. Fig. 3 highlights the total, non-confidential amounts of PFAS employed in the different use categories in Sweden, Finland, Norway and Denmark between 2000 and 2017.[44] It should be noted that the data from these Nordic countries may not be representative of other parts of the world. Reasons are that only non-confidential data are included, that substances in foodstuffs, medicinal products, and cosmetics do not have to be declared (see Section 2.2.2) and that there is no fluoropolymer or PFAS production in these

Table 2 PFAS with more than 10 assigned uses. Numbers based on counts of uses and patents, not on detections in products. The structures of these substances are shown in Fig. 2

Substance	CAS number	Assigned uses
Ammonium perfluorooctanoate	3825-26-1	14
Potassium perfluorooctane sulfonate	2795-39-3	15
Potassium *N*-ethyl perfluorooctane sulfonamidoacetate	2991-51-7	22
1-Propanaminium, 3-[[(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctyl)sulfonyl]amino]-*N*,*N*,*N*-trimethyl-, iodide (1 : 1)	1652-63-7	17
1-Propanaminium, 3-[[(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-heptadecafluorooctyl)sulfonyl]amino]-*N*,*N*,*N*-trimethyl-, chloride	38006-74-5	21
Oxirane, 2-[[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)oxy]methyl]-	122193-68-4	10
1*H*-Pentafluoroethane	354-33-6	10
Pentane, 1,1,1,2,2,3,4,5,5,5-decafluoro-	138495-42-8	12
Methyl perfluoropropyl ether	375-03-1	14
Methyl perfluorobutyl ether	163702-07-6	17
Methyl perfluoroisobutyl ether	163702-08-7	17
Ethyl perfluorobutyl ether	163702-05-4	13
Poly(oxy-1,2-ethanediyl), α-[2-[ethyl[(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctyl)sulfonyl]amino]ethyl]-ω-hydroxy-	29117-08-6	11
Polytetrafluoroethylene (PTFE)	9002-84-0	37
Poly(vinylidene fluoride) (PVDF)	24937-79-9	17
Ethylene tetrafluoroethylene copolymer (ETFE)	25038-71-5	10

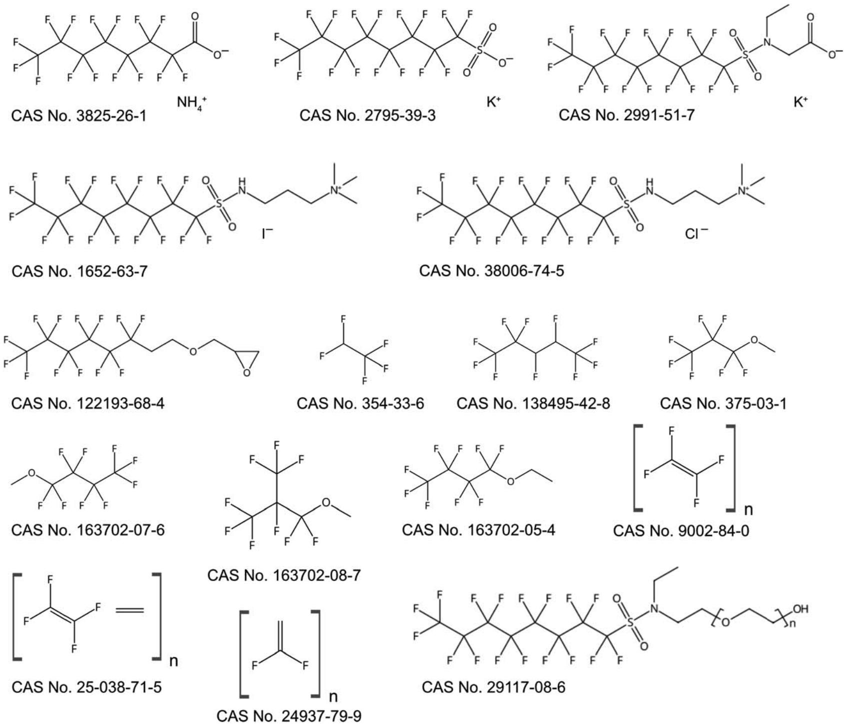

Fig. 2 Structures and CAS numbers of the PFAS with more than 10 assigned uses.

countries. Nevertheless, the data from the SPIN database provide a first indication of which uses of PFAS have been important in the last 20 years in this region.

The data illustrate that a large amount of PFAS was used in the production of plastic and rubber, the electronics industry, and coatings and paints (Fig. 3). The production of plastic and rubber does not include the production of fluoropolymers. Between 2000 and 2017, more than 3000 t of PFAS were used in the three categories previously mentioned. Around 1500 t of PFAS were used in building and construction and in lubricants and greases and around 1200 t of PFAS in the chemical industry, respectively. All other uses were below 1000 t.

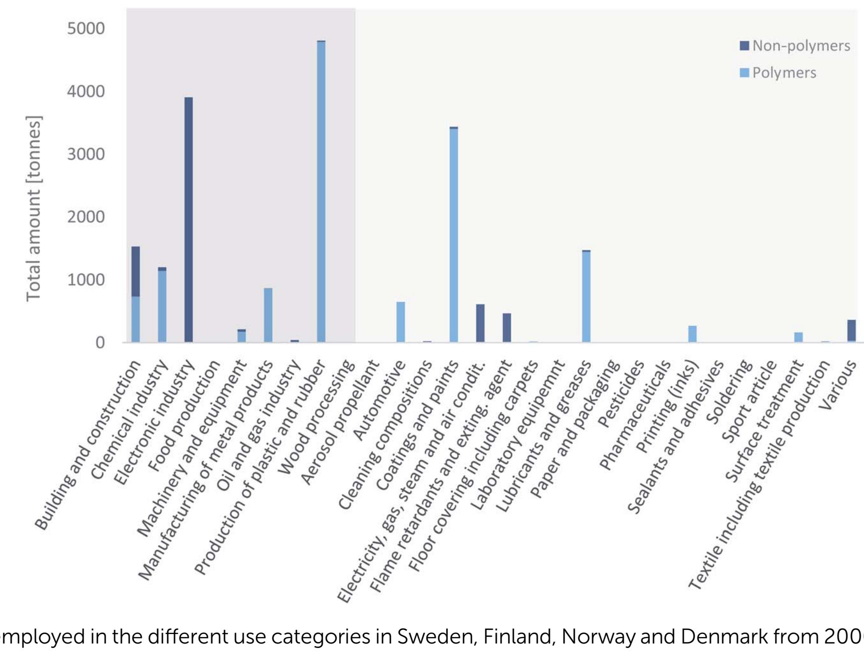

Fig. 3 Amount of PFAS employed in the different use categories in Sweden, Finland, Norway and Denmark from 2000 to 2017, as reported in the SPIN database.[44] Polymers include fluoropolymers and perfluoropolyethers. Side-chain fluorinated polymers have not been used above 0.2 t in any of the uses. Use categories with dark background are industrial branches, use categories with light grey background are other use categories.

Non-polymers were mainly used in the electronic industry, in buildings and construction, electricity, gas, steam and air conditioning supply, and flame retardants and extinguishing agents. Of the 6300 t of non-polymers used in the Nordic countries between 2000 and 2017, 5650 t (90%) were the hydrofluorocarbon (and greenhouse gas) 1*H*-pentafluoroethane (CAS no. 354-33-6). More than 70% (470 t) of the remaining non-polymeric PFAS were used in flame retardants and extinguishing agents. The SPIN database has a combined category for these two use categories, so it was not possible to distinguish them.

Polymers were mostly used in the production of plastic and rubber, coatings and paints, lubricants and greases, and in the chemical industry. At least 13 700 t of polymers were used in the Nordic countries between 2000 and 2017, and 10 000 t (73%) of this was PTFE. This percentage is a bit higher than the numbers published recently by AGC, which stated that 53% of the 320 000 t of fluoroplastics consumed worldwide in 2018 was PTFE.[81]

3.3.2 Data from the Chemical Data Reporting under the TSCA. Under the TSCA, the Chemical Data Reporting lists under "volume" the amount of a substance in a certain sector and function category or product category. However, more than 80% of the volume entries in the Chemical Data Reporting database are CBI. The certainty of the available information is therefore low, but a general statement is still possible. Table 3 highlights the non-confidential data on used and exported amounts of PFAS for the different uses based on the data reported in 2016.

The amount of used and exported PFAS was largest for functional fluids in "electrical equipment, appliance, and component manufacturing" and functional fluids in "machinery manufacturing". The exact same amounts in the two use categories are no coincidence but come from the declaration that 50% of the total amount was used for "electrical equipment, appliance, and component manufacturing" and 50% for "machinery manufacturing". 1*H*-Pentafluoroethane (CAS no. 354-33-6) accounted for 100% of the total amount in both cases. The high amounts of 1*H*-pentafluoroethane employed as functional fluids in "electrical equipment, appliance, and component manufacturing" confirm the data from the SPIN database indicating that the electronic industry is an important purchaser of this hydrofluorocarbon. The high amounts of "functional fluids" in "machinery manufacturing" could be related to refrigerants, air conditioners or other uses, but due to the broadness of the use category, nothing definite can be concluded. Also, as it was found for Europe, no data were available for amounts of non-polymeric PFAS used as processing aids under fluoropolymer production in the US, which may be expected to be a considerable contributor. The same amounts of "finishing agent" in "paint and coating manufacturing" and "paper manufacturing" are again from the declaration of 50% and 50%.

4 Discussion

4.1 Scope of the present study and uncertainties

4.1.1 Scope and uncertainties related to use categories. The present study covers many past and current uses of PFAS. The inventory is not exhaustive and it also contains uncertainties. One area of uncertainty comes from harmonizing entries to one use category that come from different sources. This is especially relevant for the comparison of amounts used, because the reported amounts from the different databases are related to more or less specific use categories that may be defined differently in different databases. Although not quite as critical, this was also a relevant point for the ESI-1.† Here, information on specific uses of PFAS was assigned to subcategories and information on broader uses to the main use

Table 3 Amounts (used + exported) that were not labelled as CBI for the different uses of PFAS from the Chemical Data Reporting under the TSCA from 2016. The rows with bold text are the uses with high amounts indicated by non-confidential data

Sector and function	Amount [t]
Paint and coating manufacturing – adhesive and sealant chemicals	0.001
Industrial gas manufacturing – air conditioners/refrigerations	138
Computer and electronic product manufacturing – solvents for cleaning and degreasing	1.03
Electrical equipment, appliance, and component manufacturing – functional fluids	**2180**
Fabricated metal product manufacturing – solvents for cleaning and degreasing	0.11
All other chemical product and preparation manufacturing – fire-fighting foam agents	190
Machinery manufacturing – functional fluids	**2180**
Miscellaneous manufacturing – solvents for cleaning and degreasing	0.10
Oil and gas drilling – surface active agents	0.022
Paint and coating manufacturing – adhesives and sealant chemicals	0.31
Paint and coating manufacturing – finishing agents	0.005
Paper manufacturing – finishing agents	0.005
Pesticide, fertilizer, and other agricultural chemical manufacturing – surface active agents	0.07
Miscellaneous manufacturing – plating agents and surface treating chemicals	1.96
Printing ink manufacturing – processing aids, not otherwise listed	0.001
All other basic inorganic chemical manufacturing – refrigerants (heat transfer fluids)	450
Rubber product manufacturing – rubber compounding	0.13
Soap, cleaning compound, and toilet preparation manufacturing – surface active agents	0.12
Textile, apparel and leather manufacturing – finishing agents	0.16

categories. Still, there were some use categories (especially from the Chemical Data Reporting database under the TSCA) that were so broad that we were not able to assign them to any category in our list. Examples are "surface active agents in all other basic inorganic chemical manufacturing", or "functional fluids in wholesale and retail trade". The PFAS listed under such categories and their quantities were not, therefore, considered in the present study.

Another area of uncertainty originates from unidentified uses. We found, for example, that PFAS are used in climbing ropes.[82] It therefore cannot be excluded that PFAS are also used in climbing harnesses, but no information was found on this. We did not have the capacity to conduct interviews with industry representatives who might have revealed additional information. We were similarly limited when it came to evaluating the copious amount of information about PFAS uses, for example in reports, scientific papers and patents. Therefore, not all PFAS uses might have been identified in the present study.

In the case of patents in particular, a great amount of information is available, but it should be noted that only some of the PFAS included in patents currently are likely to be used on the market. In addition to these uncertainties, some of the use category-specific information in the SPIN database is CBI, meaning that we may have not seen all categories. It would be desirable if such information was no longer confidential in the future, in order to inform consumers, users, and regulators.

Nevertheless, the SPIN database is a very valuable source of information and it would be much easier to compile such inventories of uses if other countries had product registries like the Nordic countries. Without such product registries, the compilation of uses and the substances used remains difficult and lengthy. It would also be advantageous if the uses under REACH were more precisely named. Current categories like "processing aids at industrial sites" or "manufacture of chemicals" are very broad and thus difficult to include.

An important question is whether the majority of the use categories is covered in the present study or whether important use categories are still missing. It is difficult to answer such a question quantitatively, but a qualitative indication is possible when the use categories of the SPIN database are compared to the categories that were identified independently of the SPIN database. Both categories match very well; only three categories had to be added to accommodate data from the SPIN database in the ESI-1† appropriately. These three categories were "machinery and equipment", "manufacture of basic metals" and "manufacture of fabricated metal products". However, with the exception of these three categories, all specific information from the SPIN database could be classified very well into the existing categories of the present study. Overall, we assume that there are no major gaps in the general use categories. However, it is quite possible that subcategories are missing. Among the uses of which we are aware, there may also be some uses where PFAS are no longer employed.

To improve the list of uses in the future, there are several possibilities. Firstly, one could try to get access to product registries of as many countries as possible. Unfortunately, not all product registries are as easily accessible as those of the Nordic countries and many developing countries do not have such a registry. The list could also be extended with information from REACH registration dossiers. These dossiers include information of uses and tonnage bands expected to be used at the time of registration. Interviews with manufacturers of products could also generate more information. However, we know from experiences with past projects that manufacturers often want the interviewers to sign a non-disclosure agreement before the interview, which prevents using the information obtained in publications. The information from such interviews could still provide some indication as to what kind of information to look for in the public domain. The same is true for market reports. They can only provide a clue of what to look for in the public domain (given that they often contain no references). A discouraging factor for researchers who may want to use market reports as data sources is that the companies who generate them often sell them for extortionate sums (*i.e.* several thousand US dollars) and that most of them are not based on thorough research.[83] Another approach could be to use artificial intelligence to systematically search product sales/industry magazines for words or phrases, such as 'fluor'.

4.1.2 Uncertainties related to substances. Uncertainties also exist regarding the substances identified for a particular use. Some of these uncertainties are already discussed in the Methods section: not all registered patents are used on the market, not all substances included in a patent are used in practice, and substances that have been detected analytically in products might be impurities in or degradation products of the actual substances. In addition, we only looked for examples of certain types of PFAS and the lists are by no means complete. Also, the substances included in the present study from the SPIN database are not substances in articles, but substances in preparations. The substances listed in the ESI-1† under U or U* are also those that were intentionally used in the products. However, impurities, reaction products upon mixing the ingredients, and degradation products of the intentionally added PFAS might also be present in products. Industrial blends are rarely pure, but can be only 80% of the registered substance, so 20% can be impurities, reaction by-products, degradation products *etc.*

In addition, industry tends to evolve around consumer needs, cost savings, and external factors such as regulatory oversight, and substances used today may no longer be relevant tomorrow. A better overview of the substances being used could be obtained if manufacturers had to list which substances are contained in a product in the safety data sheets. However, except for a few instances (*e.g.* when uses are authorized for food contact materials in Germany), this is not the case and patents are therefore often the only way to find out what products (might) contain. A better overview of the substances used would also be possible, at least for the US, if substances with tonnages below the reporting threshold of 11.34 t per year were also included in the TSCA Chemical Data Reporting database. In the EU, it would be helpful if the registration dossiers under REACH as well as other legislations were updated regularly with a more detailed breakdown of which-quantities of the substances are used in which applications.

4.1.3 Uncertainties related to quantities. The third part of the present study – identifying the key use categories in terms of quantities – also contains various uncertainties. The data from the SPIN database only represent the Nordic countries, and many industry branches have a greater presence in other countries or regions of the world than in the Nordic countries. Additionally, many of the volumes in the SPIN database are CBI. Furthermore, the SPIN database does not include all uses. An example is that foodstuff, and hence food packaging, is not reported to the SPIN database, which possibly could explain why 'packaging', which was significant in the OECD study, did not stand out in the SPIN survey. Similarly, non-polymeric PFAS such as ADONA and the GenX chemicals are used as processing aids during fluoropolymer production. The quantities of these processing aids are not captured in the statistics of the SPIN database since this activity is not ongoing in Scandinavia. However, the significant amounts of fluoropolymers produced in Europe in 2018 of about 51 000 t per year,[81] and globally of about 320 000 t per year suggest that a considerable amount of PFAS is used as processing aids in this use category in addition to what is shown in Fig. 3 under "Chemical industry".

The data from the US are only partly helpful, because a large part of the reported amounts has been claimed as CBI and only substances manufactured or imported at above 11.34 t per year at a single site have been reported. Although in some use categories large quantities of PFAS are employed, it is difficult to compare the amounts, because the unreported amounts due to CBI could be much larger than the non-confidential reported amounts. The extent of the uncertainties in the SPIN database due to the CBI cannot be estimated with the available data, but could be large. It would be helpful if regulatory agencies, such as the US EPA or the national authorities in the Nordic countries, could create a ranking of the PFAS uses (without stating any numbers) based on the entire datasets they have collected.

4.2 Findings of the present study with regard to uses

The present study is a renewed and expanded effort to systematically compile a wide range of known as well as many overlooked uses of PFAS. Besides describing the uses of PFAS, we also endeavoured to explain which functions the PFAS fulfil in these uses (see Table 4 in the Appendix). The descriptions of the functions and properties of the PFAS employed are especially important for determining "non-essential" use categories and identifying alternatives for those uses currently considered "essential".

However, as can be seen from the question marks in the Appendix it was not always possible to determine why PFAS were used or needed in a particular case. In 4% of the cases we could not clarify which function the PFAS fulfil in the use category or subcategory, and in 21% of the cases we could not clarify which property is needed to fulfil the mentioned function. For example, we do not know exactly why PFAS are employed in the ventilation of respiratory airways, in brake-pad additives, and in resilient linoleum. It would be important to engage with product manufacturers to understand what function the PFAS actually have, in order to identify appropriate replacements. Some of the uses might also be judged as "non-essential" and thus could be eliminated or discontinued.

Our study also shows that in several areas where large quantities of PFAS are employed, discussions concerning alternatives are still not underway in the public domain. In general, in recent years the focus in the search for alternatives for PFAS has been on fire-fighting foams,[84,85] paper and packaging,[86,87] and textiles.[88–91] This focus was certainly appropriate, because these are uses where PFAS are in direct contact with the environment (fire-fighting foam) or with humans (food packaging, textiles). However, our results show that PFAS are also used widely in the production of electronics and in machinery manufacturing, and at least in the Nordic countries in the production of plastic and rubber and in paints and coatings. Measuring and/or reporting emissions along the life cycles of these uses, and the search for alternatives in these use categories should therefore also be prioritized. These uses could for instance be included in the activities for which data have to be reported under the European Pollutant Release and Transfer Registry.

It would also be important to look for alternatives in industry branches that use smaller amounts of PFAS or that are not included in the SPIN database or Chemical Data Reporting database, but produce large amounts of wastewater, exhaust gases or solid waste containing PFAS. More information is needed to prioritize the various use categories, but potentially worrisome categories where environmental contamination has been documented are fluoropolymer production,[92–94] the semiconductor industry,[95,96] and metal plating.[97]

Beside the categories mentioned above, there are also uses where humans are in direct contact with PFAS and that have not yet gained much attention regarding alternatives. These include: personal care products and cosmetics (ESI-1 Section 2.28†), pesticides (ESI-1 Section 2.29†), pharmaceuticals (including eye drops) (ESI-1 Section 2.30†), printing inks (ESI-1 Section 2.33†), and sealants and adhesives (ESI-1 Section 2.35†). A search for alternatives would also be important here.

4.3 Findings of the present study with regard to substances

We can ascertain from the SPIN database that two PFAS, 1*H*-pentafluoroethane and PTFE, account for 75% of the quantities used in the Nordic countries. One explanation is that PTFE and 1*H*-pentafluoroethane are not used as additives, but as the main products. For example, entire roof structures or coatings are made out of PTFE.[30] For 1*H*-pentafluoroethane (also known as HFC-125), one of the main uses is as a heat transfer fluid and cooling agent,[44,98] which could explain the large quantities of that substance used.

Other PFAS used as surfactants are utilized in much smaller quantities probably due to their high market price. They may therefore not appear (or at least not in high amounts) in databases such as the SPIN database or the Chemical Data Reporting database, which only report substances (or amounts) above a certain threshold. PFAS used in articles that are manufactured mainly in Asia or other countries outside the EU or the US may also not appear in large amounts in the SPIN or Chemical Data Reporting database, simply because the databases do not contain information on PFAS in articles. The PFAS that we have listed as examples in the ESI-1† are mainly those used in Europe or North America. A recent publication[99] lists *e.g.* seventy PFAS from the Inventory of Existing Chemical Substances Produced or Imported in China (IECSC) that are not in the North American and European chemical inventories. These PFAS are also not in our inventory, because no information on their intended use was provided.

Concerning the currently used PFAS, it was thought – due to the voluntary phase out of all PFAS products derived from perfluorooctane sulfonyl fluoride by 3M[100] and the voluntary PFOA Stewardship Program in which eight companies agreed to phase out 95% of uses by 2015 (ref. 101) – that at least ammonium perfluorooctanoate and potassium perfluorooctane sulfonate are no longer in use in the US. However, other companies have not been prevented from taking over the market, and there has been very limited enforcement of the actual phase-out through regulation. A recent article revealed that PFAS that can break down into PFOA and PFOS are still in use in the US.[102] Those uses include coatings for medical devices, apparel, and other industries, and equipment in pharmaceutical companies. PFAS that can break down into PFOA and PFOS are also still used by semiconductor and electronics companies.[102]

4.4 Prioritisation of use categories

Based on the data from the SPIN database, the Chemical Data Reporting under the TSCA and information on the production of wastewater, exhaust gases and solid waste, we propose that the following use categories need to be prioritized for reducing/eliminating the use of PFAS. At the same time, it must be noted that fluoropolymers and hydrofluorocarbons are produced and used in much larger quantities than PFAAs and their precursors. However, PFAAs and their precursors are more critical from a toxicological point of view. Therefore, the proposal for prioritization is made for each of the three PFAS groups individually: PFAAs and precursors, hydrofluorocarbons, and fluoropolymers.

4.4.1 PFAAs and precursors

4.4.1.1 Fire-fighting foams. PFAS-containing fire-fighting foams are used for extinguishing liquid fires such as fires in oil, jet fuel, other non-water-soluble hydrocarbons, alcohols and acetone. Although relatively small quantities of PFAS are used in fire-fighting foams (class B for extinguishing flammable liquid fires), these foams are an important use category because the foams and the chemicals they contain are released directly into the environment. There are numerous reports about PFAS-contaminated sites where fire-fighting foams have been used (especially for training activities) or spilled.[61,63,103,104] Although PFAS-free class B fire-fighting foams have been developed in the meantime, PFAS-containing fire-fighting foams are still widely in use today.[65,105,106] For more information, see ESI-1 Section 2.14† and the Appendix.

4.4.1.2 Chemical industry with a special focus on processing aids in the polymerization of fluoropolymers. Important uses of PFAS in the chemical industry are their uses as processing aids in the polymerization of fluoropolymers, the production of chlorine and sodium hydroxide, and the production of other chemicals including solvents. PFAS that are used as processing aids in the polymerization of fluoropolymers are of special concern. This is because the surrounding environments at numerous sites have been heavily contaminated due to the release of the processing aids from the nearby manufacturing plants,[92–94] and considerable amounts of fluoropolymers are produced in Europe and worldwide. For more information, see ESI-1 Section 1.4.†

4.4.1.3 Surface protection of textile, apparel, leather, carpets, and paper. Considerable quantities of PFAS, especially of side-chain fluorinated polymers, have been used as surface protectors in textile, apparel, leather, carpets, and paper. These are open and dispersive uses where many consumers come into contact with the PFAS-containing products. It has also been reported that there are high emissions to air, dust, and wastewater from a textile manufacturing plant in China.[107] The side-chain fluorinated polymers contain PFAAs as impurities and they may act as important precursors to PFAAs.[108] For more information, see ESI-1 Sections 2.5, 2.16, 2.20, 2.26, and 2.40.†

4.4.2 Hydrofluorocarbons

4.4.2.1 Electronic industry. PFAS have been used in electronic devices themselves *e.g.* in flat panel displays or liquid crystal displays. However, they have also been used for the testing of electronic devices and equipment, as heat transfer fluids/cooling agents, in cleaning solutions, to deposit lubricants and to etch piezoelectric ceramic filters. Based on data from the SPIN database and the Chemical Data Reporting database under the TSCA, the most widely used substance in the electronic industry in the Nordic countries and the US is the hydrofluorocarbon 1*H*-pentafluoroethane. According to the SPIN database it is mainly used as a heat transferring agent and cooling agent. However, 1*H*-pentafluoroethane is not only of concern due to its high persistence but also because it has a global warming potential that is 3500 times that of carbon dioxide. Therefore, 1*H*-pentafluoroethane is one of the substances regulated by the Kigali Amendment of the Montreal Protocol and efforts are being undertaken to reduce the production and consumption of this substance. The search for PFAS-free alternatives is therefore even more important in this use category.

4.4.2.2 Machinery and equipment. The Chemical Data Reporting database under the TSCA lists also high amounts (more than 2000 t per year) of 1*H*-pentafluoroethane that is used as a “functional fluid” in “machinery manufacturing” in the US. This could be related to refrigerants, air conditioners or other uses, but due to the broadness of the use category, nothing specific can be concluded. Given the high amounts reported, there is an urgent need for more information on where and for which function hydrofluorocarbons, and PFAS in general, are used in this category. For more information, see ESI-1 Section 1.10† and the Appendix.

4.4.3 Fluoropolymers

4.4.3.1 Production of plastic and rubber. The SPIN database reveals that large amounts of fluoropolymers (more than 4000 t between 2000 and 2017) have been used in the production of plastic and rubber in the Nordic countries between 2000 and 2017. PFAS have been used as mould release agents, foam blowing agents, foam regulators, polymer processing aids, in the etching of plastic, as anti-blocking agents for rubber, and as curatives in the production of plastic and rubber. As polymer processing aids, fluoropolymers can increase the processing efficiency and quality of plastic and rubber.[109] The use of PFAS in the production of plastic and rubber may explain why PFAS are found, for example, in artificial turf.[110] For more information, see ESI-1 Section 2.14† and the Appendix.

4.4.3.2 Coatings, paints and varnishes. The data from the SPIN database show that large amounts of fluoropolymers (more than 3000 t between 2000 and 2017) have been used in coatings and paints in the Nordic countries between 2000 and 2017. Fluoropolymers can be used to impart oil- and water-repellency to the paints or coatings, and fluoropolymers are also used as anti-stick and anticorrosive coatings. For more information, see ESI-1 Section 2.8† and the Appendix.

4.5 Use and implications of the present study

The large number of uses that exist for PFAS, together with the large number of individual substances, makes their regulation and eventual phase-out very challenging. The approach of allowing PFAS only in "essential uses", as suggested for example in the EU strategy paper "Elements for an EU-strategy for PFAS",[5] will not be easy to implement if regulators try to assess all uses individually. An alternative approach could be to deem all PFAS uses as "non-essential" unless producers or users make a convincing case for essentiality, and that authorities set a sunset clause on "essential uses".

The number of use categories for both non-essential and essential cases is critical to estimate the amount of work that would need to be done, for example, to prepare a restriction proposal under REACH (as planned by five European countries[31]). The descriptions in the present study of where and why PFAS are used can be used to provide an overview of the uses and may also facilitate an understanding of what alternatives need to be developed and with which priority.

The information in this study may also help regulators and scientists determine which PFAS to measure in contaminated areas, in humans, in surrounding communities, and in products. To facilitate the identification of PFAS in various matrices, we provide the ESI-3 file,† which contains for each use category the name, CAS number, and exact monoisotopic mass of the substance. The ESI-3 file† also includes information on whether PFAS were identified in a patent, detected analytically in products, or reported as employed substances. Laboratories could use modern analytical methods such as suspect-screening analysis utilising accurate mass spectrometry to identify novel and emerging PFAS listed in our ESI-3.†[60,111] Patented substances may be less likely to be on the market and could be excluded or given a lower priority or weighting in suspect screening workflows. Similar lists (such as the ESI-3†) are provided by the OECD/UNEP Global PFC Group,[2] Zhang *et al.* (2020),[99] the US EPA, the NORMAN Substance Database[79] and others. An overview is provided under https://comptox.epa.gov/dashboard/chemical_lists. However, only a few of these lists also contain information on uses.

The ESI-3† may also be valuable for identifying sources of PFAS in the environment. Some uses may impart characteristic PFAS "fingerprints" (*i.e.* PFAS contamination patterns) to environmental samples that could be used to identify a source, *e.g.* through statistical methods.[112] On the other hand, many environments will be impacted by multiple sources and such fingerprinting methods could be challenging in practice.

5 Conclusions

The present study is the first of its kind to systematically compile a wide range of known as well as poorly documented uses of PFAS. The compilation is not exhaustive, but it still demonstrates that PFAS are used in almost all industry branches and in many consumer products. Some consumer products even have multiple applications of PFAS within the same product. A cell phone for example may contain fluoropolymer-insulated wiring, PFAS in the circuit boards/semiconductors, and a screen coated with a fingerprint-resistant fluoropolymer. The search for alternatives is therefore a challenging and extensive task and is important in all use categories. However, it seems particularly critical to us to replace PFAAs and their precursors in fire-fighting foams, processing aids for the polymerization of fluoropolymers and in the surface protection of textiles, apparel, leather, carpets, and paper. Hydrofluorocarbons seem to be used most in the electronics industry and in machinery and equipment. Replacing them in these categories will therefore be an important but challenging task. A search for alternatives to fluoropolymers will be important in the production of plastic and rubber and in coatings, paints, and varnishes.

A matching database of viable alternatives to PFAS would be a logical progression of the present study. It would also be helpful if environmental protection agencies, for example the US EPA, could create a ranking of PFAS uses (without providing tonnages) based on the data they have collected. A ranking without exact figures would still be better than the current situation, in which very little is known about the quantitatively most important use categories due to CBI. The TSCA reform in the US was unfortunately unsuccessful in reducing industry's excessive use of CBI. On the one hand, CBI may protect a specific industry's business, but on the other hand it also results in less protection for consumers, users, and workers from the chemicals. Even regulators are left in the dark about volumes, use categories, and PFAS used, which limits their ability to assess and prevent harm to humans and the environment.

Conflicts of interest

Jamie DeWitt is serving as a plaintiff's expert witness in several cases related to PFAS.

Appendix

Table 4 Overview of the uses of PFAS, the function of the PFAS in the uses and the properties of the employed PFAS that make them valuable for this application

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
Industry branch		
Aerospace		
- Phosphate ester-based brake and hydraulic fluids	Corrosion protection	Altering the electrical potential at the metal surface
- Gyroscopes	Flotation fluids in gyroscopes	?
- Wire and cable	High-temperature endurance, fire resistance, and high-stress crack resistance	Non-flammable polymers, stable
- Turbine-engine	Use as lubricant	Corrosion resistant, stable, non-reactive, operate at a wide temperature range
- Turbine-engine	Use as elastomeric seals	Operate at a wide temperature range
- Thermal control and radiator surfaces	Reject waste heat	Survival over a wide operating temperature range, low solar absorbance, high thermal emittance, and freedom from contamination by outgassing
- Coating	Protect underlying polymers from atomic oxygen attack	Non-reactive, very stable
- Propellant system	Elastomers compatible to aggressive fuels and oxidizers	Non-reactive, very stable
- Jet engine/satellite instrumentation	Use as lubricant	Long-term retention of viscosity, low volatility in vacuum and their fluidity at extremely low temperatures
Biotechnology		
- Cell cultivation	Supply of oxygen and other gases to microbial cells	Great capacity to dissolve gases
- Ultrafiltration and microporous membranes	Prevent bacterial growth	?
Building and construction		
- Architectural membranes *e.g.* in roofs	Resistance to weathering, dirt repellent, light	Oleophobic and hydrophobic, low surface tension, beneficial weight-to-surface ratio
- Greenhouse	Transparent to both UV and visible light, resistant to weathering, dirt repellent	Oleophobic and hydrophobic, low surface tension
- Cement additive	Reduce the shrinkage of cement	?
- Cable and wire insulation, gaskets & hoses	High-temperature endurance, fire resistance, and high-stress crack resistance	Non-flammable polymers, stable
Chemical industry		
- Fluoropolymer processing aid	Emulsify the monomers, increase the rate of polymerization, stabilize fluoropolymers	Fluorinated part is able to dissolve monomers, non-fluorinated part is able to dissolve in water
- Production of chlorine and caustic soda (with asbestos diaphragms cells)	Binder for the asbestos-fibre-based diaphragms	?
- Production of chlorine and caustic soda (with fluorinated membranes)	Stable membrane in strong oxidizing conditions and at high temperatures	Stable, non-reactive
- Processing aids in the extrusion of high- and liner low-density polyethylene film	Eliminate melt fracture and other flow-induced imperfections	Low surface tension
- Tantalum, molybdenum, and niobium processing	Cutting or drawing oil	Non-reactive, stable
- Chemical reactions	Inert reaction media (especially for gaseous reactants)	Non-reactive, stable

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Polymer curing	Medium for crosslinking of resins, elastomers and adhesives	?
- Ionic liquids	Raw materials for ionic liquids	?
- Solvents	Dissolve other substances	Bipolar character of some of the PFAS
Electroless plating	Disperses the pitch fluoride in the plating solution	Low surface tension
Electroplating (metal plating)		
- Chrome plating	Prevent the evaporation of chromium(VI) vapour	Lower the surface tension of the electrolyte solution, very stable in strongly acidic and oxidizing conditions
- Nickel plating	Non-foaming surfactant	Low surface tension
- Nickel plating	Increase the strength of the nickel electroplate by eliminating pinholes, cracks, and peeling	Low surface tension
- Copper plating	Prevent haze by regulating foam and improving stability	Low surface tension
- Tin plating	Help to produce a plate of uniform thickness	Low surface tension
- Alkaline zinc and zinc alloy plating		
- Deposition of fluoropolymer particles onto steel	Supported by fluorinated surfactants	Cationic and amphoteric fluorinated surfactants impart a positive charge to fluoropolymer particles which facilitates the electroplating of the fluoropolymer
Electronic industry		
- Testing of electronic devices and equipment	Inert fluids for electronics testing	Non-reactive
- Heat transfer fluids	Cooling of electrical equipment	Good heat conductivity
- Solvent systems and cleaning	Form the basis of cleaning solutions	Non-flammable, low surface tension
- Carrier fluid/lubricant deposition	Dissolve and deposit lubricants on a range of substrates during the manufacturing of hard disk drives	?
- Etching of piezoelectric ceramic filters	Etching solution	Acidic
Energy sector		
- Solar collectors and photovoltaic cells	High vapour barrier, high transparency, great weatherability and dirt repellency	Oleophobic and hydrophobic, low surface tension
- Photovoltaic cells	Adhesives with PFAS hold mesh cathode in place	Lower the surface tension of the adhesive
- Wind mill blades	Coating	High weatherability
- Coal-based power plants	Polymeric PFAS filter remove fly ash from the hot smoky discharge	Stable, non-reactive
- Coal-based power plants	Separation of carbon dioxide in flue gases	Lower the surface tension of the aqueous solution
- Lithium batteries	Binder for electrodes	Almost no reactivity with the electrodes and electrolyte
- Lithium batteries	Prevent thermal runaway reaction	Good heat absorption of first layer and good heat conductivity of second layer
- Lithium batteries	Improve the oxygen transport of lithium–air batteries	Great capacity to dissolve gases
- Lithium batteries	Electrolyte solvents for lithium–sulfur batteries	Bipolar character of some of the PFAS
- Ion exchange membrane in vanadium redox batteries	Polymeric PFAS are used as membranes	Resistance to acidic environments and highly oxidizing species
- Zinc batteries	Prevent formation of dendrites, hydrogen evolution and electrode corrosion due to adsorption onto the electrode surface	Low surface tension, non-reactive

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Alkaline manganese batteries	MnO_2 cathodes containing carbon black are treated with a fluorinated surfactant	?
- Polymer electrolyte fuel cells	Polymeric PFAS are used as membranes	Ion conductance
- Power transformers	Cooling liquid	Good heat conductivity
- Conversion of heat to mechanical energy	Heat transfer fluids	Good heat conductivity
Food production		
- Wineries and dairies	Final filtration before bottling with polymeric PFAS	Resist degradation
Machinery and equipment	?	?
Manufacture of metal products		
- Manufacture of basic metals	Inhibit the formation of acid mist during the electrowinning of copper	Lower the surface tension of the aqueous solution
- Manufacture of fabricated metal products	?	?
- Pickling of steel wires	Acid-pickling promoter	?
- Treatment of coating of metal surfaces	Promote the flow of metal coatings, prevent cracks in the coating during drying	Lower the surface tension of the coating
- Treatment of coating of metal surfaces	Corrosion inhibitor on steel	Non-reactive
- Etching of aluminium in alkali baths	Improving the efficient life of the alkali baths	?
- Phosphating process for aluminium	Fluoride-containing phosphating solutions help to dissolve the oxide layer of the aluminium	?
- Cleaning of metal surfaces	Disperse scum, speed runoff of acid when metal is removed from the bath, increase the bath life	?
- Water removal from processed parts	Solvent displacement	Low surface tension
Mining		
- Ore leaching in copper and gold mines	Increase wetting of the sulfuric acid or cyanide that leaches the ore	Low surface tension
- Ore leaching in copper and gold mines	Acid mist suppressing agents	Low surface tension
- Ore floating	Create stable aqueous foams to separate the metal salts from soil	Low surface tension
- Separation of uranium contained in sodium carbonate and/or sodium bicarbonate solutions by nitrogen floatation	Improve the separation	?
- Concentration of vanadium compounds	Destruction of the mineral structure, increases the specific surface area and pore channel thus facilitating vanadium leaching	Acidity
Nuclear industry		
- Lubricants for valves and ultracentrifuge bearings in UF6 enrichment plants	PFAS are used as the lubricants	Stable to aggressive gases
Oil & gas industry		
- Drilling fluid	Foaming agent	Low surface tension
- Drilling – insulating material for cable and wire	Polymeric PFAS are used as insulating material	Withstand high temperatures
- Chemical driven oil production	Increase the effective permeability of the formation	Low surface tension
- Chemical driven oil production	Foaming agent for fracturing subterranean formations	Low surface tension
- Chemical driven oil production	Heavy crude oil well polymer blocking remover	?

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Chemical driven gas production	Change low-permeability sandstone gas reservoir from strong hydrophilic to weak hydrophilic	Hydrophobic and oleophobic properties
- Chemical driven gas production	Eliminate reservoir capillary forces, dissolve partial solid, dis-assemble clogging, increase efficiency of displacing water with gas	Lower surface tension of the material
- Oil and gas transport	Lining of the pipes is made out of polymeric PFAS	Non-reactive (corrosion resistant)
- Oil and gas transport	Reduce the viscosity of crude oil for pumping from the borehole through crude oil-in-water emulsions	Hydrophobic and oleophobic properties
- Oil and gas storage	Aqueous layer with PFAS prevents evaporation loss	Lower the surface tension of the aqueous solution
- Oil and gas storage	Floating layer of cereal treated with PFAs prevents evaporation loss	Low surface tension
- Oil containment (injection a chemical barrier into water)	Prevents spreading of oils or gasoline on water	?
- Oil and fuel filtration	Polymeric PFAS are used as membranes	Non-reactive (corrosion resistant)
Pharmaceutical industry		
- Reaction vessels, stirrers, and other components	Use of polymeric PFAS instead of stainless steel	?
- Ultrapure water systems	Polymeric PFAS are used as filter	Low surface tension
- Packaging	Polymeric PFAS form moisture barrier film	Hydrophobic
- Manufacture of "microporous" particles	Processing aid	?
Photographic industry		
- Processing solutions	Antifoaming agent	Lower the surface tension of the solution
- Processing solutions	Prevent formation of air bubbles in the solution	Lower the surface tension of the solution
- Photographic materials, such as films and papers	Wetting agents, emulsion additives, stabilizers and antistatic agent	Low surface tension, low dielectric constant
- Photographic materials, such as films and papers	Prevent spot formation and control edge uniformity in multilayer coatings	Low surface tension
- Paper and plates	Anti-reflective agents	Low refractive index
Production of plastic and rubber		
- Separation of mould and moulded material	Mould release agent	Hydrophobic and oleophobic properties
- Separation of mould and moulded material	Reduce imperfections in the moulded surface	Low surface tension
- Foam blowing	Foam blowing agent	Low surface tension
- Polyol foams	Foam regulator	10.5.3.1.1.1.1 lower the surface tension of the foam
- Polymer processing aid	Increase processing efficiency and quality of polymeric compounds	Lower the surface tension of the polymeric products
- Etching of plastic	Wetting agent	Low surface tension
- Production of rubber	Antiblocking agent	Low surface tension
- Fluoroelastomer formulation	Additive in curatives	?
Semiconductor industry		
- Photoresist (itself)	Photoresist matrix, changes solubility when exposed to light	?
- Photoresist (photosensitizer)	Increase the photosensitivity of the photoresist	?
- Photoresist (photo-acid generator)	Generate strong acids by light irradiation	Able to generate strong acids
- Photoresist (quencher)	Controlling the diffusion of the acid to unexposed region	?
- Antireflective coating	Provide low reflectivity	Low refractive index

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Developer	Facilitate the control of the development process	?
- Rinsing solution	Rinsing the photoresist to remove the developer	Low surface tension
- Etching	Wetting agent	Low surface tension
- Etching	Reduce the reflection of the etching solution	Low refractive index
- Etching	Etching agent in dry etching	Strong acids
- Cleaning of silicon wafers	Etch cleaning	Strong acids
- Cleaning of integrated circuit modules	Remove cured epoxy resins	?
- Cleaning vapour deposition chamber	Remove dielectric film build up	Generation of reactive oxygen species
- Wafer thinning	Non-stick coating composition on carrier wafer	Low surface tension
- Vacuum pumps	Working fluid	Stable, non-reactive
- Technical equipment in contact with process chemical or reactive plasma	Polymeric PFAS are used in inert moulds, pipes and elastomers	Stable, non-reactive
- Multilayer circuit board	Bonding ply composition	Low dielectric constant, low dissipation factor
Textile production		
- Dyeing and bleaching of textiles	Wetting agent	Low surface tension
- Dyeing process using sulphur dyes	Antifoaming agent	Low surface tension
- Dye transfer material	Release agent	Low surface tension
- Textile treatment baths	Antifoaming agent	Low surface tension
- Fibre finishes	Emulsifying agent	Hydrophobic and oleophobic properties
Watchmaking industry		
- Lubricants	Form an oil layer and reduced wear	Non-reactive (do not oxidize, resistant to corrosion)
- Drying as production step after aqueous cleaning	Solvents in solvent displacement drying	Low surface tension
Wood industry		
- Drum filtration during bleaching	The used coarse fabric is made out of polymeric PFAS	Stable
- Coating for wood substrate	Clear coating is made out of polymeric PFAS	Stable, non-reactive
- Wood particleboard	Part of adhesive resin	Low surface tension
Other use areas		
Aerosol propellant	Aerosol propellant	Non-flammable, stable, non-reactive
Air conditioning	Working fluid	Non-flammable, stable, non-reactive
Antifoaming agent	Prevent foaming	Low surface tension
Ammunition	Make the final product rubbery and reduce the likelihood of an unplanned explosion due to shock; enable long-term storage without degradation of the polymer	Long-term stability without degradation
Apparel		
- Breathable membranes	Polymeric PFAS are used as membranes	High permeability to water vapour, but resist passage of liquid water

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Long-lasting durable water repellent finish	Provide water and oil repellence, stain resistance and soil release	Lower surface tension of the fabric, hydrophobic and oleophobic properties
Automotive		
- Car body	Weather resistance paint, no-wax brilliant top coat	Low surface tension
- Automotive waxes	Aid spreading, improve the resistance of the polish to water and oil	Lower the surface tension of the wax, oleophobic
- Windshield wiper fluid	Prevent icing of the wind shield	?
- Car body	Light, stable	Beneficial weight-to-surface ratio, stable
- Engine and steering system	Polymeric PFAS are used as sealants and bearings	Operate at a wide temperature range, non-reactive
- Engine oil coolers	Heat transfer fluid	Good heat conductivity
- Cylinder head coatings and hoses	Increase the fuel efficiency	?
- Cylinder head coatings and hoses	Reduce the fugitive gasoline vapour emissions	Low surface tension
- Electronics	Cables and wires	High-temperature endurance, fire resistance
- Fuel lines, steel hydraulic brake tubes	Corrosion protection	Non-reactive, stable
- Interior	Dirt repellent in carpets and seats	Low surface tension, oleophobic
- Brake pad additives	?	?
Cleaning compositions		
- Cleaning compositions for hard surfaces	Enhance wettability	Lower the surface tension of the cleaning product
- Carpet and upholstery cleaners	Provide stain resistance and repel soil	Low surface tension, oleophobic
- Cleaning compositions for adhesives	?	?
- Dry cleaning fluids	Stabilizer, improve the removal of hydrophilic soil	Hydrophobic and oleophobic, low surface tension
- Cleaning of reverse osmosis membranes	Remove calcium sulphate	?
Coatings, paints and varnishes		
- Paints	Emulsifier for the binder, dispersant for the pigments, wetting agent	Hydrophobic and oleophobic, low surface tension
- Paints	Enhance the protective properties of anticorrosive paints	Non-reactive
- Paints	Antifouling on ships	?
- Paints and coatings	Anti-crater, improved surface appearance, better flow and levelling, reduced foaming, decreased block, open-time extension, oil- and water repellency, dirt pickup resistance	Low surface tension, oleophobic
- Paints and coatings	Form second coat on a first coat	Low surface tension
- Coatings	Antistick and anticorrosive coatings	Low surface tension, non-reactive
- Coatings	Highly durable and weatherable	Stable, non-reactive
Conservation of books and manuscripts	Preserve historical manuscripts	Permeability to water vapour, but resist passage of liquid water
Cook- and bakingware	Prevent food from sticking to the pan/baking ware	Low surface tension, non-reactive, stable at high temperatures
Dispersions	Disperse solutions	Low surface tension
Electronical devices		
- Printed circuit boards	Use fibre-reinforced fluoropolymer layer	Low dielectric constant
- Capacitors	Separation of high voltage components (dielectric fluid)	High dielectric breakdown strength, non-flammable

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Acoustical equipment	Provide an electrical signal in response to mechanical or thermal signals	Piezoelectric and pyroelectric properties
- Liquid crystal displays (LCDs)	Provide the liquid crystal with a dipole moment	Dipoles
- Liquid crystal displays (LCDs)	Polymeric PFAS provide moisture sensitive coating for displays	Hydrophobic
- Light management films in flat panel display	Reduced static electricity build-up and dust attraction during fabrication	Low dielectric constant
- Razors	Polymeric PFFAs is used on the razor	?
- Electroluminescent lamps	Polymeric PFAS is used as coating	?
Fingerprint development	Solvent	?
Fire-fighting foam		
- Fluoroprotein (FP) foams	Fuel repellents	Low surface tension
- Film-forming fluoroprotein (FFFP) foam	Film formers, foam stabilizers	Lower the surface tension of water
- Alcohol-resistant film forming fluoroprotein (AR-FFFP) foam	Film formers, foam stabilizers	Lower the surface tension of water
- Aqueous film-forming foams (AFFF)	Film formers	Lower the surface tension of water
- Alcohol-resistant aqueous film forming foam (AR-AFFF)	Foam stabilizers	Low surface tension
Flame retardants		
- Polycarbonate resin	Flame retardants	Non-flammable
- Other plastic	Flame retardants	Non-flammable
Floor covering including carpets and floor polish	Improve wetting and levelling	Low surface tension
- Soil-release finishes for carpets	Provide water and oil repellence, stain resistance and soil release	Low surface tension, hydrophobic and oleophobic
- Aftermarket carpet protection	Provide water and oil repellence, stain resistance and soil release	Low surface tension, hydrophobic and oleophobic
- Resilient linoleum	?	?
- Laminated floor covering	?	?
- Floor polish	Improve levelling and wetting	Low surface tension
Glass		
- Surface treatment	Make glass surfaces hydrophobic and oleophobic	Hydrophobic and oleophobic
- Surface treatment	Prevents misting of glass	Hydrophobic
- Surface treatment	Dirt-repellent	Low surface tension
- Surface treatment	Fire-or weather resistant	Non-flammable, stable
- Etching and polishing	Increase the speed of etching, improve wetting	Low surface tension
- Drying as production step in glass finishing	Solvents in solvent displacement drying	Low surface tension
Household applications		
- Threads and joints	Polymeric PFAS is used for sealing	?
Laboratory supplies, equipment and instrumentation		
- Consumable materials (vials, caps, tape)	Made out of polymeric PFAS	?
- Personal protective equipment (gloves)	?	?
- Particle filters	Minimize the sorption of compounds to the filter itself	Low surface tension
- Solvents	Dissolve other substances	Hydrophobic and oleophobic

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- LC instruments	Polymeric PFAS are used in the solvent degasser	Non-reactive ?
- LC columns	Some columns are based on polymeric PFAS	?
- Reverse phase LC-solvents	can contain PFAS	?
- Seals and membranes in UPLCs, autoclaves and ovens	are made out of polymeric PFAS	Work over a wide temperature range
- Oils and greases in pumps	Form a thick oil layer and reduced wear	Non-reactive, non-flammable
- Sterilization of an insulated vessel	Sterilization medium	?
- Electro plotting	Protein-sequencing membranes are made out of polymeric PFAS	?
- Analysing the phosphoamino content in proteins	Protein-sequencing membranes are made out of polymeric PFAS	?
Leather		
- Manufacturing of genuine leather	Improve the efficiency of hydrating, pickling, degreasing and tanning	?
- Repellent treatment (genuine leather)	Provide water and oil repellence, stain resistance and soil release	Hydrophobic and oleophobic, low surface tension
- Manufacturing of synthetic leather	Polymer melt additives that impart oil and water repellency to the finished fibres	Hydrophobic and oleophobic
- Shoe brighteners	Improve the levelling of shoe brighteners	Low surface tension
- Impregnation spray	Provide water and oil repellence, stain resistance and soil release	Low surface tension
Lubricants and greases	Form a thick oil layer and reduced wear	Non-reactive, non-flammable, operate also at high temperatures, do not form sludge or varnish
Medical utensils		
- Electronic devices that rely on high frequency signals (defibrillators, pacemakers, cardiac resynchronization therapy (CRT), positron-emission tomography (PET) and magnetic resonance imaging (MRI) devices)	High dielectric insulators	High dielectric breakdown strength
- Video endoscope	Use in charge-coupled device colour filters	?
- Microbubble-based ultrasound contrast agents	Fluorinated gas inner core, which provides osmotic stabilization and contributes to interfacial tension reduction	Low solubility in aqueous media (dissolve more slowly)
- X-ray imaging	Contrast enhancement agents	Radio-opaque
- Magnetic resonance imaging	Contrast agent	Lack of a 19F endogenous background signal *in vivo* and high magnetic resonance sensitivity of 19F atoms
- Proton and 19F NMR imaging	Contrast agents	Lack of fluorine in organs and tissue
- Computed tomography and sonography	Contrast agents	Lack of fluorine in organs and tissue
- Radio-opaque materials	Polymeric PFAS has been used	Radio-opaque
- Surgical drapes and gowns	Improve water-, oil- and dirt-resistance	Hydrophobic and oleophobic, low surface tension
- X-ray films	Wetting agents, emulsion additives, stabilizers and antistatic agent	Low surface tension, low dielectric constant
- Dispersant	Facilitate the dispersion of cell aggregates	Low surface tension
- Contact lenses	Raw material	
- Retinal detachment surgery and proliferative vitreoretinal	Endotamponade gases	High specific gravity, low surface tension, and low viscosity
- Retinal detachment surgery and proliferative vitreoretinal	Intraoperative tool during vitreoretinal surgery	High specific gravity, low surface tension, and low viscosity
- Eye drops	Delivery agent	Unique combination of apolarity and amphiphility
- Filters, tubing, O-rings, seals and gaskets in dialysis machines	Made out of polymeric PFAS	Low surface tension

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Dialysis membranes	Made out of polymeric PFAS	Low surface tension
- Catheter, stents, and needles	Provide low-friction and clot-resistant coatings	Low surface tension
- Surgical patches and vascular catheter	Use of polymeric PFAS	?
- Blood transfer and artificial blood	Oxygen carrier	Great capacity to dissolve gases
- Organ perfusion	Oxygen carrier	Great capacity to dissolve gases
- Percutaneous transluminal coronary angioplasty	Oxygen carrier	Great capacity to dissolve gases
- Toothpaste	Enhances fluorapatite formation and inhibits caries	Low surface tension
- Dental floss	Allows the narrow ribbon to slip easily between close-pressed teeth	Low surface tension
- UV-hardened dental restorative materials	Improve the wetting of the set materials	Low surface tension
- Ventilation of respiratory airway	?	?
- Anaesthesia	Polymeric PFAS is used to dry or humidify breath	Hydrophobic
- Artificial heart pump	Blood compatible and durable	Non-reactive, stable
- Wound care	Cleaning burn residues	Dissolve hydrocarbon
Metallic and ceramic surfaces	Generates easily removable sludge	Hydrophobic and oleophobic
Music instruments		
- Guitar strings	Prevent loss of vibration due to residue build up	?
- Piano keys	Contain polymeric PFAS	?
- Piano	Eliminate squeaks in piano key	?
Optical devices		
- Glass fibre optics	Able to include rare earth in glass fibre optics	?
- Optical lenses	Provide optical lenses with low refractive index and high transparency	Low refractive index
Paper and packaging		
- Paper and cardboard	Provide water- and oil repellency	Hydrophobic and oleophobic
- Manufacturing of paper	Release agent for paper-coating compositions	Low surface tension
Particle physics		
- Particle accelerators	Part of the detection assemblies	Non-reactive, stable, high ionization charge density
Personal care products		
- Cosmetics	Emulsifiers, lubricants, or oleophobic agents	Hydrophobic, low surface tension
- Cosmetics	Make creams *etc.* penetrate the skin more easily	
- Cosmetics	Make the skin brighter	
- Cosmetics	Make the skin absorb more oxygen	Great capacity to dissolve gases
- Cosmetics	Make the makeup more durable and weather resistant	Hydrophobic and oleophobic, stable, non-reactive
- Hair-conditioning formulations	Enhance wet combing and render hair oleophobic	
Pesticides		
- Insecticide against the common housefly and carmine mite	Suffocation of the insect by the adsorbed fluorinated surfactant	?
- Insecticide against ants and cockroaches	?	?

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
- Formulation additives	Anti-foaming agent	Low surface tension
- Formulation additives	Dispersant, facilitate the spreading of plant protection agents on insects and plant leaves	Low surface tension
- Formulation additives	Dispersant, increase uptake by insects and plants	Low surface tension
- Formulation additive	Wetting agent for leaves	Low surface tension
Pharmaceuticals		
- Active ingredient (fulvestrant)	Estrogen antagonists, inhibits the growth stimulus that the estrogen exert on cells	?
- Active ingredient	Pharmaceutical combination of dabigatran and proton pump inhibitors	?
- Formulation additives	Dispersant in self-propelling aerosol pharmaceuticals	Low surface tension
- Formulation additives	Solvent	Hydrophobic and oleophobic
Pipes, pumps, fittings and liners		
- Pipes, pipe plugs, seal glands, pump parts, fasteners, fittings and liners	Polymeric PFAS are used for these applications	Stable, non-reactive, low surface tension, hydrophobic and oleophobic
- Working fluid for pumps in the electronics industry	Stable to reactive gases and aluminium chloride	Extremely stable, non-reactive
Plastic and rubber		
- Plastic	Polymeric PFAS micropowder as additive ?	?
- Thermoplastic	Plasticizer	?
- Bonding of rubber to steel	Allow adhesiveness bonding	Low surface tension
- Rubber and plastic	Antistatic agent	Low dielectric constant
- Resin	Improve weatherability and elasticity	Non-reactive, stable
- Polycarbonate resins	Flame retardant for polycarbonate resins	Non-flammable
Printing (inks)		
- Toner and printer ink	Enhance ink flow and levelling, improve wetting, aid pigment dispersion	Low surface tension
- Toner and printer ink	Impart water resistance to water-based inks	Hydrophobic
- Ink-yet recording heads	Make them ink repellent	Low surface tension
- Recording and printing paper	?	?
- Lithographic printing plates	?	?
Refrigerant systems		
- Refrigerant fluid system	Heat transfer fluid	Good heat conductivity
- Refrigerant compressor	Lubricants	Non-flammable
Sealants and adhesives		
- Sealants	Can be made out of polymeric PFAS	Operate at a wide temperature range, non-reactive, stable
- Silicone rubber seals	Prevents soiling	Low surface tension, hydrophobic and oleophobic
- Adhesives	Improve levelling, spreading, and the penetration of the adhesive into the pore structure of the substrates	Low surface tension
- Adhesives	Antistatic agent	Low dielectric constant
Soldering		
- Vapour phase fluids in vapour phase soldering	Heat transfer medium	Good heat conductivity
- Fluxing agent in solder paste	Low-foaming noncorrosive wetting agent	Non-reactive, stable, low surface tension

Table 4 (*Contd.*)

Use category/subcategory	Function of PFAS	Properties of the PFAS employed
Soil remediation		
- Vapour barrier material on top of contaminated soil	Evaporation retarder	?
- Surfactants to mobilize pollutants	Surfactants to mobilize soil-bound contaminants in remediation	Stable, non-degradable (during photodegradation)
Sport article		
- Ski wax	Highly water repellent	Low surface tension, hydrophobic
- (Sailing) boat equipment	Weather protection of textiles; anti-fouling protection of ship hulls	Non-reactive, stable, hydrophobic and oleophobic
- Tennis rackets	Used in coatings for tennis rackets	?
- Bicycle	Lubricants	Hydrophobic
- Climbing ropes	Provide water repellence, stain resistance and soil release	Low surface tension, hydrophobic
- Fishing lines	No water absorption, invisible in water, high knot strength	Hydrophobic
- Golf gloves	Antifouling protection for the natural sheep leather of the glove	?
Stone, concrete and tile	Impart oil and water repellency to the surface; delay oxidation and ageing of surface	Low surface tension, hydrophobic and oleophobic
Textile and upholstery		
- Surface treatment	Provide water and oil repellence, stain resistance and soil release	Low surface tension, hydrophobic and oleophobic
- Waving yarn	Facilitate waving	?
Tracing and tagging		
- Tracking air–borne pollutants	Tracer in air	Non-radioactive, chemically and thermally stable, do not occur naturally, have very low atmospheric background concentrations
- Testing ventilation systems	Tracer in air	〃
- Mapping gas and petroleum reservoirs	Tracer in gas or petroleum	〃
- Leak detection in cables, pipelines, landfill waste and underground storage tanks	Tracer in leaking material	〃
- Tracking of marked items	Tracer in the marked item	〃
Water and effluent treatment		
- Filter membranes	Polymeric PFAS minimize the sorption of compounds to the filter itself	Low surface tension
Wire and cable	Provide high-temperature endurance, fire resistance, and high-stress crack resistance	Non-flammable, operate at a wide temperature range

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References

1 R. C. Buck, J. Franklin, U. Berger, J. M. Conder, I. T. Cousins, P. D. J. Voogt, A. K. Allan, M. Kurunthachalam, S. A. van Leeuwen and P. J. J. Stefan, Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins, *Integr. Environ. Assess. Manage.*, 2011, **7**(4), 513–541, DOI: 10.1002/ieam.258.

2 OECD, *Toward a New Comprehensive Global Database of Per- and Polyfluoroalkyl Substances (PFASs) – Series on Risk Management Nr. 39*, 2018, http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV-JM-MONO(2018)7&doclanguage=en.

3 E. Kissa, *Fluorinated Surfactants and Repellents*, Marcel Dekker AG, 2001.

4 I. T. Cousins, C. Ng, Z. Wang and M. Scheringer, Why is High Persistence Alone a Major Cause of Concern?, *Environ. Sci.: Processes Impacts*, 2019, 2, DOI: 10.1039/C8em00515j.

5 Sweden_and_other_EU_countries, *Elements for an EU-Strategy for PFASs*, 2019.

6 I. T. Cousins, G. Goldenman, D. Herzke, R. Lohmann, M. Miller, C. A. Ng, S. Patton, M. Scheringer, X. Trier, L. Vierke, Z. Wang and J. C. DeWitt, The concept of essential use for determining when uses of PFASs can be phased out, *Environ. Sci.: Processes Impacts*, 2019, 1–13, DOI: 10.1039/c9em00163h.

7 R. R. Thomas, Fluorinated surfactants, in *Chemistry and Technology of Surfactants*, ed. R. J. Farn, Blackwell Publishing, 2006.

8 R. C. Buck, P. M. Murphy and M. Pabon, Chemistry, Properties, and Use of Commercial Fluorinated Surfactants, in *The Handbook of Environmental Chemistry – Polyfluorinated Chemicals and Transformation Products*, ed. T. P. Knepper and F. T. Lange, Springer Berlin Heidelberg, 2012, vol. 17, pp. 1–24, DOI: 10.1007/978-3-642-21872-9.

9 Britannica, *Surface tension*, https://www.britannica.com/science/surface-tension, published 2020, accessed August 26, 2020.

10 S. Alexander, G. N. Smith, C. James, S. E. Rogers, F. Guittard, M. Sagisaka and J. Eastoe, Low-surface energy surfactants with branched hydrocarbon architectures, *Langmuir*, 2014, **30**(12), 3413–3421, DOI: 10.1021/la500332s.

11 F. M. Fowkes, Contact Angle, Wettability, and Adhesion, Copyright, Advances in Chemistry Series, in *Advances in Chemistry*, ed. R. F. Gould, Washington DC, 1964, DOI: 10.1021/ba-1964-0043.fw001.

12 Z. Wang, I. T. Cousins, M. Scheringer and K. Hungerbühler, Fluorinated alternatives to long-chain perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkane sulfonic acids (PFSAs) and their potential precursors, *Environ. Int.*, 2013, **60**(2013), 242–248, DOI: 10.1016/j.envint.2013.08.021.

13 B. Ameduri, Fluoropolymers: The Right Material for the Right Applications, *Chem.–Eur. J.*, 2018, **24**(71), 18830–18841, DOI: 10.1002/chem.201802708.

14 J. M. Boucher, I. T. Cousins, M. Scheringer, K. Hungerbühler and Z. Wang, Toward a Comprehensive Global Emission Inventory of C4–C10 Perfluoroalkanesulfonic Acids (PFSAs) and Related Precursors: Focus on the Life Cycle of C6- and C10-Based Products, *Environ. Sci. Technol. Lett.*, 2019, **6**(1), 1–7, DOI: 10.1021/acs.estlett.8b00531.

15 Z. Wang, I. T. Cousins, M. Scheringer, R. C. Buck and K. Hungerbühler, Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, part I: production and emissions from quantifiable sources, *Environ. Int.*, 2014, **70**, 62–75, DOI: 10.1016/j.envint.2014.04.013.

16 Z. Wang, I. T. Cousins, U. Berger, K. Hungerbühler and M. Scheringer, Comparative assessment of the environmental hazards of and exposure to perfluoroalkyl phosphonic and phosphinic acids (PFPAs and PFPiAs): current knowledge, gaps, challenges and research needs, *Environ. Int.*, 2016, **89–90**, 235–247, DOI: 10.1016/j.envint.2016.01.023.

17 Z. Wang, J. M. Boucher, M. Scheringer, I. T. Cousins and K. Hungerbühler, Toward a Comprehensive Global Emission Inventory of C4–C10 Perfluoroalkanesulfonic Acids (PFSAs) and Related Precursors: Focus on the Life Cycle of C8-Based Products and Ongoing Industrial Transition, *Environ. Sci. Technol.*, 2017, **51**(8), 4482–4493, DOI: 10.1021/acs.est.6b06191.

18 Z. Wang, G. Goldenman, T. Tugran, A. McNeil and M. Jones, *Per- and Polyfluoroalkylether Substances: Identity, Production and Use*, 2020, DOI: 10.6027/na2020-901.

19 K. Prevedouros, I. T. Cousins, R. C. Buck and S. H. Korzeniowski, Sources, fate and transport of perfluorocarboxylates, *Environ. Sci. Technol.*, 2006, **40**(1), 32–44, DOI: 10.1021/es0512475.

20 Norwegian Environment Agency, *Investigation of Sources of PFBS into the Environment (M-759)*, 2017.

21 Norwegian Environment Agency, *Investigation of Sources to PFHxS in the Environment (M-961)*, 2018.

22 OECD, *Hazard Assessment of Perfluorooctane Sulfonate (PFOS) and Its Salts*, 2002.

23 POPRC, *Risk Profile: Perfluorohexane Sulfonic Acid (CAS No: 355-46-4, PFHxS), Its Salts and PFHxS-Related Compounds – Addendum*, UNEP/POPS/POPRC.14/6/Add.1, 2018.

24 POPRC, *Technical Paper on the Identification and Assessment of Alternatives to the Use of Perfluorooctane Sulfonic Acid, Its Salts, Perfluorooctane Sulfonyl Fluoride and Their Related Chemicals in Open Applications*, UNEP/POPS/POPRC.8/INF/17/Rev.1, 2012.

25 POPRC, *Consolidated Guidance on Alternatives to Perfluorooctane Sulfonic Acid and Its Related Chemicals*, UNEP/POPS/POPRC.12/INF/15/Rev.1, 2016.

26 POPRC, *Risk Profile on Pentadecafluorooctanoic Acid (CAS No: 335-67-1, PFOA, Perfluorooctanoic Acid), Its Salts and PFOA-Related Compounds – Addendum*, UNEP/POPS/POPRC.12/11/Add.2, 2016.

27 POPRC, *Risk Management Evaluation on Pentadecafluorooctanoic Acid (CAS No: 335-67-1, PFOA, Perfluorooctanoic Acid), Its Salts and PFOA-Related Compounds – Addendum*, UNEP/POPS/POPRC.13/7/Add.2, 2017.

28 POPRC, *Addendum to the Risk Management Evaluation on Perfluorooctanoic Acid (PFOA), Its Salts and PFOA-Related Compounds*, UNEP/POPS/POPRC.14/6/Add.2, 2018, http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC14/Overview/tabid/7398/Default.aspx.

29 POPRC, *Report on the Assessment of Alternatives to Perfluorooctane Sulfonic Acid, Its Salts and Perfluorooctane Sulfonyl Fluoride*, UNEP/POPS/POPRC.14/INF/13, 2019.

30 FluoroIndustry, FluoroCouncil, https://fluorocouncil.com/applications/, published 2019, accessed March 22, 2019.

31 ECHA, *Five European states call for evidence on broad PFAS restriction*, https://echa.europa.eu/de/-/five-european-states-call-for-evidence-on-broad-pfas-restriction, published 2020, accessed May 13, 2020.

32 J. Gardiner, Fluoropolymers: Origin, Production, and Industrial and Commercial Applications, *Aust. J. Chem.*, 2015, **68**(1), 13–22, DOI: 10.1071/ch14165.

33 D. Herzke, S. Posner and E. Olsson, *Survey, Screening and Analyses of PFCs in Consumer Products*, 2009, www.swereaivf.se.

34 L. M. Hodgkins, *Per- and polyfluoroalkyl substances in the Royal Canadian Navy*, 2018.

35 KEMI Swedish Chemical Agency, *Occurrence and Use of Highly Fluorinated Substances and Alternatives*, 2015, https://www.norden.org/en/publication/and-polyfluorinated-substances-nordic-countries.

36 G. H. Millet and J. L. Kosmala, Fluorine-Containing Polymers, Polychlorotrifluoroethylene, in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2000, pp. 1–6, DOI: 10.1002/0471238961.1615122513091212.a01.

37 P. Savu, Fluorine-Containing Polymers, Perfluoroalkanesulfonic Acids, in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2000, pp. 1–7, DOI: 10.1002/0471238961.1605180619012221.a01.

38 Y. Wang, W. Chang, L. Wang, Y. Zhang, Y. Zhang, M. Wang, Y. Wang and P. Li, A review of sources, multimedia distribution and health risks of novel fluorinated alternatives, *Ecotoxicol. Environ. Saf.*, 2019, **182**, DOI: 10.1016/j.ecoenv.2019.109402.

39 Norden, *Per- and Polyfluorinated Substances in the Nordic Countries – Use Occurence and Toxicology*, 2013, DOI: 10.6027/TN2013-542.

40 R. E. Banks, B. E. Smart and J. C. Tatlow, *Organofluorine Chemistry*, ed. Banks R. E., Smart B. E. and Tatlow J. C., Springer US, Boston, MA, 1994, DOI: 10.1007/978-1-4899-1202-2.

41 M. G. Costello, R. M. Flynn and J. G. Owens, Fluoroethers and Fluoroamines, in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2000, vol 11, pp. 1–12, DOI: 10.1002/0471238961.0612211506122514.a01.pub2.

42 J. E. Dohany, Fluorine-Containing Polymers, Poly(Vinylidene Fluoride), in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2000, DOI: 10.1002/0471238961.1615122504150801.a01.

43 S. Ebnesajjad and L. G. Snow, Fluorine-Containing Polymers, Poly(Vinyl Fluoride), in *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, Inc., 2000, DOI: 10.1002/0471238961.1615122505021405.a01.

44 Norden, *SPIN – Substances in preparations in Nordic countries*, http://www.spin2000.net/spinmyphp/, published 2020, accessed April 8, 2020.

45 CAS, SciFinder^n, https://scifinder-n.cas.org/, published 2019, accessed November 5, 2019.

46 Google Patents, https://patents.google.com, published 2019, accessed December 5, 2019.

47 P. Peters, *Personal Communication*, 2020.

48 F2_Chemicals, *Fluorocarbons*, http://www.f2chemicals.com/full_range.html, published 2019, accessed September 25, 2019.

49 3M, *3M™ Novec™ 7000 Engineered Fluid – Product Information*, 2014, http://multimedia.3m.com/mws/mediawebserver?66666UuZjcFSLXTtlXftMxMVEVuQEcuZgVs6EVs6E666666–.

50 3M, *3M™ Novec™ 7100 Engineered Fluid – Product Information*, 2009.

51 3M, *3M™ Novec™ 7500 Engineered Fluid – Product Information*, 2008.

52 3M, *3M™ Novec™ 7200 Engineered Fluid – Product Information*, 2009, https://multimedia.3m.com/mws/media/199819O/3mtm-novectm-7200-engineered-fluid.pdf.

53 Chemours, *Vertrel™ X-DF – Drying Agent*, 2019, https://www.chemours.com/en/brands-and-products/vertrel/products/xdf.

54 P.-E. Schulze and H. Norin, *Fluorinated Pollutants in All-Weather Clothing*, Friends of the Earth Norway, 2006.

55 G. F. Peaslee, J. T. Wilkinson, S. R. McGuinness, M. Tighe, N. Caterisano, S. Lee, A. Gonzales, M. Roddy, S. Mills and K. Mitchell, Another Pathway for Firefighter Exposure to Per- and Polyfluoroalkyl Substances: Firefighter Textiles, *Environ. Sci. Technol. Lett.*, 2020, 5, DOI: 10.1021/acs.estlett.0c00410.

56 R. M. Janousek, S. Lebertz and T. P. Knepper, Previously unidentified sources of perfluoroalkyl and polyfluoroalkyl substances from building materials and industrial fabrics, *Environ. Sci.: Processes Impacts*, 2019, **21**(11), 1936–1945.

57 H. Zhu and K. Kannan, A pilot study of per- and polyfluoroalkyl substances in automotive lubricant oils from the United States, *Environ. Technol. Innov.*, 2020, **19**, 100943, DOI: 10.1016/j.eti.2020.100943.

58 A. W. Nørgaard, P. Wolkoff and F. R. Lauritsen, Characterization of nanofilm spray products by mass spectrometry, *Chemosphere*, 2010, **80**(11), 1377–1386, DOI: 10.1016/j.chemosphere.2010.06.004.

59 A. W. Nørgaard, J. S. Hansen, J. B. Sørli, M. Levin, P. Wolkoff, G. D. Nielsen, D. Gunnar and S. T. Larsen, Pulmonary toxicity of perfluorinated silane-based nanofilm spray products: solvent dependency, *Toxicol. Sci.*, 2014, **137**(1), 179–188, DOI: 10.1093/toxsci/kft225.

60 K. A. Barzen-Hanson, S. C. Roberts, S. Choyke, K. Oetjen, A. McAlees, N. Riddell, R. McCrindle, P. L. Ferguson, C. P. Higgins and J. A. Field, Discovery of 40 Classes of Per- and Polyfluoroalkyl Substances in Historical Aqueous Film-Forming Foams (AFFFs) and AFFF-Impacted Groundwater, *Environ. Sci. Technol.*, 2017, **51**(4), 2047–2057, DOI: 10.1021/acs.est.6b05843.

61 X. Dauchy, V. Boiteux, C. Bach, C. Rosin and J. F. Munoz, Per- and polyfluoroalkyl substances in firefighting foam concentrates and water samples collected near sites impacted by the use of these foams, *Chemosphere*, 2017, **183**, 53–61, DOI: 10.1016/j.chemosphere.2017.05.056.

62 B. J. Place and J. A. Field, Identification of novel fluorochemicals in aqueous film-forming foams used by the US military, *Environ. Sci. Technol.*, 2012, **46**(13), 7120–7127, DOI: 10.1021/es301465n.

63 W. J. Backe, T. C. Day and J. A. Field, Zwitterionic, cationic, and anionic fluorinated chemicals in aqueous film forming foam formulations and groundwater from U.S. military bases by nonaqueous large-volume injection HPLC-MS/MS, *Environ. Sci. Technol.*, 2013, **47**(10), 5226–5234, DOI: 10.1021/es3034999.

64 A. Rotander, A. Kärrman, L. M. L. Toms, M. Kay, J. F. Mueller and M. J. Gómez Ramos, Novel fluorinated surfactants tentatively identified in firefighters using liquid chromatography quadrupole time-of-flight tandem mass spectrometry and a case-control approach, *Environ. Sci. Technol.*, 2015, **49**(4), 2434–2442, DOI: 10.1021/es503653n.

65 M. Mumtaz, Y. Bao, L. Liu, J. Huang, G. Cagnetta and G. Yu, Per- and Polyfluoroalkyl Substances in Representative Fluorocarbon Surfactants Used in Chinese Film-Forming Foams: Levels, Profile Shift, and Environmental Implications, *Environ. Sci. Technol. Lett.*, 2019, **6**(5), 259–264, DOI: 10.1021/acs.estlett.9b00154.

66 W. A. Gebbink, S. Ullah, O. Sandblom and U. Berger, Polyfluoroalkyl phosphate esters and perfluoroalkyl carboxylic acids in target food samples and packaging-method development and screening, *Environ. Sci. Pollut. Res.*, 2013, **20**(11), 7949–7958, DOI: 10.1007/s11356-013-1596-y.

67 I. K. Dimzon, X. Trier, T. Frömel, R. Helmus, T. P. Knepper and P. De Voogt, High Resolution Mass Spectrometry of Polyfluorinated Polyether-Based Formulation, *J. Am. Soc. Mass Spectrom.*, 2016, **27**(2), 309–318, DOI: 10.1007/s13361-015-1269-9.

68 M. Kotthoff, J. Müller, H. Jürling, M. Schlummer and D. Fiedler, Perfluoroalkyl and polyfluoroalkyl substances in consumer products, *Environ. Sci. Pollut. Res.*, 2015, **22**(19), 14546–14559, DOI: 10.1007/s11356-015-4202-7.

69 J. Bečanová, L. Melymuk, Š. Vojta, K. Komprdová and J. Klánová, Screening for perfluoroalkyl acids in consumer products, building materials and wastes, *Chemosphere*, 2016, **164**, 322–329, DOI: 10.1016/j.chemosphere.2016.08.112.

70 C. Blom and L. Hanssen. *Analysis of Per- and Polyfluorinated Substances in Articles (M-360)*, 2015.

71 F. Xiao, S. A. Golovko and M. Y. Golovko, Identification of novel non-ionic, cationic, zwitterionic, and anionic polyfluoroalkyl substances using UPLC-TOF-MS E high-resolution parent ion search, *Anal. Chim. Acta*, 2017, **988**, 41–49, DOI: 10.1016/j.aca.2017.08.016.

72 D. Borg and J. Ivarsson, *Analysis of PFASs and TOF in Products*, 2017, http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-4901.

73 K. V. Vejrup and B. Lindblom, *Survey of Chemical Substances in Consumer Products – Analysis of Perfluorooctanesulfonate Compounds in Impregnating Agents*, Wax and Floor Polish Products, 2002.

74 M. J. A. Dinglasan-Panlilio and S. A. Mabury, Significant residual fluorinated alcohols present in various fluorinated materials, *Environ. Sci. Technol.*, 2006, **40**(5), 1447–1453, DOI: 10.1021/es051619.

75 S. Fiedler, G. Pfister and K. W. Schramm, Poly- and perfluorinated compounds in household consumer products, *Toxicol. Environ. Chem.*, 2010, **92**(10), 1801–1811, DOI: 10.1080/02772248.2010.491482.

76 GMI, *Fluorotelomers Market Report*, 2016.

77 GMI, *Fluorochemicals Market Report*, 2018.

78 GMI, *Perfluoropolyether Market Report*, 2019, https://www.gminsights.com/industry-analysis/perfluoropolyether-market.

79 NORMAN, Norman Substance Databse, https://www.norman-network.com/nds/susdat/susdatSearchShow.php.

80 Z. Wang, I. T. Cousins, M. Scheringer, R. C. Buck and K. Hungerbühler, Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, part II: the remaining pieces of the puzzle, *Environ. Int.*, 2014, **69**, 166–176, DOI: 10.1016/j.envint.2014.04.006.

81 AGC, *Fluoroplastics*, https://www.agcce.com/fluoroplastics/, published 2018, accessed June 6, 2020.

82 Edelrid, *Das weltweit erste PFC freie Kletterseil*, https://www.edelrid.de/de/microsite/kletterseil-swift-eco-dry.php, published 2020, accessed April 24, 2020.

83 Opinion.org, *Fake Market Research*, https://opinion.org/market-research-industry-clogged-with-spam/, published 2018, accessed February 13, 2020.

84 ECHA, *Fighting fire with fluorine-free foams*, https://echa.europa.eu/fluorine-free-foams, accessed June 18, 2020.
85 DOD, *DOD Funds Firefighting Foam Research for a PFAS-Free Alternative*, https://www.defense.gov/Explore/News/Article/Article/2018096/dod-funds-firefighting-foam-research-for-a-pfas-free-alternative/, published 2019, accessed June 18, 2020.
86 ChemSec, *PFC-free food packaging tray*, https://marketplace.chemsec.org/Alternative/PFC-free-food-packaging-tray-354, accessed June 18, 2020.
87 ChemicalWatch, *Denmark announces advisory ban on PFCs in food packaging*, https://chemicalwatch.com/36900/denmark-announces-advisory-ban-on-pfcs-in-food-packaging, published 2015, accessed June 18, 2020.
88 Rudolf, *BIONIC-FINISH®ECO*, https://www.rudolf.de/en/technology/bionic-finish-eco/, accessed June 18, 2020.
89 SympaTex, *Our solution: Sympatex avoids harmful chemistry*, https://www.sympatex.com/en/sustainability/our-solution-closing-the-loop/reduction-in-the-use-of-chemicals/, accessed June 18, 2020.
90 DEPA, *Alternatives to Perfluoroalkyl and Polyfluoro- Alkyl Substances (PFAS) in Textiles*, 2015, http://www2.mst.dk/Udgiv/publications/2015/05/978-87-93352-16-2.pdf.
91 S. Schellenberger, P. Gillgard, A. Stare, A. Hanning, O. Levenstam, S. Roos and I. T. Cousins, Facing the rain after the phase out: performance evaluation of alternative fluorinated and non-fluorinated durable water repellents for outdoor fabrics, *Chemosphere*, 2018, **193**, 675–684, DOI: 10.1016/j.chemosphere.2017.11.027.
92 Y. Pan, H. Zhang, Q. Cui, N. Sheng, L. W. Y. Yeung, Y. Guo, Y. Sun and J. Dai, First Report on the Occurrence and Bioaccumulation of Hexafluoropropylene Oxide Trimer Acid: An Emerging Concern, *Environ. Sci. Technol.*, 2017, **51**(17), 9553–9560, DOI: 10.1021/acs.est.7b02259.
93 W. A. Gebbink, L. Van Asseldonk and S. P. J. Van Leeuwen, Presence of Emerging Per- and Polyfluoroalkyl Substances (PFASs) in River and Drinking Water near a Fluorochemical Production Plant in the Netherlands, *Environ. Sci. Technol.*, 2017, **51**(19), 11057–11065, DOI: 10.1021/acs.est.7b02488.
94 A. B. Lindstrom, J. E. Galloway and M. J. Strynar, D. Knappe, M. Sun, S. Newton and L. K. Weavers, Emerging Per- and Polyfluoroalkyl Substances (PFAS), *Highly Fluorinated Compounds Social and Scientific Discovery Northeastern*, University Social Science Environmental Health Research Institute, Boston, 2017.
95 A. Y. C. Lin, S. C. Panchangam and C. C. Lo, The impact of semiconductor, electronics and optoelectronic industries on downstream perfluorinated chemical contamination in Taiwanese rivers, *Environ. Pollut.*, 2009, **157**(4), 1365–1372, DOI: 10.1016/j.envpol.2008.11.033.
96 C. Y. Tang, Q. S. Fu, A. P. Robertson, C. S. Criddle and J. O. Leckie, Use of reverse osmosis membranes to remove perfluorooctane sulfonate (PFOS) from semiconductor wastewater, *Environ. Sci. Technol.*, 2006, **40**(23), 7343–7349, DOI: 10.1021/es060831q.
97 H. Hauser, L. Füglister and T. Scheffelmaier, *Verwendung von Fluortensiden in Der Galvanikbranche*, 2020.
98 NIH, Pubchem, U.S. National Library of Medicine National Center for Biotechnology Information, https://pubchem.ncbi.nlm.nih.gov/, published 2019, accessed September 25, 2019.
99 X. Zhang, X. Sun, R. Jiang, E. Y. Zeng, E. M. Sunderland and D. C. G. Muir, Screening New Persistent and Bioaccumulative Organics in China's Inventory of Industrial Chemicals, *Environ. Sci. Technol.*, 2020, **54**, 7398–7408.
100 CSRwire, *3M Phasing Out Some of its Specialty Materials*, https://www.csrwire.com/press_releases/25065-3M-Phasing-Out-Some-of-its-Specialty-Materials, published 2000, accessed June 6, 2020.
101 USEPA, *Fact Sheet: 2010/2015 PFOA Stewardship Program*, https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/fact-sheet-20102015-pfoa-stewardship-program, accessed June 8, 2020.
102 BloombergLaw, *Older PFAS That EPA Thought Obsolete Still Used, Agency Told*, 2020, https://news.bloomberglaw.com/environment-and-energy/older-pfas-that-epa-thought-obsolete-still-used-agency-told.
103 I. T. Cousins, R. Vestergren, Z. Wang, M. Scheringer and M. S. McLachlan, The precautionary principle and chemicals management: The example of perfluoroalkyl acids in groundwater, *Environ. Int.*, 2016, **94**, 331–340, DOI: 10.1016/j.envint.2016.04.044.
104 G. Munoz, M. Desrosiers, S. V. Duy, P. Labadie, H. Budzinski, J. Liu and S. Sauvé, Environmental Occurrence of Perfluoroalkyl Acids and Novel Fluorotelomer Surfactants in the Freshwater Fish Catostomus commersonii and Sediments Following Firefighting Foam Deployment at the Lac-Mégantic Railway Accident, *Environ. Sci. Technol.*, 2017, **51**(3), 1231–1240, DOI: 10.1021/acs.est.6b05432.
105 A. R. Angusfire, *FFFP – Alcohol resistant film forming fluoroprotein*, http://angusfire.co.uk/products/foam-concentrates/product-range/ar-fffp/, published 2019, accessed October 23, 2019.
106 S. H. Korzenioswski, R. C. Buck, D. M. Kempisty and M. Pabon, Fluorosurfactants in Firefighting Foams: Past and Present (Chapter 1), in *Perfluoroalkyl Substances in the Environment*, ed. Kempisty D. M., Xing Y. and Racz L., CRC Press, 2019.
107 F. Heydebreck, J. Tang, Z. Xie and R. Ebinghaus, Emissions of Per- and Polyfluoroalkyl Substances in a Textile Manufacturing Plant in China and Their Relevance for Workers' Exposure, *Environ. Sci. Technol.*, 2016, **50**(19), 10386–10396, DOI: 10.1021/acs.est.6b03213.
108 H. Holmquist, S. Schellenberger, I. van der Veen, G. M. Peters, P. E. G. Leonards and I. T. Cousins, Properties, performance and associated hazards of state-of-the-art durable water repellent (DWR) chemistry for textile finishing, *Environ. Int.*, 2016, **91**, 251–264, DOI: 10.1016/j.envint.2016.02.035.

109 SpecialChem, *What are Fluoropolymers-based PPA?*, https://polymer-additives.specialchem.com/centers/fluoropolymers-as-polymer-processing-aid, published 2020, accessed June 4, 2020.

110 Unknown, *Polyethylene composition for artificial turf*, patent EP1672020, 2006.

111 Y. Wang, N. Yu, X. Zhu, H. Guo, J. Jiang, X. Wang, W. Shi, J. Wu, H. Yu and S. Wei, Suspect and Nontarget Screening of Per- and Polyfluoroalkyl Substances in Wastewater from a Fluorochemical Manufacturing Park, *Environ. Sci. Technol.*, 2018, **52**(19), 11007–11016, DOI: 10.1021/acs.est.8b03030.

112 J. W. Washington, C. G. Rosal, J. P. McCord, M. J. Strynar, A. B. Lindstrom, E. L. Bergman, S. M. Goodrow, H. K. Tadesse, A. N. Pilant, B. J. Washington, M. J. Davis, B. G. Stuart and T. M. Jenkins, Nontargeted mass-spectral detection of chloroperfluoropolyether carboxylates in New Jersey soils, *Science*, 2020, **368**(6495), 1103–1107, DOI: 10.1126/science.aba7127.

APPENDIX F

Report Review Comments

Summary of comments on draft Water Resource Report

March 16, 2025, *W&S responses updated October 7, 2025*

Data Requests

Data Request	Town Staff	Date Requested	Status
Assessors data (number of bedrooms); GIS layers: Overlay district maps	Alec Wade	Assessors data last requested April 25, 2025 Overlay maps have not been requested	Received.
Salt storage volume	Edward Kukkula	May 13, 2025	Received.
Codman Hill Road landfill – information on landfill and monitoring			Received.

Sub-task A, Draft 1 Report Comments

Commentor	**Comments**	**W&S Response**	**Status**
Les Fox	P 17 – typo: IS known	Will correct typo.	Addressed.
	P 21 – On watersheds/basins – Table 2.2 Designate which of these local watersheds align to SUASCO and which to Merrimac basins or major watersheds. Better yet, create an overlay showing this. Add a description of the hierarchy of water sheds or basins - a big picture of how the water flows/drains among	Section 2.6 has been updated to provide a clear distinction between surface watersheds and groundwater basins.	Addressed

Commentor	Comments	W&S Response	Status
	the minor and major basins. Can the map show the basin divides? The map Figure 2-10 doesn't show the components of SUASCO, Merrimac. Suggest adding some explanatory text near the beginning of the document with definitions of the elements of the hierarchy describing their inter-relationship. For example: watershed, basin, sub-basin, etc.		
	P 24. Check the number of fire ponds and cisterns with Chief Kivlan. He may have updated information. He'll be presenting on this topic at the March 18 WRC meeting. We are hoping he will have information on the status of cisterns and ponds: when last inspected, testing for sustained withdrawal, etc. We should update the final report with the	In contact with Chief Kivlan to obtain this information. I have received an updated number for the total number of ponds and cisterns, and have inquired about status. Janet provided 28 cisterns and 19 fire ponds in her edited version of the report	Addressed.

Commentor	Comments	W&S Response	Status
	most recent information.		
	P 25. Another comment on basins/watersheds. In the Fig 2-11 map do the areas outlined in red correspond to various scales of basins or watersheds?	The red lines indicate the groundwater basin boundaries. This is included in the legend and basins are labeled on maps.	Addressed.
	The Beaver Brook watershed is shown but not SUSASO - or is SUSASO everything not Beaver Brook? Explain.	SUASCO is everything outside of Beaver Brook – see figure referenced in response for Page 21 comment. We will update descriptions and graphics to clarify difference between watersheds, sub-basins, and MWI boundaries.	Addressed.
	P 26. Fix “preserves preserving”	Will correct this.	Addressed.
	Table 2.3. These areas add up to 11.4 sq mi which is more than the 10.4 sq mi of municipal Boxborough. Suggest adding a note of explanation. Perhaps the aquifer area includes portions outside Boxborough?	This has been removed as the original reference was not clear.	Addressed.
	P 27. The Planning Board will have an article for the May 2025 Town Meeting seeking to clarify that the water resource protections under	It was moved and approved to pass over Article 44, therefore no action was taken. A revised article was not brought to the October 2025 STM.	No action.

Commentor	Comments	W&S Response	Status
	the Zoning Bylaw for APD and those arising from the BOH regulations for wellhead Zone II and IWPS are not in conflict. May want to footnote the outcome of the 2025 ATM that will "rationalize" the APD and BOH protections.		
	P 29. Just a comment/note that the town is in a good place now with 8% impervious surface cover, and that the Planning Board and /or the BOH should take steps to ensure this is not degraded. For example, additional regulations on developed areas, required use of Perf-pavement, strong measures to improve recharge, etc.	Noted.	No Action.
	P 30. Add to Figure 3.1 What is model for percentage of evapotranspiration for the first two cases (natural ground cover, 10-20% impervious surface)?	The evapotranspiration numbers were cut off – will update this figure so that they're shown.	Addressed.
	Indicate Boxborough's	Added 8% point to graphic.	Addressed.

Commentor	Comments	W&S Response	Status
	current 8% IC in Figure 3.2		
	P 34. There are Fort Ponds in both of the neighboring towns of Acton and Littleton. Does this refer to one of them or both? Since the watersheds are all connected, most likely it includes both but perhaps one is more critical for protection of Boxborough's water resources. Clarify.	We will review and remove or update this text to clarify the connection.	Addressed.
	Add a link to the MADEP site that lists the hazardous waste sites, or, since links can change, note that they can be found on the MADEP pages.		Addressed.
Janet Keating	P 2-3: Do we have information on land use more current than that reported in 2016?	MassGIS – 2016 Unless town has land use layer that has not been shared MassGIS layer is most current data	No Action.
	P2-3: Is there a more current reference for this information? *(Boxborough Land Use chart)*	Same comment as above	No Action.
	P2-4: Is there a more current reference for this information?	Same comment as above	No Action.

Commentor	Comments	W&S Response	Status
	(Boxborough Land Use and Land Cover table)		
	P2-4: One could consider that there are land uses for wetlands, just not direct human use.	From MassGIS data	No Action.
	P2-4: Should this be <1? Otherwise, the total would be greater than 100%.	Will update.	Addressed.
	P2-5: Figures 2.2, 2.3 and 2.4 do not indicate the date of the source information used to create the maps. Are the sources listed in gray font at the bottom right of the image? Were these maps created by accessing MassGIS? If so, a secondary reference to the date on which MassGIS was accessed could be provided.	Update maps to include data source and date	Addressed.
	P2-13: Provide a reference to the most recent maps.		Addressed.
	P2-13: Proposing to delete "this work" as it could be misunderstood to be the work of this Water Resources report.		Addressed.

Commentor	Comments	W&S Response	Status
	P2-14 (Flood Hazard Map): Is this based on the most current maps?	Yes.	No Action.
	P 2-19: At which juncture of Fort Pond Brook?	https://www.boxborough-ma.gov/357/Fort-Pond-Brook Location (on google maps)	Addressed.
	P2-19: Are there impaired waters in the Merrimack River Watershed?		Addressed.
	P2-20: [updated with] Information provided by FD Chief during 3/18/2025 WRC meeting.		Addressed.
	P2-20: Why are these two roads on the same line?	Updated. All roads on separate lines	Addressed.
	P2-22: Although a Boxborough 2023 Plan is referenced, the data referenced in the Open Space and Recreation Plan may be dated. Is the Plan is a secondary source, referencing older data? Are there newer data?	Updated to remove referenced data.	Addressed.
	P2-22: What is the relationship between area in sq. mi. and recharge in million gpd? How was recharge determined?	Added language to discuss more on relationship between area and recharge Did not discuss how recharge was determined but listed the factors that impact recharge rate	Addressed.
	P3-25: The cited source for Figure 3.1 is U.S. Climate	Removed “within Boxborough” language	Addressed.

Commentor	Comments	W&S Response	Status
	Resilience Toolkit, 2020. Relationship Between Impervious Cover and Surface Runoff. This appears to be a generic schematic on urbanization and a rise in IC. However, is there increased urbanization in Boxborough? Is the phrase "within Boxborough" apt since the schematic is not specific to the town.		
	P3-25: Is use of the 2003 model the current state of practice? Is there a newer model by the Center for Watershed Protection or another entity?	*See if there is a newer model for urbanization and water quality see if there is a similar graphic Did not find a newer model – found other sources using the same graphic or referencing the 2003 CWP model. This source says (about CWP 2003 "this relationship has been substantiated by many studies over the years (Ourso and Frenzel, 2003, Roy A.H. et. Al., 2003, Walsh, C.J. et al., 2007)	No Action.
	P3-25: Is the estimate of 8% based on the use of the Center for Watershed Protection's Impervious Cover Model? If so, can you state, "Based on a site-specific	Added "based on the MassGIS Impervious Cover Layer" after 8%	Addressed.

Commentor	Comments	W&S Response	Status
	application of the model, Boxborough's current IC levels are estimated to be 8%." Will model input parameters and output be provided as an appendix to this report?		
	P3-26: This section should also include information on the Massachusetts DOT salt storage sheds that were the cause of contamination of groundwater and water supplies in the western portion of Boxborough, for which 6.5M was contributed to the Littleton Water Department project to extend a water line to properties west of I-495.	Added in paragraph about this in report	Addressed.
	P3-28: What is the basis of this number (Figure 2.2)? Table 2.1 shows 3% Agricultural land.		Addressed.
	P3-28: What is the date of the information that was included in the 2023 Open Space and Recreational Plan? If the 2% estimate is from the	Added statement to report	Addressed.

Commentor	Comments	W&S Response	Status
	2023 Plan, is it still true that the agricultural sector comprises 2% of the town's total land area? In other words, has there been any conversion of agricultural land to other uses since the time that the 2% estimate was made?		
	P3-29: Is this 2% of the total area of the town or of the watershed area? Maybe this could be clarified by stating the size of the agricultural land in the Elizabeth Brook watershed and the size of the Elizabeth Brook watershed.	Will review percentage of Elizabeth Brook watershed that is agricultural land.	Addressed.
	P3-30: What is the street address of this club?	Removed inaccurate information about country club.	No Action.
	P3-30: What regulatory agency requires this monitoring and has received the data from the required monitoring? Do we have these data?	Removed info on BCC	No Action.
	P3-30: leachate contamination of surface and groundwater.	Add to end of sentence	Addressed.

Commentor	Comments	W&S Response	Status
	P3-30: Need to add a description of the closed municipal landfill on Codman Hill Road, its proximity to Elizabeth Brook, and the monitoring that is done there. Do we have data on the monitoring that is done from the Board of Health or a MassDEP database?	Included landfill information provided by the town.	Addressed.
	P3-30: I do not think that this is categorically true.	Define brownfield vs superfund	Addressed.
	P3-30: Are there any Brownfield or Superfund sites in Acton, Littleton, Stow, or Harvard? Are these sites located sufficiently outside of shared watersheds such that they will not affect water quality in Boxborough?	adding language about number of potential brownfield sites to report	Addressed.
	P3-30: Add citation to the MassDEP Energy & Environmental Affairs Data Portal and date accessed	Edited text and added footnote	Addressed.
	P3-30: How many of these have been cleaned up, or closed? How many are active and have known impacts to	Additional information on Brownfields requested from the Town.	Addressed.

Commentor	Comments	W&S Response	Status
	groundwater or surface water quality? Are any of these responsible for past or current discharges of OHM to surface water/wetlands?		
	P3-30: Should add information about the PFAS release sites in Town. MassDEP also sent Requests for Information (RFI) to industrial businesses on Swanson and Codman Hill Road to ask about potential PFAS sources because of the PFAS contamination of Public Water Supply Wells at condominiums and other locations west of I-495. Data on contamination in these PWS wells is available Energy & Environmental Affairs Data Portal. The RFI letters are in the Waste Site Cleanup portion of the DEP data portal. Energy & Environmental Affairs Data Portal	Added section to report for "PFAS Release Sites".	Addressed.

Commentor	Comments	W&S Response	Status
Bryon Clemence	Figures – Indicate data sources, if possible, e.g. USGS, Mass. DEP, etc.	Will update maps/figures to include data sources where they are missing.	Addressed.
	Maps showing drainage subbasins (Figure 2.2, etc.). Highlight boundary between Merrimack and SuAsCo basins. Add boundaries to legend.		Addressed
	Explain the significance in the text (not sure where): Merrimack and SuAsCo basins are state-designated and have important regulatory implications in Boxborough (e.g. the Interbasin Transfer Act). The subbasins are important for water resource planning. Do they also have regulatory implications (e.g. the MS4 stormwater permit)? Section 2.6 gets into this. Should this be in the Introduction, as well?	Will add to Section 2.6.	Addressed
	Will the Introduction also have a drainage basin map? It would help to explain Boxborough's water situation and the goals of the study.	Will add to introduction section	Addressed
	Either section 1.0 Introduction or 2.0 should summarize Boxborough's infrastructure and reference where they are fully described	Noted. More detailed info will be provided in future sections.	Addressed.

Commentor	Comments	W&S Response	Status
	(e.g. private water supply and sewerage, water to be partially supplied by Littleton, electricity supplied by Littleton, three MassDOT highways, etc.).		
	At some point, section 2 and 3 should highlight some of the key regulatory requirements, e.g. snow dumps and the Aquifer Protection District and the BoH Groundwater Protection. Section 7 would address them in detail, of course.	Section 7 will cover a review of town regulations.	Addressed.
	Pg. 2-3 and 2-4. What is the source of the agricultural use? Does it include forestry? Forestry accounts for a lot of the agriculture here. This should affect water quality less than crop and animal operations (as discussed in section 3.2.4). For "Chapter" land, forestry is generally under Chapter 61, but a some of it occurs on Chapter 61A land too.	Land use data does not specify type of agriculture use. This data came from the Land Cover/Land Use GIS layer from MassGIS.	No Action.
	Pg. 2-3. Land Use vs. Land Cover. Can this also explain how the land use areas are calculated? For instance, is the 41% residential based on		Addressed.

Commentor	Comments	W&S Response	Status
	parcel area, assessor's records, zoning, etc.		
	Pg. 2-4. Is any impervious cover naturally occurring (e.g. rock outcrops)? Are single-family homes, etc. accounted for in the 8% and in Figure 2.4?	Will check data source to determine impervious cover type. Impervious cover does not include naturally occurring formations, and it does include single-family homes (and other buildings).	Addressed.
	Pg. 2-8. Where do the soil classes come from (e.g. NRCS)?	**Add data source to report	Addressed.
	Pg. 2-8 and Figure 2-7. Is the description of bedrock geology sufficient for our needs. There are several USGS reports that provide more detail and discuss applicability to water resources (e.g. the Nashoba Terrane, fracture mapping, etc.).	Section 5.6 covers groundwater recharge rates by groundwater basin.	Addressed.
	Pg. 2-13. It would be more intuitive to list flood hazard areas A/AE first. They are more likely to flood, and they are regulated more extensively. Also note that A/AE is 1 in 100 years and X is 1 in 500 years, on average.		Addressed.
	Pg. 2-17, 1st paragraph. Should watersheds be referred to as river basins, consistent with the state Surface Water Quality Standards (310 CMR 4.00)? While the SuAsCo is identified as a separate basin, it		Addressed.

Commentor	Comments	W&S Response	Status
	also flows to the Merrimack River, eventually. It's the Beaver Brook watershed that's in the Merrimack River basin. Everything else is in the SuAsCo basin. Although, as noted on page 2-19, it's the Assabet River that Boxborough drains to. That is impaired, which I believe affects our MS4 permit.		
	There is some doubt about the boundary of the Beaver Brook watershed. I believe part of Wolf Swamp drains south to Eldridge Pond. Do we have good topo maps that can verify this?	We are not developing our own watershed boundaries. These boundaries are either from a HUC watershed or they are the MWI/SWMI boundaries.	
	Pg. 2-17, 3rd paragraph. Note that wastewater needs are in section 6.		Addressed.
	Pg. 2-19, mid-page. Isn't Eldridge Pond on Harvard-Boxborough town line?	Yes, Eldridge Pond is located on the town line along Elizabeth Brook.	Addressed.
	Pg. 2-19, last paragraph. This is not consistent with section 2.6 and Table 2.2, where SuAsCo is 66% and Merrimack is 34%. SuAsCo should be the larger number.		Addressed.
	Pg. 2-21, Figure 2.11. This figure maps streams in greater detail than the other maps. What accounts for the difference? Should we attempt to	Will check for layer consistence. One includes MassDEP wetlands layer while the other just has Hydro25k layer.	Addressed

Commentor	Comments	W&S Response	Status
	make them more consistent?		
	Shouldn't Ludstrom Road Pond be Eldridge Pond? I'm not familiar with North Ludstrom Road Pond.	Ludstrom pond label is from the MassGIS hydro25k layer. The layer comes with waterbody labels that cannot be edited.	Addressed.
	Pg. 2-22, 2nd paragraph. There are also local laws; Boxborough has a local Wetland Bylaw and regulations.	Additional information will be included in the review of town regulations.	Addressed.
	Pg. 2-22, 3rd paragraph. Boxborough relies on groundwater for drinking water supply; firefighting utilizes surface waters, as well. Some of the private wells are regulated by DEP as small Public Water Systems (PWS). (There may be a better place to say this, or it may need to be repeated elsewhere.) We should confirm IEP as the source of the recharge area delineation; I believe the Aquifer Protection District map is similar, and I've seen a different source cited for that. Section 7 can address this when we get there.	Will include in Section 7.	Addressed.
	Pg. 2-23, 1st paragraph. Good to note that the BoH Groundwater Protection Regulation	Covered in section 5	No Action.

Commentor	Comments	W&S Response	Status
	applies to "facilities" within certain areas throughout the town. The APD applies to surficial aquifers. There is some overlap (e.g. the Zone IIs), but also areas of town that are covered by neither. The BoH Regulation is modeled on requirements of the DEP Drinking Water Regulations (310 CME 22.00).		
	Pg. 3-24. Other potential contamination sources are the closed landfill, floor drains, firefighting (PFAS), and building demolition (at construction sites). Should we mention airborne contaminants? For instance, EPA recently determined that exhaust from leaded aviation fuel is a health risk, and Boxborough is in the flight path of an airport.	Added firefighting PFAS to PFAS section The most common emerging contaminants have been included in the report.	Addressed.
	Pg. 3-24, section 3.2. This gets confusing because stormwater runoff applies to things like roadways, as well (but not things like septic systems). I'd also like to note that many of the NPS contaminants are		Addressed.

Commentor	Comments	W&S Response	Status
	naturally occurring or even necessary (nutrients), but human activities can make them problematic. I suggest deleting the references to road salt until we have information from the town and MAssDOT, since there are other deicing chemicals. Phosphorus is often a limiting nutrient for aquatic life.		
	Pg. 3-25. A source of pathogens could be runoff from failed septic systems (certain types of failure anyway). Does “oil” refer to heating oil; otherwise it wouldn’t be a fuel.		Addressed.
	Pg. 3-25, sec. 3.2.1 At some point, will we want to indicate that virtually the entire town is an aquifer recharge area, since water supply wells are located throughout town?		Acknowledged.
	Pg. 3-26. Suggest changing Road Salt to Deicing Chemicals; see comment above.		Addressed.
	Pg. 3-27, 1st paragraph. I believe the DPW garage is in the Guggins Brook watershed, and the MassDOT maintenance facility is in the Elizabeth		Addressed.

Commentor	Comments	W&S Response	Status
	Brook watershed. We'll be looking at other sources, as well (e.g, parking lots and private roads).		
	Pg. 3-27, section 3.2.3. Septic Systems should probably be changed to Wastewater Disposal. Generally, facilities generating less than 10,000 gallons per day use septic systems regulated by the Boxborough Board of Health. Facilities generating more than 10,000 gallons per day require a Groundwater Discharge permit from DEP and use small, package wastewater treatment plants.		Addressed.
	P. 3-28, Cropland Operations. Is phosphorus one of the less soluble compounds?		Addressed.
	P. 3-28, last paragraph. I'm not sure that agricultural operations must conform to these.		Addressed.
	P. 3-29, sec. 3.2.5. Would Soil Disturbance be a better heading for this? Erosion isn't limited to construction sites.		Addressed.
	P. 3-29, last paragraph.		Addressed.

Commentor	Comments	W&S Response	Status
	Boxborough doesn't have any golf courses, at this time. At one point the property now owned by Campanelli on Beaver Brook Road was approved for a golf course. I believe that approval expired and/or Campanelli has said they have no plans to include it in their permit renewal.		
	P. 3-30, sec. 3.2.7. We should include Boxborough's closed landfill? We work out how to get information on it.	Requested information on the landfill from the town.	Addressed.
	P. 3-30, last paragraph. Could we provide more detail? Are the 45 sites active? One or two of them are PFAS releases and are active as far as I know.		Addressed.

Sub-task B, Draft 2 Report Comments

Commentor	Comments	W&S Response	Status
Les Fox	For convenience of reference and comment tracking please add a rev number or date in the footer. It can be deleted in the final version.	Will add.	Addressed.
	p 2-2. Would like a short section on best estimate of the fraction of residences (or population) served by DEP regulated PWS vs unregulated private wells. I did an analysis about 5 years ago and concluded about 52% of residences were/are on private wells, with 48% on PWS. At the time I used an average of 2.43 persons per residence and made no distinction between condos and SFH. This data will be essential to our public outreach and education.	This is an intensive process that involves requesting and reviewing data from MassDEP and is outside of the scope of this project. Added to Section 8: Recommendations. This information will also be useful when calculating commercial vs residential use (detailed analysis included in recommendations)	Addressed.
	p 2-7. Add an comment or subtitle on Fig 2.4 stating that Boxborough's impervious cover is 8%. The text says "as shown in Fig 4 Boxborough's impervious cover is 8%", but it is difficult to get that from the figure. Evidently the darker shaded areas indicate some high percentage of impervious cover, clustered around commercial development, etc. Is there some quantitative meaning to the lighter shade of grey that	Will update.	Addressed.

Commentor	Comments	W&S Response	Status
	applies to just about everything else, eg., some lower average?		
	p 2-19. The draft report says Mill Pond in Littleton is the source for Beaver Brook. However, Beaver Brook originates in Wolf Swamp in Boxborough. It then flows into and then out of Mill Pond in Littleton, then winds its way, finally discharging into Forge Pond in Westford. I think that is the end of the named Beaver Brook, since the outlet of Forge Pond is Stony Brook. Please review the narrative for consistency regarding impaired waters in Boxborough. The draft says there are no listed impaired waters. This is at odds with Fig 2.11 "Impaired Waters Map." If some nearby currently impaired bodies are a threat to Boxborough, please discuss.	Will update.	Addressed
	p 3-25 protection of ~~PROTECT~~ aquifer		Addressed
	p 3-27. MADOT salt sheds have been identified as a source of ground water contamination. This is common knowledge for long-time residents, but that knowledge is being lost. It would be helpful if you could include a footnote or reference to a DEP report on some of this	Will update.	Addressed

Commentor	Comments	W&S Response	Status
	history. and in particular when it happened.		
	p 3-27 3.3.3 Wastewater disposal. .... areas WITHOUT a sewer system.		Addressed
	p 3-30. Section 3.2.7 Solid Waste Disposal Facilities. Please include a short paragraph about the old inactive and now capped dump, located at the site of the transfer station. This was provided with monitoring wells that are (or should be) still in use. For details on the history and current state contact Jim Garreffi at Nashoba Boards of Health, the town's agent. You could also contact Bryan Lynch, Water Resources Committee and member of the Boxborough BOH. I will send contact info.		Addressed
	p 3-31. 3.2.8 Brownfield and super fund sites - says there are three potential sites that have brownfield properties. We should consider putting something in the report about this, but treat with circumspection. I'll contact you.		Addressed.
	p 3-31 3.2.10 PFAS. Aqueous Film FORMING Foam		Addressed.
	p 4-42. ... understand how this growth may impact ~~THE~~ Boxborough's...		Addressed.
	p 4-44. Fig 4.2 Buildout map. Add comment		Addressed.

Commentor	Comments	W&S Response	Status
	indicating that the dots indicate single family houses.		
Bryon Clemence	Please include commercial land use and development. It's significant. For example, CDM calculated commercial water demand to be 0.11 mgd in 2002 and 0.43 mgd at build-out. For Figure 4.1, would a better title be Zoning Map?	Section 5.3.3 has been added to cover commercial water usage.	Addressed.
	I see a problem with the map of additional buildings, Figure 2.4. The map shows additional dwellings on at least 2 reduced frontage lots that cannot be subdivided, according to the special permits that authorized them. Details below. The map shows 9 new buildings on 5 lots on Burroughs Road. All of these are reduced frontage lots with about 5 to 10 acres and 50 feet of frontage each. They are served by two common driveways. There are 4 houses there now, and one more could be built. The build-out probably assumed these lots could be developed with a new subdivision road(s), since there is not enough frontage, otherwise. However, the special permits approving 2 of	The assessment is determining high level water usage and recharge by basin, and a parcel by parcel analysis is greater detail than the scope of this planning level assessment.	No action.

Commentor	Comments	W&S Response	Status
	these lots prohibit further subdivision. I suspect this is true for the other 3 lots, as well. Therefore, at least 5 to 8 of the 263 additional buildings identified in Figure 2.4 could not be built. I mention these 5 lots only because I know them personally. It may apply to other lots in town, as well. I’m trying to find out how many.		

Draft 3 Report Comments

<table>
<tr><th>Commentor</th><th>Comments</th><th>W&S Response</th><th>Status</th></tr>
<tr><td rowspan="2">Les Fox</td><td>Les completed an analysis of parcels that contain multi-family units – details provided in email.</td><td>Miscounting of multi-family properties has been addressed and all multifamily properties are accounted for.</td><td>Addressed.</td></tr>
<tr><td>Three parcels have been identified where water is supplied by either LWD or AWD. “The second can be used to complete the water supply and demand picture for external supply, which if course includes most of the area west of I-495. It think it would make sense to include all the areas being supplied by AWD or LWD in presenting an accurate picture of total town demand, even though the water supply is external.”
<table>
<tr><th colspan="3">Notes - parcels/properties with water service from LWD or AWD</th></tr>
<tr><td>Complex</td><td>Assessor parcel(s)</td><td># of Units</td></tr>
<tr><td>Note Meenmore Condos accessed from Littleton via Leonard Rd. Ind-Com District Water supplied by LWD via private service.</td><td>02-014</td><td>96 (counted above)</td></tr>
</table></td><td>Text in section 5.1 Water Supply updated to discuss the interconnections.</td><td>Addressed.</td></tr>
</table>

<table>
<tr><th>Commentor</th><th>Comments</th><th>W&S Response</th><th>Status</th></tr>
<tr><td></td><td><table>
<tr><td>80 & 90 Central Street Office Park District. Water supplied by LWD</td><td>11-054, 06-021</td><td>No residential</td></tr>
<tr><td>Joyce Industrial Park 235 Summer Road Ind-Com District. Water supplied by Acton WD.</td><td>20-044</td><td>No residential</td></tr>
</table></td><td></td><td></td></tr>
<tr><td></td><td>p 5-3 Fig 5.1. More contrast between the shading for the IWPA and Zone II areas would be nice.</td><td>Will update map.</td><td>Addressed.</td></tr>
<tr><td></td><td>pp 5-4 – 5-9 5.3 Current Drinking Water Usage, 5.4 Future Drinking Water Demand: Inaccurate representation of multi-family dwellings.

Also included a spreadsheet summarizing PWS vs private wells for multi-family and SFH dwellings, east and west of 495</td><td>The assessment has been updated to accurately reflect multifamily dwellings.

Information on homes that receive water from individual private wells vs PWS is not readily accessible for inclusion in this report and has been added as a recommendation for future analysis in Section 8.</td><td>Addressed</td></tr>
<tr><td></td><td>P 5-6 and following on future water demand. Include some estimates of current and projected commercial</td><td>Commercial water usage for existing developed and undeveloped</td><td>Addressed.</td></tr>
</table>

Commentor	Comments	W&S Response	Status
	demand/usage. There is significant land behind the hotel and the 1414 Mass Ave properties that is currently zoned OP. Also consider an extreme case where all this area is developed into dense housing under a future zoning scenario. This would entail additional PWS but still drawing on the water resource. These estimates would be useful to inform possible future discussions with Littleton and/or Acton to supply water to Boxborough.	commercial properties is being added to section 5.3.3 and 5.4.2. The buildout analysis only considered single family residential buildout and not maximum buildout of dense housing. This is included as a recommendation in Section 8.	
	P5-6 Last sentence: what is meant by "ensure long-term water security"?	This is being updated per Janet's comment	Addressed.
	P 5-9. "projected population from anticipated new development". Does this assume no changes to zoning or significant uses? Clarify.	This is projected under current zoning. Will update for clarity.	Addressed.
	P 5-10 5.5 Well Alternatives. What is the main message or conclusion of this section?	Will update to include an introduction.	Addressed.
	P 5-17 5.7 Overview. "… recharge sources appear to be adequate to address future development demand". This is an important and key conclusion! Highlight, set off in a box, etc. Will inclusion of future commercial demand change this? Add comment on this.	Will add a highlight box.	Addressed.
	P 6-2 6.2 Middle of para: Add word "These types of facilities.."	Will update.	Addressed
	P 6-6 6.4 Environmental Risk Assessment. Does this include	We have updated the environmental risk assessment and	Addressed.

Commentor	Comments	W&S Response	Status
	the results of the very recent updates to flood maps?	it now includes the new flood maps. The updated flood maps will be included in Figure 2.8 but not in the buildout.	
	P 6-7 Table 6.4 and discussion. Explain the septic system tiering – definitions and/or criteria. Is there a key message from this section? Highlight it.	Will update to include definitions, criteria, and key message.	Addressed.
John Markiewicz	For Figure 5.1 , It might be helpful to the reader (public) to have a Table, by Groundwater Basin showing the address of each well by type. Figure 5.1 has a great deal of very useful information and this type of a Table might make it easier to understand.	Will create a table with a list of drinking water supply wells	Addressed.
	I did not see a definition of "limited soils" in Section 6.	Will add definition of “limited soils”	Addressed
Bryan Lynch	My request would be to have an overlay of the zone 2 and IWPA well protection areas over the parcels of land and house lots under the well protection areas.	Create a map with these layers.	Addressed.
Janet Keating	P4-33: Footnote 20 and 29 use U.S. Census and other footnotes uses United States Census	Will update footnote references for consistency.	Addressed
	P4-34: Skipped Footnote 21?	Will update footnote reference numbering.	Addressed
	P4-34: I know that the superscript numbers are to flag a footnote but it could be hard for some to read with two	Will update Table 4.1 to have a data source column	Addressed

Commentor	Comments	W&S Response	Status
	different sized numbers. What about a column for Data Source between Population and Average Annual Population Change?	rather than footnote references.	
	P4-36: This is an assumption. Can you say, “The estimated growth trajectory is predicted over a 25-year period, which could create a significant demand on the town’s water resources over a relatively short timeframe.”	Will update text per recommendation.	Addressed
	P4-37: Can you simplify and say, “While population projections can estimate increases in the number of residents, the actual location …”	Will update text per recommendation.	Addressed
	P4-37: reside? “settle” feels outdated and more appropriate to agricultural land use	Will update text per recommendation.	Addressed
	P4-38: Which Department, specifically?	Will update to note that this came from the Planning Department	Addressed
	P4-40: Previous paragraph states, “The following data layers were used as constraints to development in the buildout analysis:. . ." This sentence says after removing the constraints listed above. So, are there 3,059 buildable acres with or without the constraints? How many acres are buildable by-right without the constraints listed on page 4-38?	Will reword this section. This is intended to say that constrained areas, which were listed above, have been removed from the buildable area within the town. After removing the constrained area from the total area, we are left with 3,059 acres of buildable area.	Addressed

Commentor	Comments	W&S Response	Status
	P4-41: Are the colors of the legend identified by MassGIS or can you change these? There are a lot of zoning maps being produced by the Town for various purposes including compliance with the MBTA Communities Act. In those maps, yellow has been used consistently to show Agricultural/Residential areas. Other land uses have a color scheme different than this figure. Would it be possible to adopt the same color scheme as the figures that are currently being used by the Town Planner? I think this will help communicate this information and reduce confusion across multiple boards that are generating zoning maps.	Colors will be updated in maps to align with existing planning maps.	Addressed
	P4-42: Verb tense?	Will revise	Addressed
	P4-44: At this point in the analysis, is the model run compliant with all zoning requirements or just the existing zoning and setback requirements?	Just zoning and setback requirements.	Addressed
	P4-47: Change title in title block to Potential Buildout - Additional Buildings Map	Will update Figure 4.2	Addressed.
	P5-3: Should the legend indicate that the Approved Wellhead Protection Areas (Zone II) are DEP Approved?	Legend will be updated.	Addressed.
	P5-4: What about the wells that serve municipal buildings?	Will update text to clarify.	Addressed
	P5-4: Do you mean all water systems, or only private drinking water wells?	RGPCD = Residential Gallons per Capita Day (Massachusetts **Sta**	Addressed

Commentor	Comments	W&S Response	Status
		ndard = **65** gal/capita/day) Will update text to clarify.	
	P5-4: Add a List of abbreviations and acronyms to the document preface material		No action.
	P5-4: Previously this was written as U.S. in the text and in the footnote reference. Make Footnotes 29, 42 and 43 consistent in format	Will update footnotes for consistency.	Addressed
	P5-5: Is this the database referenced in this sentence?	Will add footnote reference.	Addressed
	P5-5: US or U.S.?	Will revise.	Addressed
	P5-6: What is meant by ensure long-term water security? New idea/not supported?	Will update this sentence for clarity.	Addressed
	P5-7: The legend states Buildable Area and then gives usage in MGY. Is it true that while this figure uses a color fill by basin and therefore includes all properties in that basin, buildable or not, the MGY categories are based on buildable area only? If so, this information could be described in the text introducing the figure.	Legend needs update – should say “groundwater usage” rather than “buildable area” (carryover edit from previous map that wasn’t updated)	Addressed.
	P5-8: UMDI was defined in Section 4	Will remove definition.	Addressed
	P5-8: My experience with the use of the term conservatism is that it is vague and can mean two very different things, depending on the reader. Suggesting some more specific language here	Will update.	Addressed

Commentor	Comments	W&S Response	Status
	5-10: The units are not proposed; just assumed for the purpose of this analysis. Want to make sure this is not misread and create concern among residents	Will update.	Addressed
	P5-11: These are Drinking Water Supply Alternatives (not necessarily alternatives to Wells because they are all well based alternatives)	Will update heading name.	Addressed
	P5-11: Maybe a footnote for the DEP portal where one can look up these well ID's?	Will add footnote.	Addressed
	P5-11: Are all of the PWS ID's listed in this paragraph impacted? Are all the PWS ID's listed in this paragraph going to be phased out by connection to the Trumbull well?	Will confirm with W&S staff working on the Littleton-Boxborough connection project.	
	P5-11: serving? servicing?	Will update.	Addressed
	P5-12: How is this defined?	"Phase 1 would serve a low service area in Boxborough west of I-495 and along Massachusetts Avenue east to Hill Road and north to Whitcomb Road…. At a later date, the Town could proceed with construction of the Phase II high service area on Hill Road, inclusive of a booster pumping station and storage tank."	Addressed
	P5-14: What does the bright yellow line show? Is the	The yellow line is the Littleton-	Addressed

Commentor	Comments	W&S Response	Status
	Finished Extension line shown? Does this map show only the alternatives evaluated in prior reports and not in this report? In that case, these are not Proposed Alternatives from the analysis that W&S has done. Maybe Previously Identified Drinking Water Alternatives?	Boxborough finished extension. Will update the colors in the legend to match. Will also update the title of map.	
	P5-15: Do you have a hyperlink for this report?	Will add hyperlink if available	Not available
	5-18: Is there a typical ratio of drinking water usage to recharge rate that is used to support the conclusion that the recharge sources are adequate (i.e., recharge rate is 30x estimated drinking water usage) or is it just that the usage is less than the recharge rate? Is there some margin of safety or other factor used to account for uncertainty in the analysis?	There is not typical ratio of drinking water usage to recharge rate.	Addressed
	P6-2: Give street names/location aid	Will add locations	Addressed
	P6-2: Does this include Applewood Village condominiums?	No, Applewood Village is not included in the septic count. Text added to report to clarify.	Addressed
	P6-3: Where is Table 6.1?	Will update table number.	Addressed
	P6-3: The order of Groundwater Basins is different in the tables in Section 6, compared to the tables in Section 5.	Will update.	Addressed
	P6-3: Fix format to be consistent with other call outs; do we need all caps?	Will update.	Addressed

Commentor	Comments	W&S Response	Status
	P6-6: Tech edit: author citations in this section followed by period when a comma is used to separate author and date in footnotes in other sections	Will check all footnotes for consistency.	Addressed
	P6-7: Include this table	Will update table numbering. This should be referencing Table 6.4.	Addressed
	P6-8: B. Lynch suggested adding a category identifying septic systems situated within Zone 1's to drinking water wells.	Zone 1 is added as a standalones category for Tier 1 properties. Tier 1 now consists of properties either located within a zone 1, or properties within FEMA 1%, wetland/waterbody buffer, and on limited soils.	Addressed
	P6-8: What additional information will be provided in Section 7?	Will add title of section 7 for more information.	Addressed
	P6-8: What are the reasons that NABH does not have information on 40% of the systems in place? Aren't these systems also posing a potential environmental risk, particularly if we do not know the performance of those systems?	Title 5 inspections are done during property transfers, less frequent but still required are inspections before any renovations that impacts the septic systems capacity (such as adding an addition to a house or increases the overall footprint of the area the system is serving). Homes that haven't been	Addressed

Commentor	Comments	W&S Response	Status
		sold or added to won't have title 5 inspection.	
	P6-8: What information is available from NABH on Tier 2 systems? Table 6.5 could include both Tier 1 and 2 status.	We only reviewed tier 1 properties for this assessment. Tier 2 would be added as a next step in section 8.	Addressed
	P6-8: We should consider aggregating data so that personal identification information is not presented in Appendix A.	Tier 1 Title 5 Inspections in Appendix D are updated to only list the street name and not the number.	Addressed.
	P6-9: How are the wetland areas shown on Figure 6.2? The legend indicates blue markings will be used but are these obscured by Tier 1 color fill?	Wetlands are not shown on this map – removing from legend.	Addressed
	P8-12: Is this measured data? The recharge rates in Section 5.7 are modeled.	This is modeled.	Addressed
	P9-15: Not having seen the information to be included in this Appendix, there is the assumption that street addresses and/or parcel IDs would be presented. What are the privacy concerns the Town (WRC, BOH) should consider in presenting data that has identifying information?	Same response as above.	Addressed
Bryon Clemence	General comment. How are we going to account for areas with known water quality problems? For instance, we know where PFAS and sodium levels are high. This is based largely on	Information received from Les and added to report.	Addressed

Commentor	Comments	W&S Response	Status
	PWS data, and we have some PFAS data from private wells. Can these be shown on maps? It would give the public a much greater understanding of our water situation.		
	Page 5-1, 2nd paragraph. Should this be Figure 5.1, rather than 5.2? I would say there are two interconnections with LWD—the Central Street and Leonard Road interconnections are separate. A third interconnection with LWD is under construction and scheduled to completed soon. There is also an interconnection on Summer Road with the Acton Water District. These four interconnections could be shown on Figure 5.1, and it help know the quantities of water that each provides.	Will double check all figure numbers before final report. The four interconnections will be added to the map.	Addressed.
	Page 5-2. The last sentence says that 46 PWS wells are located "in the IWPA." Isn't it more accurate to say that the 46 PWS wells each have an IWPA?	Correct, will update.	Addressed
	Page 5-4. Townwide water usage is based on 2020 census data and 65 gpcd. Can the census data be updated for 2025? Should this include a range? For instance, 80 gpcd is sometimes used for actual water usage. So a range could be based on 65 to 80 gpcd.	The most recent census data is from 2020, although estimates are available for 2023. For the calculations in this report, we are using a rate of 65 gpcd for consistency.	Addressed.
	Page 5-6, Table 5.2. Population projections and water usage should reflect the census data, updated as necessary. There are several ways this could be done for the subbasins. The simplest (and least accurate) would be to	Calculations were re-done to account for all multi-family housing.	Addressed.

Commentor	Comments	W&S Response	Status
	multiply the subbasin projections by the ratio of the two populations: 5506/3626 = 1.52. Another would be to account for multifamily housing. Altogether, I would expect current residential water use to be around 0.36 to 0.44 mgd. I would expect current commercial use to be around 0.11 to 0.25 mgd, for a total of 0.47 to 0.69 mgd (although as Kevin noted, this reflects only potable commercial use; some commercial or industrial developments could have much higher water needs).		
	Page 5-13, Figure 5.4. Color coding for the new LWD mains (blue vs. yellow) doesn't match the legend.	Will update map.	Addressed.
	Page 6-6 to 6-8. We should be careful about the risk implied by Tier 1 and Tier 2. Tier 1 and Tier 2 appear to include properties where only a portion of the lot is located in a risk area(s). Some of these properties may include areas with no risk for septic systems. Tier 1 and Tier 2 could be used as guidelines for further evaluation, and not as final determinations. The text should make this clear. Also, as Bryan Lynch noted, distance between septic systems and water supply wells could be a further risk factor.	Will include text explaining the tier mapping and that the septic system may be outside of the risk area.	Addressed.
	Page 8-11. Is the Data Collection step based on existing data?	This could be based on existing data and some will need to be collected.	Addressed.
	We have a question about the groundwater basin areas in Tables 2.2 and 5.75. The total area in Table 2.2 is 6,649 acres, or 10.39 sq. mi. (the area of Boxborough).	Additional text has been added to the report to explain the difference in areas. Another step was	Addressed.

Commentor	Comments	W&S Response	Status
	The total area in Table 5.75 is 38.30 sq. mi.	added to compare usage across the entire basin vs our calculated usage within the town.	

Final Report Comments

Commentor	Comments	W&S Response	Status
Les Fox	Page 2-17 of the report has the following statement, noting in particular the highlighted sentence. *"Boxborough relies on a network of surface water features specifically designed for fire protection. The Town maintains a system of 28 cisterns and 17 fire ponds strategically located throughout the town. See Figure 2.13 for locations. An additional fire pond may be developed north of Route 111 in a central location."* **The text in yellow should be deleted.**	Text has been deleted.	Addressed.
	Explain and clarify basin terminology Analysis by basin and sub-basin are key to the analysis. The term "sub-basin" first appears on p 2-15 and is defined in terms of the hierarchy of USGS Hydrologic Unit Codes. Provide an introduction to the basin concept earlier in the report. Also, explain or note the difference in terminology relative to the Inter-basin Transfer Act (ITA) and the Massachusetts Water Quality Standards at (314 CMR 4.00), where these are designated as river basins for regulatory purposes. For example, the HUC-8 Merrimack River Sub-basin is one of 14 named river basins in the ITA.	Text added to Introduction. ITA and Mass Water Quality Standards text has been added to 2.6.1.	Addressed.
	Table 5.10 – Estimated future drinking water demand by basin. Estimates of future residential demand are based on population growth models, but no estimates of future commercial demand are given due to lack of a planning framework or assumptions.	Updated future commercial drinking water demand to be a "worst case" scenario of maximum buildout	Addressed.

Commentor	Comments	W&S Response	Status
	Nonetheless, can worst-case estimates be made for future commercial development and demand?	based on building size zoning.	
	7.2.1 Septic System Regulations Note the link to this document is broken (https://www.boxborough-ma.gov/DocumentCenter/View/4999/Subsurface-Disposal-of-Sewage-Regulations-Draft-2025) but the document can be found at https://www.boxborough-ma.gov/DocumentCenter/View/4997/Septic-Regulations-Draft-2025	Link has been updated.	Addressed.
	Funding sources. Can we add a section listing recommended sources for funding additional work?	Funding sources section added Section 8.3	Addressed.
	Appendices - Revise as noted below, depending on the report version. Some are out of order or mislabeled. 1. Appendix B – Revise per Clemence comments below on recharge calculations, here and in of Section 5. 2. Appendix C – Septic System Inspections. Add the reports and data. Close up title page with body of text. 3. Appendix D – Town-wide Water Balance. Pages out of order, close up. 4. Appendix E – PFAS articles. Needs a title page. 5. Appendix F – Will these WRC comments and W&S responses be incorporated in Appendix F, updated from Aug 12, 2025?	1, 2. Appendices revision, reordering, addressed. 3. Unsure what is meant by "Close up title page with body of text." Pages appear to be in order. 4. Appendix header precedes article. 5. Appendix F will incorporate final comments.	Addressed.

Commentor	Comments	W&S Response	Status
Bryon Clemence	Add "Phase 1 – Preliminary Assessment**"** to the title of the report. The full title would then be: Comprehensive Water Resources Report Phase 1 – Preliminary Assessment Town of Boxborough September 2025 This is consistent with the RFP: "The overall goal of Phase 1 is a preliminary assessment of the Town's water resource needs." This would help address comments asking why some things weren't included in the report—they may be done in later phases.	Updated cover text.	Addressed.
	Revise page ES-1 as follows: The Town of Boxborough is dedicated to understanding and managing its water resources as development expands. **This report is the first phase in implementing Action 1.1.4.2 of the Town's Master Plan: "Plan for long-term water supply and wastewater management.** Without a municipal water or sewer system, the town relies on a decentralized network of private and small ...	Text updated.	Addressed.
	On pages ES-2 and 8-18: Revise the following on these pages and on page 5-19: Based on this analysis, groundwater ***italics quantity*** a ppears to be sufficient for current and future drinking water needs**, under current practices whereby most properties are served by their own private wells.** However, further analysis **of** ~~**on the quality**~~ ~~**of this**~~ groundwater ***italics quality*** ~~**to provide**~~ **is needed** to **evaluate**	Text updated in all locations.	Addressed.

Commentor	Comments	W&S Response	Status
	whether clean drinking water is available for all. ~~to residents is needed.~~ **Furthermore, if Boxborough had to develop a municipal water system, it is not clear whether a well(s) of sufficient capacity, and meeting the State's requirements, could be developed to access the water.**		
	On pages ES-2 and 8-18: Change recommendation no. 5 as follows: 5. Identify additional properties to be placed under **protection for water supply purposes** ~~conservation~~.	Text updated in both locations.	Addressed.
	On pages ES-2 and 8-18: Add the following recommendations: 6. Evaluate the Town's firefighting needs. 7. Continue to discuss regional water supply options with neighboring towns, including an interconnection with the Massachusetts Water Resources Authority (MWRA). 8. Follow up with further evaluations recommended in this report, including additional work needed to address the water-related Actions in the Town's Master Plan.	Recommendations have been added.	Addressed.
	In Section 5.5 and Appendix B, the recharge rates are still for the entire 38.5 sq. mi. groundwater basin, not for Boxborough's 10.4	Text has been added to 5.5 explaining in more detail why the entire groundwater	Addressed.

Commentor	Comments	W&S Response	Status
	sq. mi. (shown on Figure 5.6). In Table 5.14, the demands in columns 3, 4, and 5 are specific to Boxborough, but recharge in the last column is for the entire groundwater basin. There is also an error in the last column of Table 5.14: for East Fort Pond Brook, 51 MGY should be 511, to agree with Appendix B. This would make the total recharge 6,780 to 15,996 MGY. However, the table should not be comparing Boxborough's demand with the recharge for entire groundwater basin. If we pro-rated recharge at 27%, the percentage of the basin in Boxborough, the total recharge would be 1,837 to 4,319 MGY. But this is approach is probably too simplistic; it doesn't account for the areas of individual surficial geologic units within the town. GIS should be able to calculate those areas in Boxborough readily. The table in Appendix B should show totals for the Area and Recharge Rate columns. This table also appears to have blank cells, although this seems to be caused by the page break. This could be clarified by showing this table on one page or breaking the page between West Fort Pond Brook and Elizabeth Brook.	basin was used for recharge calculations. Error in Table 5.14 has been corrected. Appendix B updated.	
	The document heading that appears in Adobe should match the title of the report. In one version of the report, it read "Env. Assessment ..." The first few words of the heading be should make it clear that it is "Box. Comp. Water Res. Rep. 2025," or something like that, since only the first few words will be visible in the Adobe heading. This involves the pdf	Will update in final PDF	Addressed.

Commentor	Comments	W&S Response	Status
	metadata under file information properties.		
Janet Keating-Connolly	Section 6.4, page 6-6 references 164 Tier I properties, page 6-6 references 168 Tier 1 properties, Table 6.4 lists 164 Tier I properties, Section 6.5, page 6-9 references 116 Tier 1 properties twice.	Updated throughout (correct number is 168)	Addressed.
	Table 6.5 separates 57 systems into either pass or fail but the total column lists 73 septic systems. Are there more septic systems listed in Appendix C than there are Tier 1 properties for which information was available from Nashoba Associated Boards of Health (NABH)? The text indicates information was available for 68 Tier 1 properties, including 9 failures. Were any of the failures listed in Appendix C converted to pass (in other words, is there an accounting for repeated entries in the table in Appendix C)? If there are repeated properties in Appendix C, this would also affect the reported total of 68 Tier 1 properties (v. systems) for which information is available, as listed in Table 6.6 and throughout Section 6, where applicable.	Updated throughout. 64 pass (with or without conditions), 9 fail (Total = 73). All inspection results are the most recent that we have received from NABH for the property.	Addressed.
	Please add a note or describe the inclusive dates of the data set used to create Tables 6.5 and 6.6. Is it a correct reading of the information in Table 6.5 that there are currently 9 septic systems in Boxborough known to the NABH to be failing? I can anticipate reader questions about corrective actions for these 9 systems.	Text added to Section 6.5.	Addressed.
	Can you provide to the WRC the original unredacted information on Tier 1 Septic System Inspections from the NABH, as	Will provide this with final deliverable.	Addressed.

Commentor	Comments	W&S Response	Status
	appears in Appendix C? Did W&S prepare additional files to support the statistics presented in Chapter 6? If so, please provide those files as well for committee use (but not		
	Please bookmark the pdf so the reader can easily jump to sections, tables, figures, appendices, etc.	Will update in final draft.	