FINAL TECHNICAL REPORT

Utilizing the Surficial Geology of the Northeast United States to Improve NEHRP Site Effect Classifications in HAZUS-MH: Collaborative Research with NESEC and the NESEC State Geologists

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ABSTRACT

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We have completed an 18-month study to assess whether site effect classifications derived from *Wald and Allen* (2007), hereafter referred to as the *Wald Methodology*, can significantly improve the accuracy of HAZUS-MH earthquake loss estimations in the Northeast region. The study encompasses four unique pilot regions in Connecticut, Maine, Massachusetts and Vermont selected on the basis of diversity of topography and surficial deposits, high population density and proximity to seismic zones. A significant portion of the four pilot regions is underlain by extensive regions of marine clay and glacial lacustrine sediments that, when exposed to ground shaking, is at greatest risk for damage to property and lives. In addition, all of the pilot areas contain regions of fine to medium grained sediments with shallow water tables that are also moderately to highly susceptible to amplified ground motion.

We utilized a two-pronged approach to assess the validity of using the *Wald Methodology* to classify surficial geology for HAZUS-MH loss estimations in the Northeast. First, NEHRP site classifications were derived from a first-order site condition map created using the *Wald Methodology*. These site classifications were then checked against independently derived local site classification maps for accuracy. Second, the effects that local surficial materials maps and the *Wald Methodology* classifications had on HAZUS-MH earthquake loss estimations were analyzed. The results from these two assessments indicate that the *Wald Methodology* underestimates classifications in the extreme categories (NEHRP categories A and E).

This research directly addresses the need to provide local and regional emergency managers with more accurate information for locating and prioritizing earthquake mitigation projects, and thereby improving

the effectiveness of earthquake mitigation and reducing earthquake losses in the future. The authors of this study conclude that: 1) the *Wald Methodology* underestimates classifications in the extreme categories; 2) use of surficial mapping provides higher resolution information due to the larger scale of the source material; 3) the main reason for the discrepancy between the *Wald Methodology* and detailed surficial mapping is due to the fact that detailed mapping is interpreted by geologists and therefore, provides greater insight into the third dimension, something the *Wald Methodology* is unable to do. For example, in the Connecticut Valley of Massachusetts many sand and gravel deposits that might be classified as D soils by the *Wald Methodology* are underlain by lacustrine silts and clays, which the geologist would classify as E soils. However, this last conclusion is based on common sense and needs to be verified by the collection of actual shear wave velocity data. Thus, one of the main recommendations of the study is to collect shear wave velocity data from representative surficial materials to either confirm or refute the classifications made from the surficial materials maps by the geologists.

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1.0 INTRODUCTION

In this investigation, we assess whether surficial materials classifications derived from *Wald and Allen* (2007), hereafter referred to as the *Wald Methodology*, can significantly improve the accuracy of earthquake loss estimations in FEMA's HAZUS-MH hazard analysis software. The HAZUS-MH earthquake model is designed to produce loss estimates for use by federal, state, regional and local governments in planning for earthquake risk mitigation, emergency preparedness, response and recovery. The primary goal of the study is to develop recommendations for an enhanced National Earthquake Hazard Reduction Program (NEHRP) site classification map for the Northeast region. In order to establish recommendations for an enhanced NEHRP site classification map, HAZUS-MH earthquake loss estimations derived from the *Wald Methodology* site classification maps are compared to estimations derived from local site classification maps to ascertain the appropriateness of wider implementation across the region.

In the absence of user-supplied soils maps, the HAZUS-MH software assumes an average soil condition for the entire study region. Given the lack of uniformly available geologic maps for much of the Northeast region, many end-users tend to rely on the default soil classification for their earthquake scenarios. As earthquake damage is significantly affected by underlying soils and surficial materials, such reliance places a significant constraint on the accuracy of the HAZUS-MH outputs vis-à-vis spatial distribution of economic damages and loss of life. It is for this reason that cost-effective methodologies that estimate soil type based on proxy parameters (e.g., topography, slope, etc) have the potential to address significant gaps in available geologic data and to serve as an improved baseline upon which to conduct seismic hazard assessments. To our knowledge, however, no comprehensive analysis of the accuracy of these methodologies, or suitability of their use in hazard assessment programs, exists for the Northeast region.

The study area encompasses four unique pilot regions in the Northeast region, selected on the basis of diversity of topography and surficial deposits, population density and proximity to areas of high seismic activity. In Connecticut, the pilot region is Hartford County. It spans the central lowland and extends to the uplands on its western and eastern margins, includes the Capitol City, and the International Airport (Figure 2). In Maine, the pilot region is the Portland 1:100,000-scale quadrangle, which spans the populous southern Maine region extending from Portland, Maine's largest city, on the coast to the border with New Hampshire on the west (Figure 3). In Massachusetts, the pilot region is a 24-quadrangle area extending along the Connecticut River valley from the Vermont border to the Connecticut border (Figure 4). In Vermont, the pilot region is Chittenden County, which includes Burlington, Vermont's most populated city (Figure 5).

In this report, we will present and discuss the comparative results of HAZUS-MH earthquake scenarios utilizing the *Wald Methodology* site class estimations and local surficial materials data for each of the four pilot regions. Importantly, we will present a number of maps and graphs that will further illustrate the suitability of the *Wald Methodology for* use in the Northeast region through direct comparison of surficial materials estimations to local data. Specifically, we will outline the results of ArcView Spatial Analyst analyses that describe the *Wald Methodology's* level and direction of divergence from NEHRP site categorizations according to local data and expertise. These results are presented in map and graphical form, with the former providing important insight into the geographic distribution of areas of poor correlation. The overall goal of the direct comparisons of the *Wald Methodology's surficial* materials estimations to local data is to further analyze the implications of utilizing the methodology in HAZUS-MH.

2.0 BACKGROUND

2.1 The HAZUS-MH Software

HAZUS-MH is a powerful risk assessment methodology developed by the Federal Emergency Management Agency (FEMA) for analyzing potential losses from earthquakes. When estimating potential losses from an earthquake, HAZUS-MH assesses the effect of local variations in surficial geology to amplify or mitigate the shaking experienced during an earthquake. In order to estimate this local site effect, HAZUS-MH requires information about the local surficial geology. HAZUS-MH classifies local surficial geology using five NEHRP site classifications. These site classifications can be seen in Table 1.

NEHRP Site Classification Category	Description	Mean Shear Wave Velocity to 30m
A	Hard Rock	> 1500 m/s
B	Firm to hard rock	760-1500 m/s
C	Dense soil, soft rock	360-760 m/s
D	Stiff soil	180-360 m/s
E	Soft clays	< 180 m/s

Table 1: NEHRP Site Classifications

HAZUS-MH assumes a single site classification, category D, for the entire Northeast region. As discussed further in *Section 2.3: HAZUS-MH Earthquake Loss Model Soils Data*, this site classification does not reflect the actual variance of surficial geology in the Northeast, which lowers the accuracy of earthquake loss estimations in the region.

2.2 Seismicity in the Northeast

The Northeastern United States has a long and documented history of earthquakes. Major seismic events that have occurred within the region include the 1638, 1727 and 1755 earthquakes, which have estimated magnitudes of 6.5, 5.9, and 6.0, respectively (Wheeler, et. al. 2001). More recent earthquakes of particular note that have affected the Northeast include a pair of damaging, magnitude 5.5 earthquakes that occurred in 1940 near Ossipee, NH. Since 1975, moderate size earthquakes have occurred in Central New Brunswick, Central NH, Northern NY State and Quebec. In total, approximately 40 to 50 earthquakes are detected annually in or near the Northeast. Figure 1 depicts earthquake activity in the Northeast and adjacent Canada from 1975 - 2011.

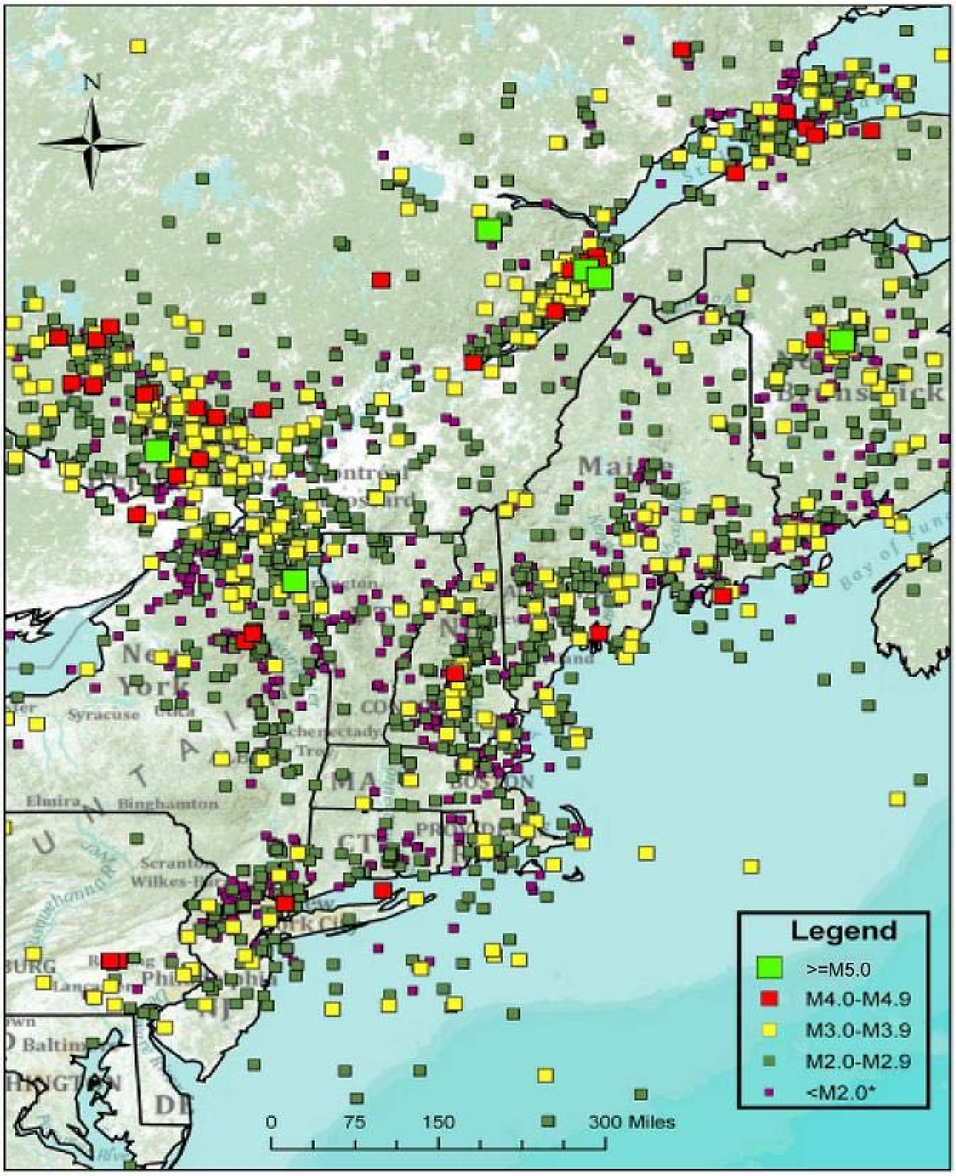

Figure 1. Northeast US and Adjacent Canadian Earthquakes 1975-2011
(Source: Weston Observatory, Boston College)

Potential earthquake losses in the Northeast , when annualized, add up to about $5.3 billion dollars a year. The Northeast ranks fourth in the nation for annualized losses, according to a 2008 study released by the Federal Emergency Management Agency (FEMA). Northeast states ranking among the top 20 high-loss potential loss states include, New York, New Jersey and Massachusetts. Earthquake loss estimates are annualized to factor in historic patterns of frequent smaller earthquakes with infrequent but larger events. The $5.3 billion annual estimate is extremely conservative and includes only capital losses to buildings and business interruption losses. It does not include damage and losses to critical facilities, transportation, utility lifelines or indirect economic losses.

The cities in the Northeast are among the most densely populated areas in the United States, which places more people at risk in the event of an earthquake. The area impacted by an earthquake in the Northeast can be up to 10 times greater than the same magnitude event occurring on the West coast due to our regional geology. (Frankel, 1994) Importantly, the Northeast is home to many older and historic structures that are not designed to withstand the impacts of an earthquake. These structures, which include schools, hospitals and fire stations, are built of un-reinforced masonry (i.e., "red brick") and are particularly vulnerable to damage or collapse in the event of an earthquake. While some states in the Northeast have adopted seismic provisions into their state building codes, the coverage, scope and enforcement of these codes vary by state and community. While there are many uncertainties about what causes earthquakes in the Northeast, one thing is certain: earthquakes will continue to occur in this region, placing lives and property at risk.

2.3 HAZUS-MH Earthquake Loss Model Soils Data

The HAZUS-MH methodology and software are flexible enough so that locally developed soils data and inventories that more accurately reflect the local environment can be substituted, resulting in increased accuracy. For this reason, users are advised to import their own soil maps. To include the effects of soils, users of HAZUS-MH must supply a soil map that conforms to the site classification system of the National Earthquake Hazard Reduction Program (NEHRP). As most geologic maps are not laid out in accordance with the NEHRP scheme, the services of a geologist or geotechnical engineer are typically required to convert the classification system on the user-supplied map to the one used in HAZUS-MH.

Importantly, given the lack of uniform availability of soil data for cities and towns and the expense of developing these maps, users of HAZUS-MH rely heavily on the default soil-mapping scheme. This default-mapping scheme assumes an average soil condition for the entire study region, thereby placing a significant constraint on the accuracy of the loss estimations. In the Northeast US, HAZUS-MH assumes a single, default soil type of Category “D” within the NEHRP site classification system. Category D is described as hard rock with a shear wave velocity range of 180-360 m/s (See Table 1).

As available geologic maps of the Northeast reveal, soils types vary widely even at the city and town level (see Section 2.5 Geologic Setting of Pilot Regions). Soil type can have a significant effect on the intensity of ground motion during a seismic event. As past seismic events have shown, the geographic distribution of damage may be influenced markedly by local soil conditions. Soft soils, which are prevalent in key areas of the Northeast, tend to amplify certain frequencies within the ground shaking, resulting in greater damage.

2.4 Availability of Detailed Surficial Materials Data for the Northeast Region

While high-resolution (1:24,000 or greater) or lower resolution (1:250,000) geologic maps are generally available from geologists, regional U. S. Geological Survey offices, state geological surveys, regional planning agencies, or local government agencies, these maps are not uniformly available for much of the Northeast region. Where maps do exist, quality and resolution vary considerably from location to location.

As outlined in *Wald Methodology*, the lack of uniformly available geologic maps of sufficiently high resolution was a significant driving factor behind the development of a proxy methodology to determine soil type. While the *Wald Methodology* was tested with success in numerous locations around the globe, it remains to be seen whether the methodology produces a reasonable estimation of surficial material types in areas characterized by laterally and vertically discontinuous glacial and non-glacial materials of variable thickness. If proven suitable for the Northeast region, the *Wald Methodology* would be a highly cost-effective solution to better assessing the earthquake risk of cities and towns through HAZUS-MH software. In *2.5 Geologic Setting of Pilot Regions,* we describe the four pilot regions that were chosen to assess the appropriateness of wider deployment of the *Wald Methodology* in the Northeast for loss estimation purposes.

2.5 Geologic Setting of Pilot Regions

2.5.1 Connecticut Pilot Region

Hartford County was selected as a Connecticut pilot area of interest. Although the areas of highest seismic event frequency in Connecticut are to the southwest and southeast, the Hartford County area is largely covered by glacial lake clays and fine sands (Stone et al, 1992) that have a high liquefaction potential (Figure 2). The County contains the Capitol city of Hartford and has the second highest population, estimated to be 879,835 as of 2009. Significant seismic events were recorded for Hartford in 1837 and 1840 (IMM=5), followed by events in 1925 and 1942. The county is situated within an urban corridor, which extends northward into Massachusetts and south and southwest into NYC. Significant seismic events in adjacent states and offshore can be felt by county residents.

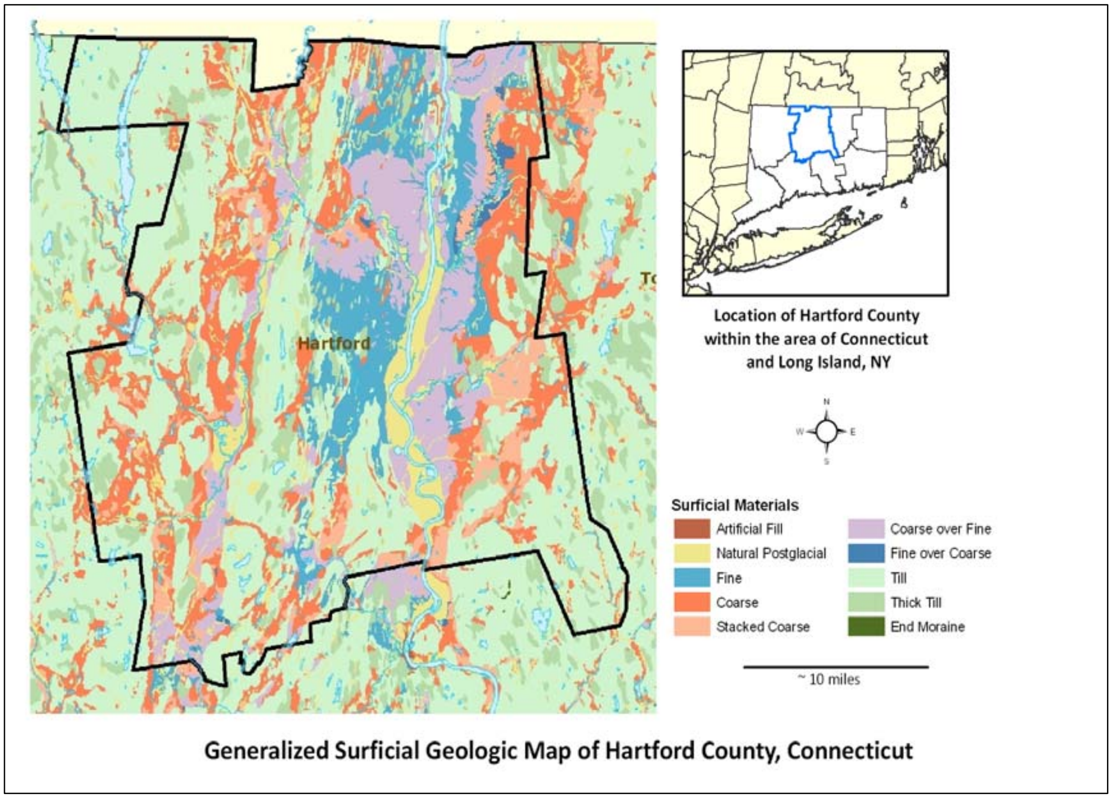

Figure 2. Connecticut Pilot Region: Generalized Surficial Geologic Map

Hartford County is located in north central Connecticut (Figure2). Most of the County lies within the Mesozoic Hartford Basin, a half graben and broad topographic lowland in central Connecticut. The lowland is characterized by gently eastward dipping sedimentary rocks and basalt flows, which produce steep traprock ridges accompanied by talus slopes. The eastern and western margins of the County extend into the Paleozoic crystalline rocks of the uplands. Unconsolidated surficial materials overlie the bedrock. These materials were produced during the end of the Pleistocene when glacial ice deposited an unsorted mixture of sediment with particle sizes ranging from boulders to clay. This deposit called glacial till, is generally less than 15 feet thick. Glacially formed streamlined hills composed of dense till greater than 100 feet thick occur throughout the state. These drumlins delineate the course of glacial movement, trending from northwest to southeast across the state. Glacial meltwater streams and rivers produced sorted deposits of sand and gravel. Ponded meltwater produced thick sequences of fine grained sands and glacial lake clays. The southern part of Glacial Lake Hitchcock, represented by thick deposits of fine sands and tens of meters of varved clays, occupies central Hartford County. Today, the Connecticut River bisects the ancient glacial lake in Hartford County. Where these very fine grained materials are saturated, there is particular concern about their structural vulnerability in response to seismic activity. The surficial materials mapping in Connecticut includes identification of textural variation in subsurface layers of all materials overlying the bedrock. These 'stacked' units are important for identification of seismically vulnerable areas underlying more stable material.

2.5.2 Maine Pilot Region

For this comparison, the Maine Geological Survey used the surficial geologic map of the Portland 1:100,000-scale quadrangle (Tolman, 2006). The quadrangle spans the populous southern Maine region extending from Portland, Maine's largest city, on the coast to the border with New Hampshire on the west (Figure 3). This map area has complete coverage of surficial geology at the 1:24,000 scale, developed using a consistent field mapping methodology, and subsequently compiled at the 1:100,000 scale with minor generalization. Furthermore, this map area covers a broad range of topography, including coastal lowlands and areas of high relief in the western mountains; the surficial deposits subsequently include nearly every variety found in the state, making this area an excellent test for this comparison.

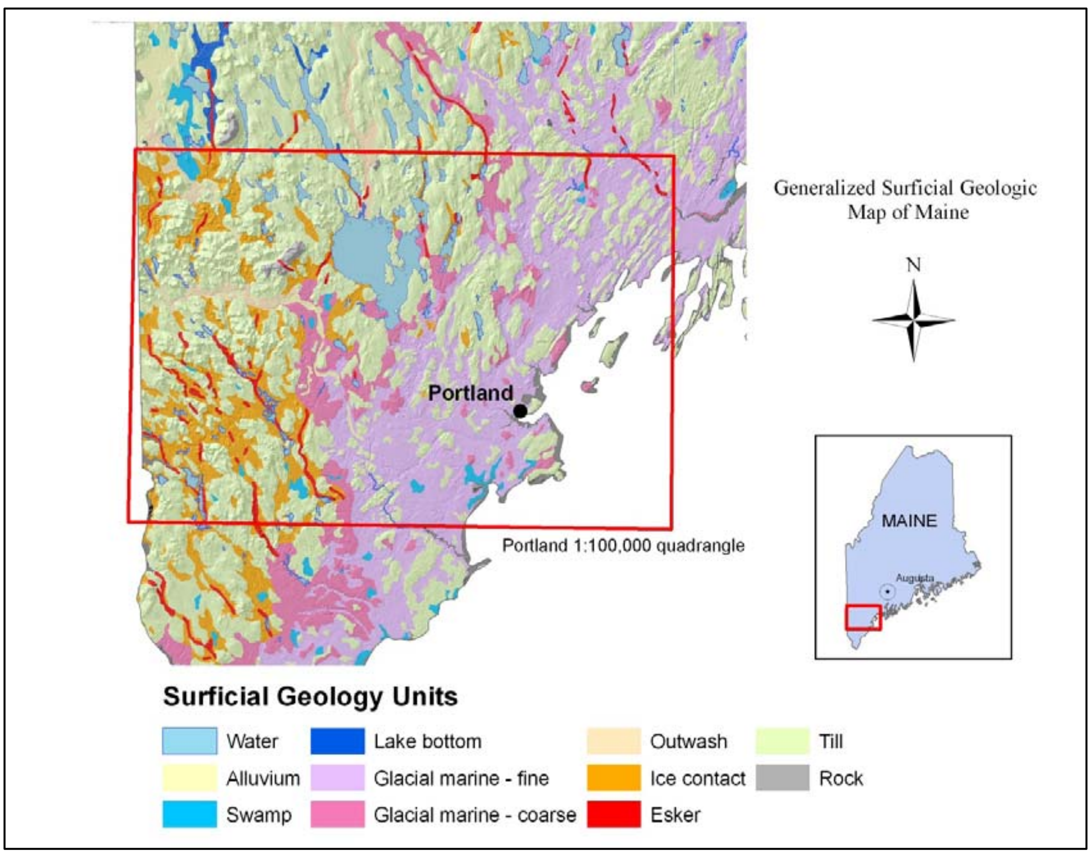

Figure 3. Maine Pilot Region: Generalized Surficial Geologic Map

Southwestern Maine is underlain with a broad range of granitic and metamorphic bedrock geological units (Osberg and others, 1985) upon which is draped a mantle of generally thin deposits of glacial and glacial-marine origin (Thompson and Borns, 1985). The Wisconsinan ice sheet sculpted the bedrock landscape and deposited an unsorted and heterogeneous lodgment till of boulders, gravel, sand, silt and clay as it advanced. As the ice sheet retreated from this portion of Maine between 15,000 and 13,000 years ago (Borns and others, 2004), additional ablation till was deposited, much as a series of narrow discontinuous moraines. Meltwaters also produced various ice-contact deposits including kames and eskers. Glacial meltwaters reworked deposits in the immediate vicinity of the ice sheet margin into broad outwash plains of coarse gravel and sand. Large deltas of well-sorted stratified sand and gravel developed where the meltwaters entered the ocean. As ice retreated from southern Maine, the ocean inundated the immediate coastal areas where the crust had been depressed by the weight of glacial ice and was slow to rebound. As a consequence, a thick veneer of glacial marine clay and silt, the Presumpscot Formation, blankets the landscape in many coastal areas. In several narrow valleys of western Maine, moraines draped across valleys, disrupting the southward drainage of glacial meltwaters and impounding waters for several thousands of years. Varved lake clays from several of these glacial lakes underlie valleys in the study area.

2.5.3 Massachusetts Pilot Region

The area selected for study in Massachusetts includes a 24-quadrangle area extending along the Connecticut River valley from the Vermont border to the Connecticut border (Figure 4). This area was selected because the geology varies from thin till over crystalline igneous and metamorphic rock on either side of the Connecticut River valley to very thick sequences of varved clay within the confines of the valley. In addition, the area contains the cities of Springfield and Holyoke, both of which are located on loose unconsolidated glacial sediments. Springfield is the third largest city in Massachusetts with a population exceeding 150,000.

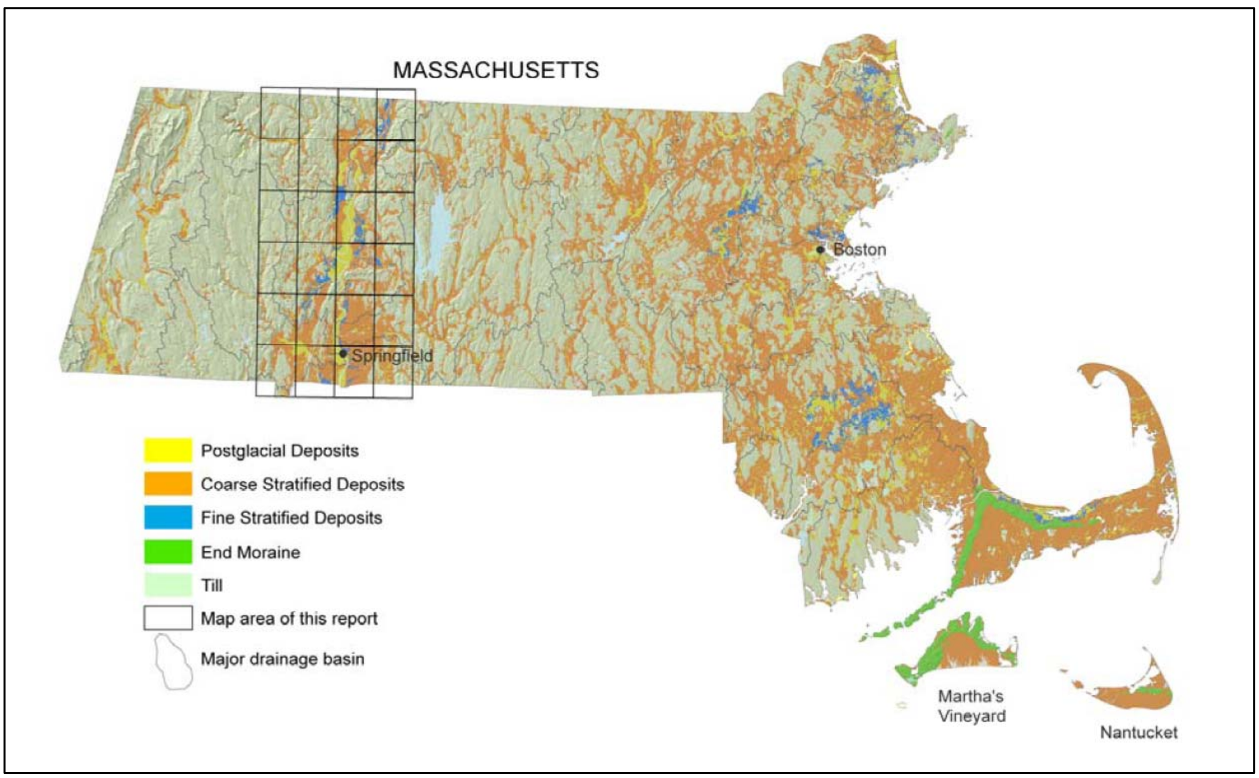

Figure 4. Massachusetts Pilot Region: Generalized Surficial Geologic Map

The study area spans the entire width and length of the Connecticut River Valley in Massachusetts (Figure 4). The Connecticut River valley is a Mesozoic rift basin produced by crustal extension about 220 million years ago resulting in a basin within which up to 4 km of sedimentary material was deposited over crystalline metamorphic and igneous basement rocks. These same basement rocks are exposed on either side of the Connecticut valley. The edge of the rift valley is delineated on the east by a large normal fault known as the East Border Fault. The valley is up to 40 km wide in the south near the Connecticut border and approximately 8-10 km wide at the north end. The sedimentary cover rocks in the valley are comprised of arkosic sandstones, up to 3 basalt lava units, mudstones and conglomerates. Units generally dip to the east 10° to 25°.

In the uplands to the east and west of the valley, the dominant rocks are metamorphic and include gneisses and schists. The rocks are foliated with a north-south trend. The uplands also contain igneous rocks including granodiortie, granite and monzodiorite.

All of Massachusetts was glaciated. The ice sheet left behind a veneer of glacial till over the entire landscape consisting of a heterogeneous mixture of boulder, cobble, gravel, sand, silt and clay sized material. The till ranges in thickness from 0 to perhaps 15 meters, with bedrock exposed in some of the higher elevations. A few drumlins of thicker till do occur throughout the study area.

In addition, as the ice was retreating from Massachusetts, a large glacial lake, referred to as Glacial Lake Hitchcock, occupied the valley and extended from Rocky Hill, CT as far north as Saint Johnsbury, VT. The lake existed for over 4000 years. The shoreline today can be approximated by the 300-foot elevation contour. As a result of this lake, the sedimentary rocks in the Connecticut valley are overlain by up to 30 m of varved clay. Several streams carrying material from the melting glaciers deposited large amounts of sand and gravel into the lake forming large deltas. Many of the deltas were built into the lake over the varved clay deposits. These clay deposits and any wind blown sediments, coarse-grained glaciofluvial deposits or river alluvium deposits overlying these varved clays are considered very unstable with regard to seismic shaking.

2.5.4 Vermont Pilot Region

Chittenden County is in proximity to historic and quite active zones of earthquake events in Southern Quebec and the Adirondacks (Ebel et al, 1995). Adjacent to Lake Champlain, Burlington - the state's largest city, is located in western Chittenden County (Figure 5). The city contains many masonry buildings and critical/essential facilities including schools, police, and fire stations and Fletcher Allen Health Care, the state's largest hospital. IBM, a high tech manufacturer and one of the state's largest employers, is also located in the County.

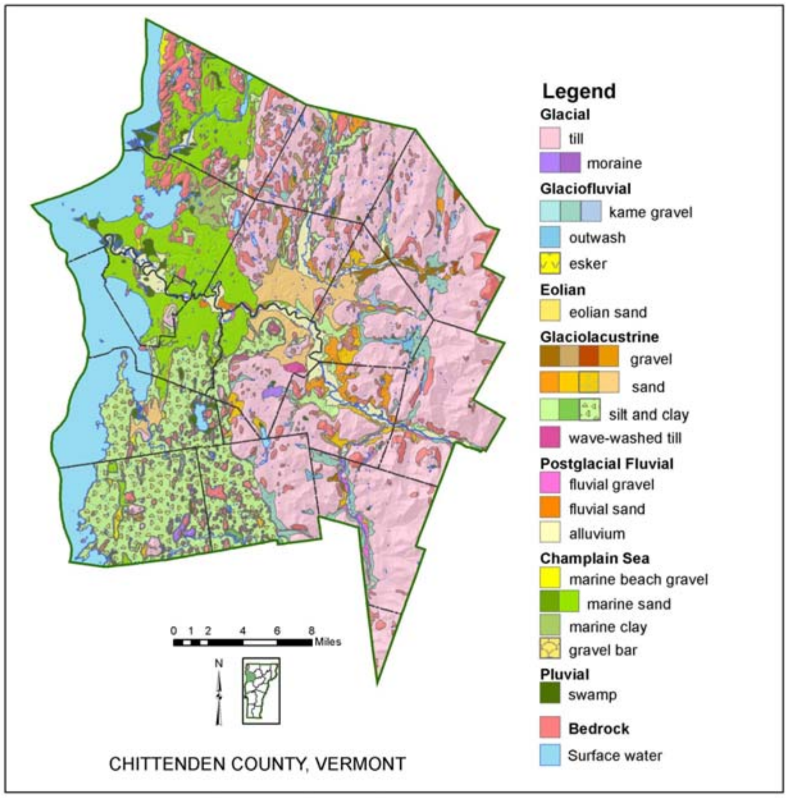

Figure 5. Vermont Pilot Region: Generalized Surficial Geologic Map

Chittenden County is underlain by lower Cambrian rift clastics and volcanics in the east and Cambro-Ordovician shelf sequence meta-sediments capped by shale in the west. Much of Chittenden County lies at elevations low enough to have been under standing water during and following retreat of the Wisconsinan ice sheet. Glacial lake sediments, primarily varved silt and clay, are broadly distributed. Ice-contact sediments are rare either because they were never deposited locally or because they are covered by younger sediments. Unvarved Champlain Sea silt/clay is deposited directly on top of varved Lake Vermont sediments indicating a rapid transition from fresh water to salt-water conditions and the rapid ~100 m drop in water level. Often interlayered with fine and very fine sand, Champlain Sea "mud" is broadly distributed (Wright, 2003). Evidence for delta sands prograded into Lake Vermont can be found in the central part of the County. Lake Champlain (Elev. 95 feet) and its waterfront shoreline are below downtown Burlington (approx. elev. 200 feet) which is located on a delta that formed in the Champlain Sea. Bedrock outcrops and associated till are also common in the lowlands and dominant toward the heights of the Green Mountains to the east.

2.6 Earthquake Events for Loss Estimation Scenarios

The following three regional earthquakes listed in Section 2.6.1 were selected and loss estimates run using HAZUS-MH. An initial run was completed using HAZUS Default soils and a second run incorporating *Wald Methodology* soils. The results of these runs are illustrated in Section 2.6.2. In all three studied events, incorporation of the Wald soils data into HAZUS MH resulted in a consistent decrease in estimated impact and economic losses.

2.6.1 Earthquake Scenarios

Location:	Cape Ann, MA
Origin Time:	2PM
Magnitude:	6.00
Epicenter (lat/long):	42.70 / -70.30
Depth:	10.00m
State(s) Affected:	CT, MA, ME, NH, RI, VT

Table 2. Cape Ann Earthquake Epicenter Scenario

Location:	Central New Hampshire
Origin Time:	2PM
Magnitude:	6.50
Epicenter (lat/long):	43.39 / -71.61
Depth:	10.00m
State(s) Affected:	CT, MA, ME, NH, RI, VT

Table 3. Central New Hampshire Earthquake Epicenter Scenario

Location:	Boston, MA
Origin Time:	2PM
Magnitude:	6.00
Epicenter (lat/long):	42.36 / -71.06
Depth:	10.00m
State(s) Affected:	CT, MA, ME, NH, RI, VT

Table 4. Boston Earthquake Epicenter Scenario

2.6.2 Analysis of HAZUS-MH Earthquake Scenarios

Cape Ann, Massachusetts Earthquake Epicenter Results

	Economic Loss			Injuries / (Deaths)	
	Default	Wald	%Δ	Default	Wald
CT	$5.77M	$1.23M	↓79%	2 (0)	0 (0)
MA	$1.96B	$1.38B	↓30%	581 (11)	420 (8)
ME	$97.6M	$61.6M	↓37%	31 (0)	20 (0)
NH	$263M	$175M	↓33%	83 (1)	56 (1)
RI	$64.2M	$43.3M	↓33%	23 (0)	16 (0)
VT	$1.27M	$0	↓100%	1 (0)	0 (0)
TOTAL:	**$2.43B**	**$1.67B**	**↓31.3%**	721 (12)	512 (9)

Table 5: Cape Ann Earthquake Epicenter Scenario HAZUS-MH Summary Results

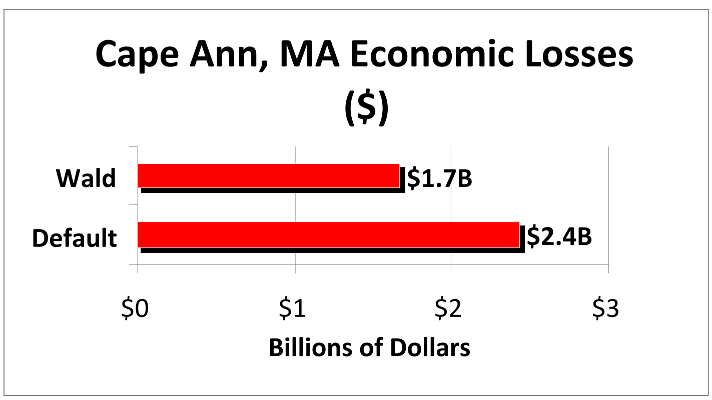

Table 6: Cape Ann Earthquake Epicenter Scenario HAZUS-MH Economic Losses Results

Central New Hampshire Earthquake Epicenter Results

	Economic Loss			Injuries / (Deaths)	
	Default	Wald	%Δ	Default	Wald
CT	$44.8M	$24.5M	↓45%	16 (0)	10 (0)
MA	$2.50B	$1.61B	↓36%	786 (15)	541 (10)
ME	$351M	$217M	↓38%	105 (2)	68 (1)
NH	$5.38B	$2.93B	↓45%	2,868 (147)	1,128 (49)
RI	$91.9M	$62.4M	↓32%	33 (0)	23 (0)
VT	$214M	$72.5M	↓66%	64 (1)	24 (0)
TOTAL:	**$8.58B**	**$4.91B**	**↓42.8%**	3872 (165)	1793 (60)

Table 7: Central New Hampshire Earthquake Epicenter Scenario HAZUS-MH Summary Results

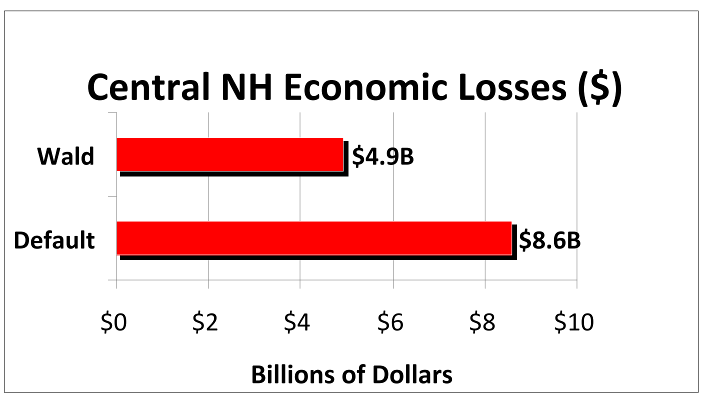

Table 8: Central New Hampshire Earthquake Epicenter Scenario HAZUS-MH Summary Results

Boston, Massachusetts Earthquake Epicenter Results

	Economic Loss			Injuries / (Deaths)	
	Default	Wald	%Δ	Default	Wald
CT	$121M	$54.9M	↓55%	43 (1)	22 (0)
MA	$61.0B	$51.3B	↓16%	36449 (2082)	27965 (1566)
ME	$26.5M	$16.2M	↓39%	10 (0)	6 (0)
NH	$393M	$227M	↓42%	119 (2)	71 (1)
RI	$472M	$317M	↓33%	119 (2)	84 (2)
VT	$5.21M	$0.52M	↓90%	2 (0)	0 (0)
TOTAL:	**$62.0B**	**$51.9B**	**↓16.3%**	36742 (2087)	28148 (1569)

Table 9: Boston, Massachusetts Earthquake Epicenter Scenario HAZUS-MH Summary Results

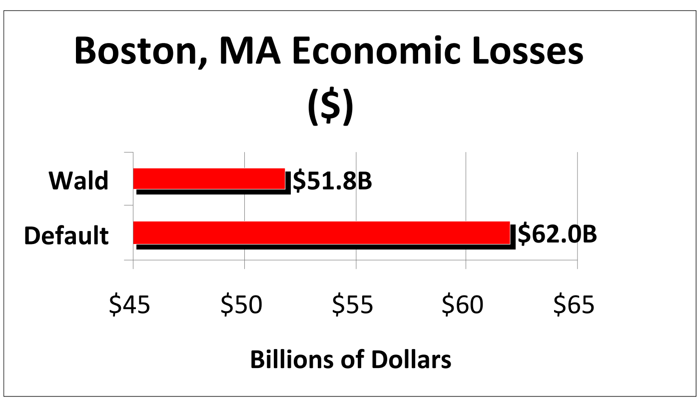

Table 10: Boston, Massachusetts Earthquake Epicenter Scenario HAZUS-MH Summary Results

3.0 METHODOLOGY

The NESEC State Geologists were asked to select four (4) pilot regions in the Northeast United States for which detailed surficial materials datasets were readily available in a GIS compatible format. As data resolutions vary widely, the team was advised to only pick from datasets of sufficiently high resolution for project purposes (i.e., 1:100,000 or larger scale).

In order to perform the most comprehensive analysis of the *Wald Methodology*'s suitability for estimating surficial materials in the Northeast, the State Geologists were advised to choose areas that contained a diversity of surficial materials. Given the study's importance for emergency management purposes, where numerous such areas existed within individual NESEC states, precedence was given to more heavily populated areas. Finally, the State Geologists were advised that the preferred study region size ranged from the city/town level to the county level. These size constraints were designed to ensure reasonably large coverage of the diverse surficial geology in the Northeastern US while also seeking to avoid potential data-processing issues with the HAZUS-MH software. Once the four (4) pilot regions were selected (see *Background*), the State Geologists provided NESEC with the surficial materials datasets.

In order to validate the Wald Methodology through HAZUS, surficial materials must be classified into one of the five possible NEHRP categories: A, B, C, D, or E (See *Table 1*). Whereas the *Wald Methodology* classifies surficial materials into NEHRP categories by design, the datasets provided to NESEC by the State Geologists classify surficial materials into upwards of 30 unique, descriptive categories (e.g., lacustrine clay, fluvial, beach deposits, etc). An extensive literature review was conducted and numerous meetings were held between NESEC and the State Geologists to ascertain the best available methodology for translating the latter categories into the five NEHRP categories. Ultimately a suitable methodology was found (See *3.1 Cadwell Methodology*) that served as an effective baseline for conversion of detailed surficial materials datasets into the five NEHRP categories. As discussed in greater detail in Section 3.1, it is important to note that the Cadwell methodology was based upon geologic studies specific to the State of New York. Due to differences in geology between New York and the four pilot region states (e.g., stacking of surficial materials, etc.), the State Geologists were granted professional discretion to modify classification of select individual surficial material types into NEHRP categories based on additional documented factors that would affect mean shear wave velocities.

3.1 Cadwell Methodology

The Cadwell methodology served as the baseline for conversion of detailed surficial materials datasets into the five NEHRP categories. Included here is a brief description of the Cadwell methodology, followed by a description of its use and adaptation to the four pilot regions. As described in detail below, discretion was awarded to the State Geologists to make minor modifications to this scheme, where necessary, in order to enhance the accuracy of NEHRP category designations in their specific pilot region.

Cadwell (2003) made a list of the 32 surficial units found on the Surficial Geologic Map of New York State (Cadwell, 1991) (1:250,000 scale) and assigned generalized NEHRP site class values to each unit for use in HAZUS by the New York State Emergency Management Office He tested shear-wave velocity means and ranges in Onondaga, Dutchess, Columbia and Westchester counties for eight surficial materials (See Tables 11 and 12).

In cases where Dr. Cadwell determined that surficial materials did not fall clearly into one NEHRP category (e.g., when mean shear wave velocity readings showed significant variation by location and/or fell on the boundary of two NEHRP category ranges), *two* NEHRP values were assigned. The first of two values listed for these surficial materials represents Dr. Cadwell's best estimation.

As seen in the range table (Table 12), some materials tested in upper and lower ranges varying from NEHRP site classes B to E. There are also some materials that Dr. Cadwell recommended a different NEHRP class other than the value assigned based on mean velocity alone. As Dr. Cadwell had deceased by the time of this study, it was not possible to ascertain his full rationale, though these exceptions are worth noting. For instance, the mean for "till" which comprises over 50% of the 1:250,000 map is 664m/sec, well centered in the "C" class. Dr. Cadwell recommended going with a better performing "B" if one was to apply a single value across tills statewide. It can also be noted that in the case of lacustrine silt and clay, the mean value is 312m/sec, which is in the "D" class though the ranges in Rensselear and Duchess counties start as low as 70m/sec and 82m/sec respectively. Dr. Cadwell recommended the more conservative value "E" as the first value for these surficial materials.

Surficial material ( ) = Total # locations	Onondaga County S-wave velocity	Rensselaer County S-wave velocity	Dutchess County S-wave velocity	Columbia County S-wave velocity	Westchester County S-wave velocity	Mean S-wave velocity
Fill (16)	116 m/s				253 m/s	175 m/s
Outwash (24)	103 m/s	208 m/s	155 m/s	368 m/s	313 m/s	231 m/s
Kames (20)	288 m/s	195 m/s	331 m/s	440 m/s	271 m/s	305 m/s
Lake sand (19)	114 m/s	289 m/s	300 m/s	569 m/s	164 m/s	287 m/s
Lake silt & clay (23)	165 m/s	292 m/s	378 m/s	356 m/s	298 m/s	312 m/s
Alluvium (10)	116 m/s		171 m/s	472 m/s	183 m/s	216 m/s
Till (36)	982 m/s	513 m/s	484 m/s	734 m/s	607 m/s	664 m/s
Swamp (2)					186 m/s	186 m/s

Table 11: Shear-Wave Velocity Means in Onondaga, Dutchess, Columbia and Westchester Counties

Surficial Material	Onondaga County	Rensselaer County	Dutchess County	Columbia County	Westchester County	Mean
Fill	76-181 m/s (8)				150-364 m/s (8)	175
Outwash	84-117 m/s (4)	197-308 m/s (3)	75-324 m/s (5)	367-368 m/s (2)	149-700 m/s (10)	231
Kames	100-704 m/s (3)	91-411 m/s (3)	82-445 m/s (6)	383-539 m/s (7)	271 m/s (1)	305
Lake sand	95-133 m/s (4)	86-350 m/s (6)	82-254 m/s (6)	568-569 m/s (2)	164 m/s (1)	287
Lake silt & clay	157-478 m/s (7)	70-1114 m/s (7)	82-467 m/s (4)	370-419 m/s (3)	233-363 m/s (2)	312
Alluvium	105-125 m/s (3)	137 m/s (1)	109-437 m/s (3)	427-518 m/s (2)	183 m/s (1)	216
Till	232-1077 m/s (11)	106-675 m/s (4)	109-797 m/s (8)	371-1163 m/s (6)	194-1311 m/s (7)	664
Swamp					152-219 m/s (2)	186

Table 12: Shear-wave Velocity Ranges in Onondaga, Dutchess, Columbia and Westchester Counties

3.1.1 Cadwell Methodology – Connecticut Pilot Region

The highest potential for structural failure of unconsolidated material overlying bedrock occurs during shaking of fine grained, water saturated sands and clays (Figure 6). These materials may be considered 'soft soils' with lower shear wave velocities relative to other glacial deposits. Glacial outwash sand and gravel deposits are considered to have somewhat higher shear wave velocities. Thick till is considered to have moderate shear wave velocities. Where glacial outwash deposits overlie soft soils there may be a higher potential for increased amplitude shaking and ground failure. The highest shear wave velocities are characterized by till and bedrock. Some shear wave velocity data is available for unconsolidated materials in several NY Counties (Cadwell, 2003) however, the data cannot be used directly for Connecticut materials. Connecticut surficial materials mapping incorporates landform interpretation to produce a three dimensional distribution of textures using a morphosequence model of deglaciation to characterize the unconsolidated materials overlying bedrock (Stone et al, 1992). No standardized shear-wave velocity data exists for Connecticut surficial materials. Shear wave velocity data may be geographically variable, dependent on the geologic setting, degree of saturation, and environment of deposition.

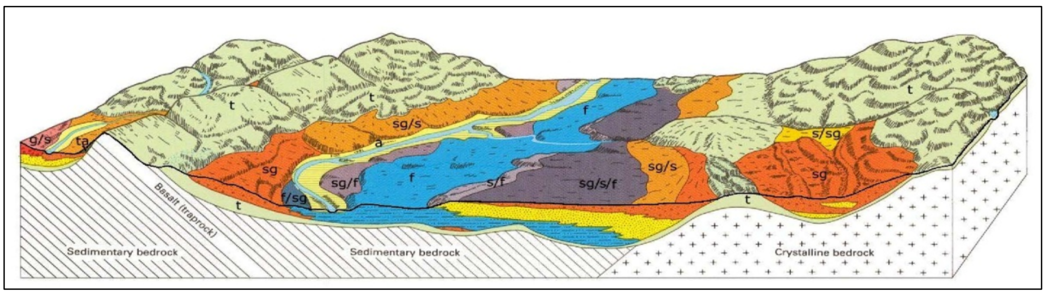

Figure 6: Block Diagram Depicting Connecticut Surficial Materials on the Landscape

For the purposes of the NESG/NESEC analysis within the HAZUS-MH seismic hazard analysis, the following interim NEHRP classifications are presented for Hartford County, Connecticut:

Table 13: NEHRP Classifications Hartford County, Connecticut*	
A	Crystalline Rock & Till (till < 15' thick)
B	Sedimentary Rock & Till (till < 15' thick)
C	Thick Till (> 15 ft thick)
D	Glacial outwash sand & gravel
E	Glacial lake clays and fines; stacked units involving fines c/f; f/c; s/f; postglacial deposits (saturation and subunit dependent); AF c=coarse-grained deposits; f=fines (fine sand, silt, and clay); s=sand; AF= artificial fill postglacial deposits = alluvium and swamp
*classifications are Hartford County specific; geographically variable dependent on the geologic setting, degree of saturation, and environment of deposition. County and material specific shear wave velocity data is needed for more accurate prediction.	

3.1.2 Cadwell Methodology – Maine Pilot Region

The surficial geologic map of the Portland 1:100,000-scale quadrangle includes 23 mapped units. The glaciolacustrine unit is further divided into 18 deposits from distinct glacial lakes that all have similar origins and materials and are therefore treated as one unit for this exercise.

Using the Cadwell (2003) classifications as guidance, the Maine Geological Survey assigned NEHRP class values to each of the surficial units (Table 14). We focused particular attention on the Presumpscot Formation, drawing on several publications to assess the appropriate classification for this unit. In their study of slope stability in the Presumpscot Formation, Devin and Sanford (1990) note the particular susceptibility of the formation to landslides and describe its sensitivity (ratio of undisturbed undrained shear strength to remolded undrained shear strength) as "slightly sensitive to medium quick" using the Rosenqvist (1953) sensitivity classification. Reynolds (1995) describes the Presumpscot as a strain-softening soil. In our own investigations of the 1996 Rockland, Maine landslide (Berry and others, 1996), we determined a minimum p-wave velocity in the Presumpscot of 177 m/s using a 12-channel seismic refraction system. Presumably, s-wave velocities at this same location would be lower.

3.1.3 Cadwell Methodology – Massachusetts Pilot Region

The greatest threat to structures is assumed to occur in areas containing loose, unconsolidated fine-grained sand, silt and clay sediments that are saturated and have a fairly shallow water table. These sediments have the lowest shear wave velocities. Another complicating factor is that many coarser glacial stratified deposits in the Connecticut Valley overlie fine grained silts and clays and are therefore, also assumed to have low shear wave velocities. These fine-grained silts and clays were deposited when Glacial Lake Hitchcock occupied the valley following the last major glaciation. The existence of Lake Hitchcock in the valley plays a major role in controlling the distribution of fine-grained sediments and the vulnerability of structures to shaking. Coarse glacial stratified deposits laid down by meltwater streams that are not underlain by silts and clays of Lake Hitchcock are assumed to have a slightly higher shear wave velocity. Thick till has moderate shear wave velocities. The highest velocities are located in bedrock with a thin cover of glacial till. To our knowledge, no standardized shear wave velocity data is available for the surficial deposits of Massachusetts.

For the purposes of the HAZUS-MH seismic hazards analysis, Table 15 provides the rationale for the NEHRP classifications proposed for the deposits located in the Massachusetts portion of the Connecticut Valley.

Table 14: NEHRP Classifications Portland Maine		
Unit	Description	NEHRP Soil
af	Artificial fill	E
Ha	Stream alluvium - sand, silt, gravel and organic material deposited on floodplains of modern streams	D
Hw	Wetlands - Peat, muck, and./or fine-grained inorganic sediments in poorly drained areas	E
Hbd	Coastal beaches and sand dunes - sand	D
Hls	Beach deposits on modern lake shores - sand and gravel	D
Hsd	Landslide deposit - poorly sorted sediments in prehistoric landslide	E
Qe	Eolian deposit - sand deposited by wind action.	C
Qst	Stream terraces - sand, gravel, and silt deposited on former flood plains.	D
Pl	Glaciolacustrine deposits - sediments deposited in temporary ice-dammed or sediment-dammed lakes. Includes deltas consisting of sand and gravel, and lake-bottom sand, silt, and clay	E
Pmrs	Marine regressive deposit - sand, gravel, and silt deposited in shallow marine waters during late-glacial regression of the sea	C
Pms	Marine shoreline deposits - beach and dune deposits ranging from sand to gravel	C
Pmn	Marine nearshore deposits - sand, gravel, and silt deposited by wave and current action in shoreline and nearshore shallow marine environments.	C
Pp	Presumpscot Formation - silt, clay, and sand deposited on the sea floor	E
Pmf	Submarine fan - sand and gravel deposited on the seafloor at the glacier margin	C
Pmd	Glaciomarine deltas - flat-topped sand and gravel deposits graded to the contemporary late-glacial sea level	C
Pm	Marine deposits, undifferentiated - sand and gravel of uncertain origin	D
Pg	Glacial stream deposits - sand and gravel deposited by glacial meltwater streams	C
Pge	Eskers - ridges of sand and gravel deposited by meltwater streams in subglacial channels	C
Phm	Hummocky moraine - glacial till with hummocky topography	D
Prm	Ribbed moraine - clusters of bouldery till ridges deposited on valley floors	C
Pem	End moraine complexes - clusters of closely spaced end moraines deposited at the receding margin of the last glacial ice sheet	C
Pt	Till - loose to very compact, poorly sorted, massive to weakly stratified mixtures of sand, gravel, silt deposited directly from glacial ice	C
Ptd	Thin drift - areas with abundant bedrock outcrops and generally less than 10 feet of surficial sediments	B

Table 15: NEHRP Classifications Connecticut River Valley, Massachusetts[1]			
NEHRP	Description	Maps Units Included	Rationale
A	Crystalline igneous and metamorphic rocks and thin till (<10-15 ft thick)	Crystalline igneous and metamorphic rock outcrops, shallow bedrock and areas of thin till over crystalline rocks	High strength, indurated rocks with highest shear wave velocities
B	Sedimentary rocks and thin till (<10-15 ft thick)	Sedimentary rocks of Mesozoic age consisting of shale, sandstone, siltstone and conglomerate and areas of thin till over sedimentary rocks	Moderate strength rocks with some weathering, not as indurated as crystalline rocks
C	Thick till (>=10-15 ft thick)	Thick till usually associated with drumlins	Compact to fairly compact heterogeneous mixture of cobbles, sand, silt and clay
D	Glaciofluvial sand and gravel and alluvial fan deposits	Coarse stratified glacial and alluvial fan deposits	Coarse grained unconsolidated sand and gravel deposited in upland areas outside the limits of glacial Lake Hitchcock (300 foot elevation contour)
E	Glacial lake clays, coarse grained deposits overlying fines, loose talus and artificial fill	Coarse stratified deposits overlying lake clays, silts and fine sands; fine stratified deposits of Lake Hitchcock; talus; inland dunes; stream terrace deposits; swamp deposits; floodplain alluvium; artificial fill	Loose, unconsolidated deposits including varved clays, coarse deposits overlying varved clays, stream terrace and floodplain alluvium with probable shallow water table, saturated swamp deposits and loose artificial fill

[1]Classifications are specific to the Connecticut River valley and are interpreted from the surficial geology as mapped by Stone and DiGiacomo-Cohen (2010). Actual shear wave velocities may vary over short geographic distances and depending on grains size distribution, stacking of units in the third dimension and level of saturation.

3.1.4 Cadwell Methodology – Vermont Pilot Region

The Vermont Geological Survey (VGS) applied the generalized NEHRP site class assignments of Cadwell (2003) to the 26 surficial units in Chittenden County, Vermont based on 1:62.500 VGS Mapping (Vermont Center for Geographic Information, Data Layer: GeologicSurficial_SURFICIAL62K). Table 14 shows the translation of the Cadwell first choice site classes to the surficial deposits of Chittenden County in our GIS attribute table.

Table 16: Cadwell Classification Translations Vermont Pilot Region

LITHCODE	FEATURE_TY	LITHNAME	NEHRP Site Class
al	Postglacial fluvial deposit	alluvium	D
fg	Postglacial fluvial deposit	fluvial gravel	C
fs	Postglacial fluvial deposit	fluvial sand	C
bc	Glaciolacustrine deposit	boulders in clay	E
bg	Glaciolacustrine deposit	beach gravel	D
dg	Glaciolacustrine deposit	delta gravel	C
ds	Glaciolacustrine deposit	delta sand	C
ls	Glaciolacustrine deposit	lake sand	D
lg	Glaciolacustrine deposit	lake gravel	C
ls	Glaciolacustrine deposit	lake sand	D
ps	Glaciolacustrine deposit	pebbly sand	C
stc	Glaciolacustrine deposit	silt, silty clay, and clay	E
vc	Glaciolacustrine deposit	varved clay	E
wt	Glaciolacustrine deposit	wave-washed till	B
ek	Glaciofluvial	esker	C
k	Glaciofluvial deposit	isolated kame	C
kt	Glaciofluvial deposit	kame terrace	C
ow	Glaciofluvial deposit	outwash	D
bgm	Champlain Sea deposit	marine beach gravel	D
mc	Champlain Sea deposit	marine clay	E
psm	Champlain Sea deposit	pebbly marine sand	C
t	Glacial deposit	till	B
m	Glacial deposit	moraine	C
es	Eolian deposit	eolian sand	B
p	Pluvial deposit	swamp, peat and/or muck	E
r	Bedrock exposure	bedrock exposure	A

3.2 Geographic Information System (GIS) Methodologies

In order to assess the suitability of the *Wald Methodology* site class estimations for inclusion in HAZUS-MH, we first downloaded the Vs30 ASCII dataset for the East Coast from the USGS Vs30 Server website. This data was then imported into MS Access and properly formatted into a table that contained latitude, longitude, and a Vs30 value for each point from the ASCII data. Following this process, the formatted ASCII table was displayed as XY point layer dataset in Arc Map using the appropriate Geographic Coordinate Systems North American Datum 1983 (GCS NAD 1983). This newly created point layer dataset was then converted to a raster using the IDW tool in Arc Toolbox. Default cell-size parameters were confirmed to be appropriate given the resolution of the ASCII point layer dataset. Importantly, the value column in the raster contained the Vs30 value for each raster pixel. In order to translate these values to HAZUS-MH compatible soil classes, we added an additional “Type” field that described the corresponding NEHRP category for each Vs30 value. Last, the raster was converted to features (i.e., shapefile) using the Raster to Features tool in the ArcMap Spatial Analyst toolbar. This shapefile served as the basis for comparisons of local surficial materials datasets to the *Wald Methodology* site class estimations. Furthermore, by opening ArcCatalog and importing this polygon shapefile into a new personal geodatabase, it also served as the HAZUS-MH compatible *Wald Methodology* soils map for future inclusion pending the outcome of suitability analyses.

Once the *Wald Methodology* site class estimations shapefile was created, it was then compared individually to the four pilot region shapefiles as provided by the NESEC State Geologists. The process used to accomplish this task was the Minus tool within the ArcMap Spatial Analyst toolset. The Minus tool allows for a specified, common numeric column in two layers to be compared via subtraction. The output of a Minus tool analysis is a third layer that shows the result of the subtraction of the two layers (i.e., if the value in layer X’s column is 50 and the value in layer Y’s column is 25, the Minus tool will output a value of +25 for that particular point). In order to utilize the Minus tool properly, the “A” through “E” NEHRP categories had to be reclassified into digits 0 through 5, respectively. Following this reclassification, the Minus tool was utilized to determine the *Wald Methodology* layer’s degree of divergence from the local surficial materials datasets. Outputs include integers -3 through +3, indicating the number of NEHRP categories that the *Wald Methodology* diverges from the local surficial materials datasets. The sign of the integer indicates the direction the *Wald Methodology* estimation would need to travel to obtain the “true” value based upon NEHRP categories A and E being defined as the lowest (0) and highest (5) values, respectively. For example, if the Minus tool output value was +2, the *Wald Methodology* assumed too low of a NEHRP category, and would need to be increased two NEHRP categories to agree with the local surficial materials dataset. The resulting output maps of the Minus tool comparisons for each of the four pilot regions can be seen in Figures 9, 11 and 13.

GIS was also used to quantify, by percentage of overall study area, the *Wald Methodology’s* divergence from the local surficial materials datasets by number and direction of NEHRP categories. This was accomplished by calculating the total area of each of the integer outputs from the Minus tool maps (i.e., the individual cumulative areas of +3, +2, +1, 0, -1, -2, and -3). An additional comparison was made utilizing GIS which assessed the percentage of each study area occupied by the five NEHRP categories, both for local surficial materials datasets and for the *Wald Methodology*. A graph was produced for each study area that compared these percentages side-by-side. Importantly, these graphs, which only used overall study area occupied by each NEHRP category, are only to be used as compliments to the output maps of the Minus tool. They are not effective standalone assessment tools, as overall area percentages may correlate well between the two methodologies while spatial distribution may not.

4.0 ANALYSES & MAPS

This section presents study maps as well as accompanying graphs that illustrate the level of agreement between the *Wald Methodology* site class estimations and local surficial materials data.

In this study, we produced 14 unique maps that served as the basis for our analysis. As described in *Section 3.2. GIS Methodologies*, maps were analyzed spatially and quantitatively to ascertain the suitability of the *Wald Methodology* site class estimations for the Northeast as compared to default HAZUS-MH classifications (i.e., all "D" in the NEHRP scheme). For each of the four pilot regions, we produced three GIS-compatible maps: (1) the State Geologist provided surficial materials coded into NEHRP categories, (2) the *Wald Methodology* generated surficial materials, also coded into NEHRP categories, and (3) a spatial quantification of the *Wald Methodology's* level of agreement with the State Geologist provided classifications. The third map in each sequence is the most important, as it displays both the degree and level of agreement, as well spatial locations where these occur in order to identify areas successfully or unsuccessfully estimated by the *Wald Methodology.*

As a necessary complement to the spatial assessments contained in the third map, we also produced two analysis charts for each pilot region: (1) a side-by-side comparison of the percent area occupied by each NEHRP category, as defined by the *Wald Methodology* and local surficial materials data, and (2) a chart that quantifies the *Wald Methodology*'s divergence from the State Geologist NEHRP categories (by number and direction of NEHRP categories, with "A" defined as the lowest NEHRP category and "E" defined as the highest). Positive or negative integers represent the *Wald Methodology*'s divergence from the State Geologist NEHRP categories, with the number and sign of the integer indicating the change that would need to be applied to the Wald category to make it equivalent to the NEHRP category based on shear wave data. For example, a "+3" would indicate the Wald category was too low by 3 NEHRP categories. This would be an example of positive divergence, in which the *Wald Methodology* assigns a lower NEHRP category than that based on shear wave data, thereby tending to underestimate potential damages. Negative divergence occurs when the *Wald Methodology* assigns a higher NEHRP category than that based on shear wave data, thereby tending to overestimate potential damages.

It is important to note that these analysis charts, strictly speaking, are non-spatial assessments. Area percentages of individual NEHRP categories may correlate well between the two methodologies, while the spatial distribution may not. For that reason, the charts serve as a useful complement to the spatial assessments contained in the third map for each pilot region, but were not used as standalone assessment tools.

4.1 Comparative Analysis of Surficial Materials Classifications (Wald vs. Local)

4.1.1 Connecticut Pilot Region

As discussed in *Section 2.4: Geologic Setting of the Pilot Regions*, the Connecticut River Valley is characterized by a wide variety of surficial materials types. Figure 7, which contains a compilation of the three key GIS-compatible maps described above for the Connecticut Pilot Region, illustrates this variation quite clearly. While the State Geologist provided surficial materials dataset includes regions of all five NEHRP site classes in significant percentages by total land area, the *Wald Methodology* generated map is almost exclusively limited to NEHRP categories B, C and D. As such, the *Wald Methodology* significant underestimates the presence of A soils (i.e., very hard rock) and E soils (i.e., the softest soils) in the region.

Beyond the absence of Categories A and E in the *Wald Methodology* generated map – an issue that is common to all four pilot regions – Figure 7 reveals that the *Wald Methodology* captures some areas of thin till (less than 15 feet thick) overlying sedimentary bedrock classified as B, in agreement with the Geological Survey estimate. Postglacial deposits adjacent to the Connecticut River are characterized by the *Wald Methodology* as C, whereas the State Geological Survey estimates that these areas are more vulnerable to seismic events due to their degree of saturation and underlying fine-grained sediment, and classifies these areas as E. The *Wald Methodology* also characterizes coarse grained areas as D whereas the geologic mapping for this County shows numerous coarse grained deposits with underlying fine grained materials, elevating the classification to E.

The analysis charts (Figure 8), when taken together with the spatial analysis illustrated in the previously introduced maps, reveal a number of key findings for the Connecticut Pilot Region. In 12% of the total study area, the *Wald Methodology* is in exact agreement with the local surficial materials data. In 68% of the study area, the *Wald Methodology* is within one NEHRP category of the local surficial materials assessed NEHRP value (i.e., if local value is assessed at "C" soils, Wald estimates B, C, or D 68% of the time). Importantly, in 21% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an underestimation of damages in HAZUS-MH (i.e., Wald's estimated NEHRP Category too low in a scheme where A, "very hard rock," is defined as lowest, and E, "soft soils," is defined as highest). In 10% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an overestimation of damages in HAZUS-MH.

With regards to individual surficial materials types, the *Wald Methodology* does not capture the significant areas of A and E soils in the Connecticut Pilot Region. It also significantly overestimates the prevalence of C soils. While Figure 8 shows that the total study area determined to have D soils by the *Wald Methodology* is in close agreement with the local surficial materials data, further inspection of the map in Figure 7 reveals poor spatial correlation – the *Wald Methodology* assigns D classifications to areas that are primarily assessed as E soils based on local data and expertise.

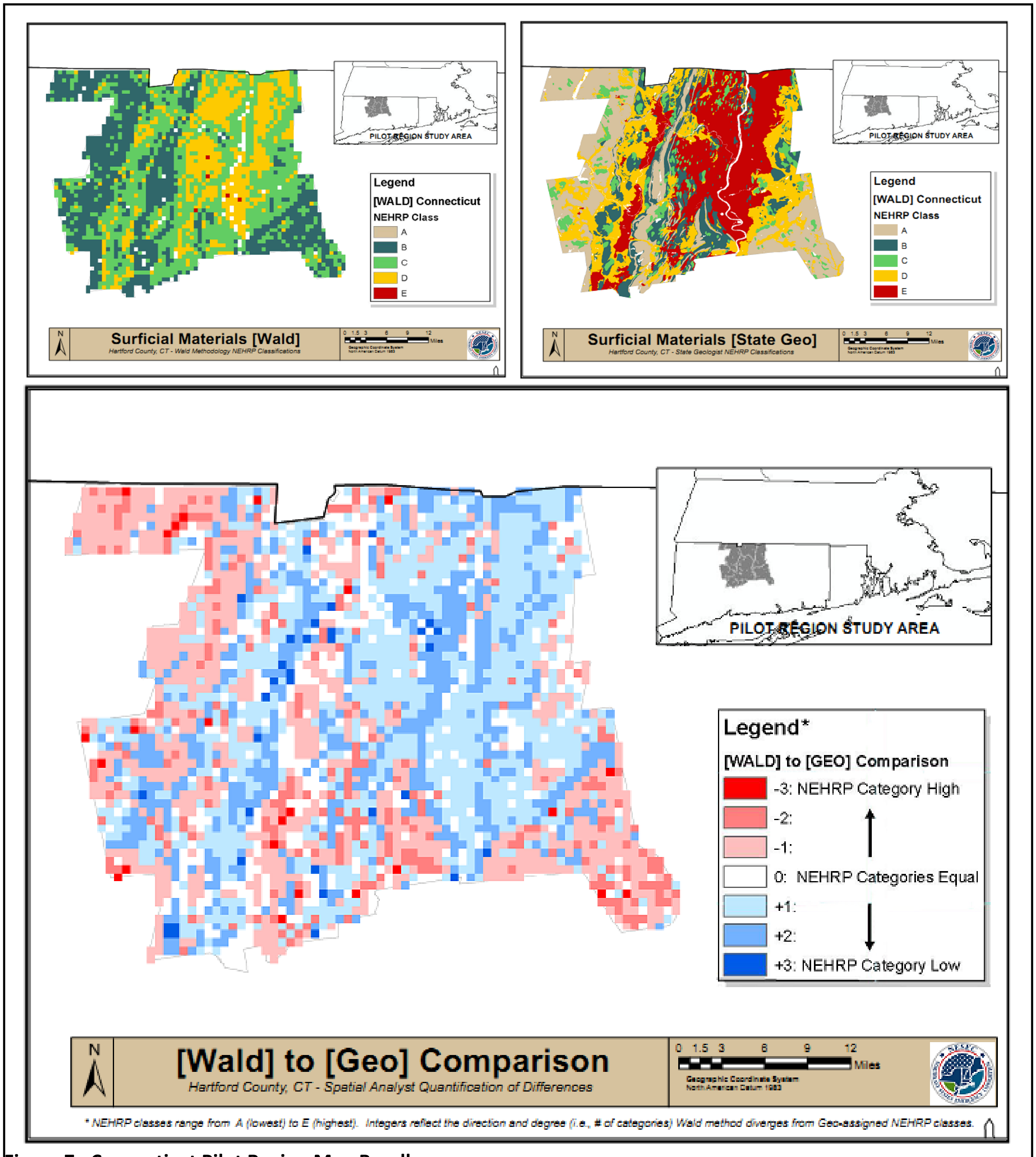

Figure 7: Connecticut Pilot Region Map Bundle

Top (L) map illustrates NEHRP categorizations based on local surficial materials data. Top (R) map illustrates NEHRP categorizations based on the Wald Methodology. The bottom map illustrates the Wald map's level of agreement with local soils data; more muted colors indicate areas of better agreement.

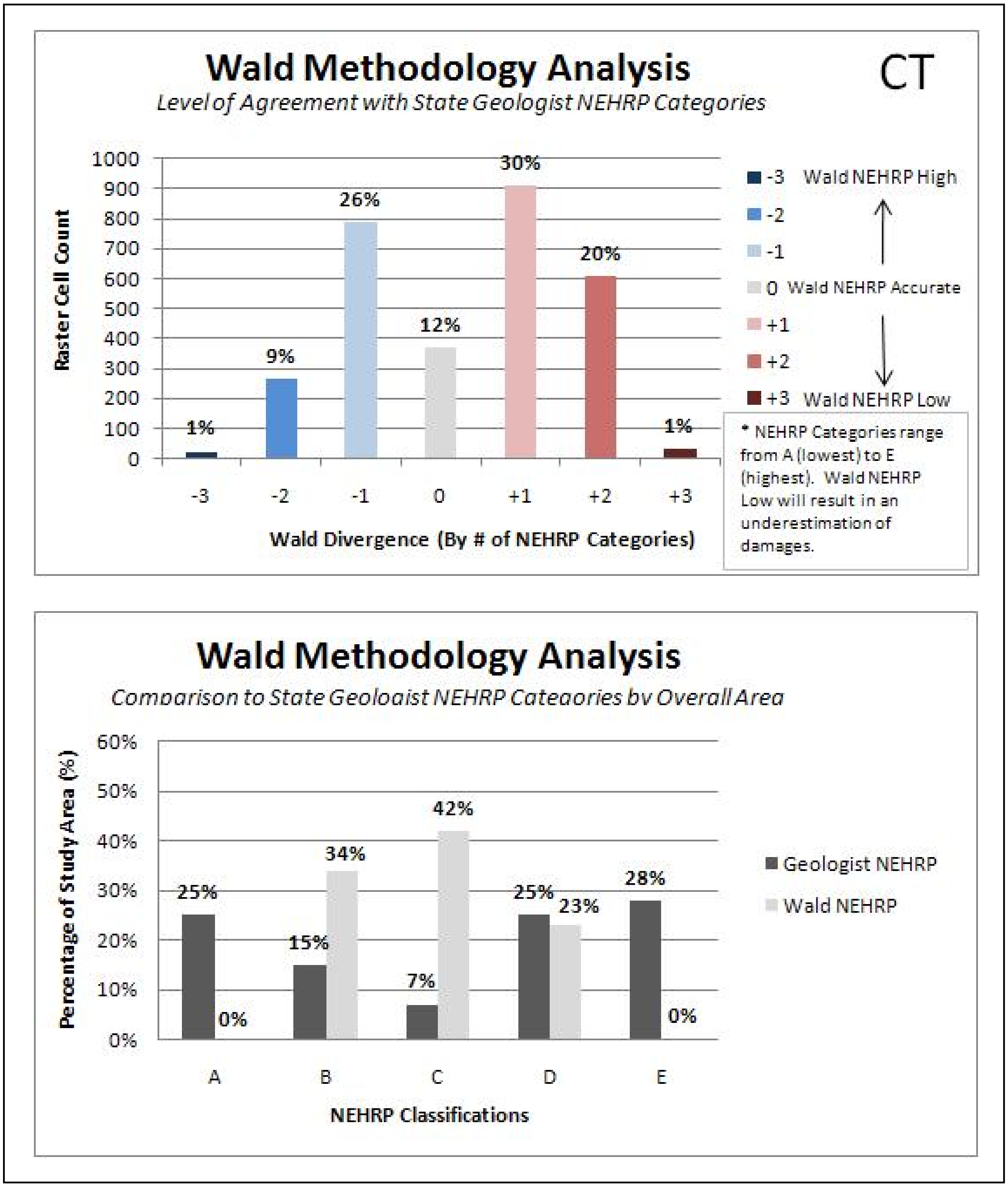

Figure 8. Connecticut Pilot Region Analysis Charts

The top graph quantifies (% study area) the Wald methodology's divergence from the State Geologist NEHRP categories by number and direction of NEHRP categories. Nonzero integers represent divergence, whereas zero indicates the percentage of pilot area where the Wald methodology agrees with State Geologist classification. The bottom graph is a side-by-side comparison of the area (%) occupied by each NEHRP category using both methodologies.

4.1.2 Maine Pilot Region

As discussed in *Section 2.5: Geologic Setting of the Pilot Regions*, the Maine Pilot Region is characterized by a wide variety of surficial materials types. Figure 9, which contains a compilation of the three key GIS-compatible maps described above for the Maine Pilot Region, illustrates this variation quite clearly. While the surficial materials dataset provided by the Maine Geological Survey includes regions of NEHRP site classes B, C, D, and E in significant percentages by total land area, the *Wald Methodology* generated map is limited primarily to NEHRP categories B, C and D. As such, the *Wald Methodology* significantly underestimates the presence of E soils (Softest Soils) in the region.

Beyond the absence of Categories A and E in the *Wald Methodology* generated map – an issue that is common to all four pilot regions – Figure 9 reveals that the *Wald Methodology* captures the gentle relief areas of Maine's southern coastal plain reasonably well. The methodology is not as well suited to areas of complex glacial and glacial-marine sedimentation, including identifying the relatively seismically susceptible soils of intermontaine glacial lakes and clay deposits of the marine invasion that immediately followed deglaciation.

The analysis charts (Figure 10), when taken together with the spatial analysis illustrated in Figure 9, reveal a number of key findings for the Maine Pilot Region. In 33% of the total study area, the *Wald Methodology* is in exact agreement with the local surficial materials data. In 81% of the study area, the *Wald Methodology* is within one NEHRP category of the local surficial materials assessed NEHRP value (i.e., if local value is assessed at "C" soils, Wald estimates B, C, or D 81% of the time). Importantly, in 19% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an underestimation of damages in HAZUS-MH (i.e., Wald's estimated NEHRP Category too low in a scheme where A, "very hard rock," is defined as lowest, and E, "soft soils," is defined as highest). In only 1% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an overestimation of damages in HAZUS-MH.

With regards to individual surficial materials types, the *Wald Methodology* does not capture the significant areas of E soils in the Maine Pilot Region. It also significantly overestimates the prevalence of D soils. Figure 10 reveals strong quantitative agreement in the total percent of C soils within the study region. Further inspection of the map in Figure 9 reveals moderately strong spatial correlation in B, C and D soils, as evidenced by the prevalence of white, or "zero," regions and the muted shades of blue and red throughout.

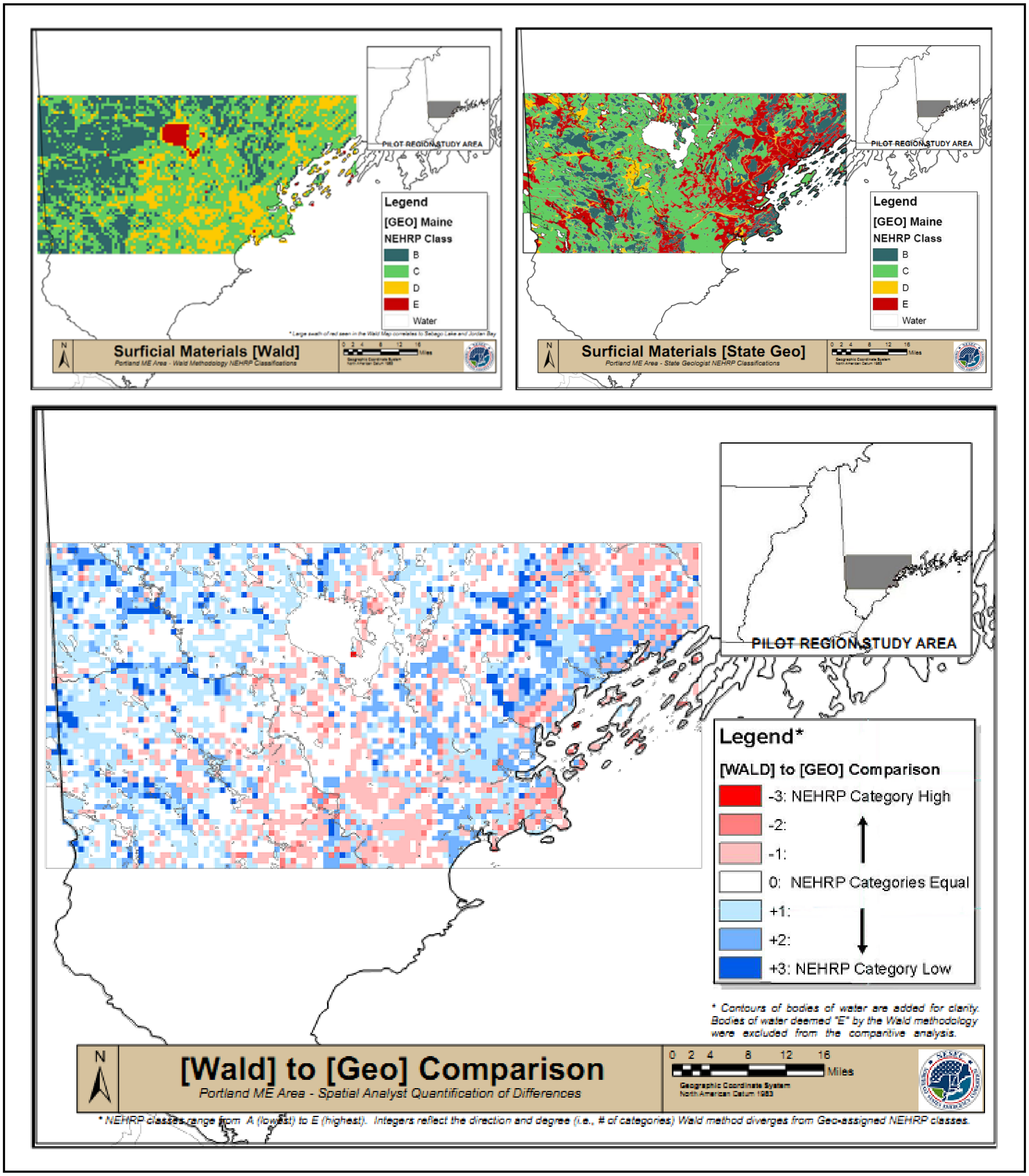

Figure 9: Maine Pilot Region Map Bundle

Top (L) map illustrates NEHRP categorizations based on local surficial materials data. Top (R) map illustrates NEHRP *categorizations based on Wald methodology. The bottom map illustrates the Wald map's level of agreement with local soils data; more muted colors indicate areas of better agreement.*

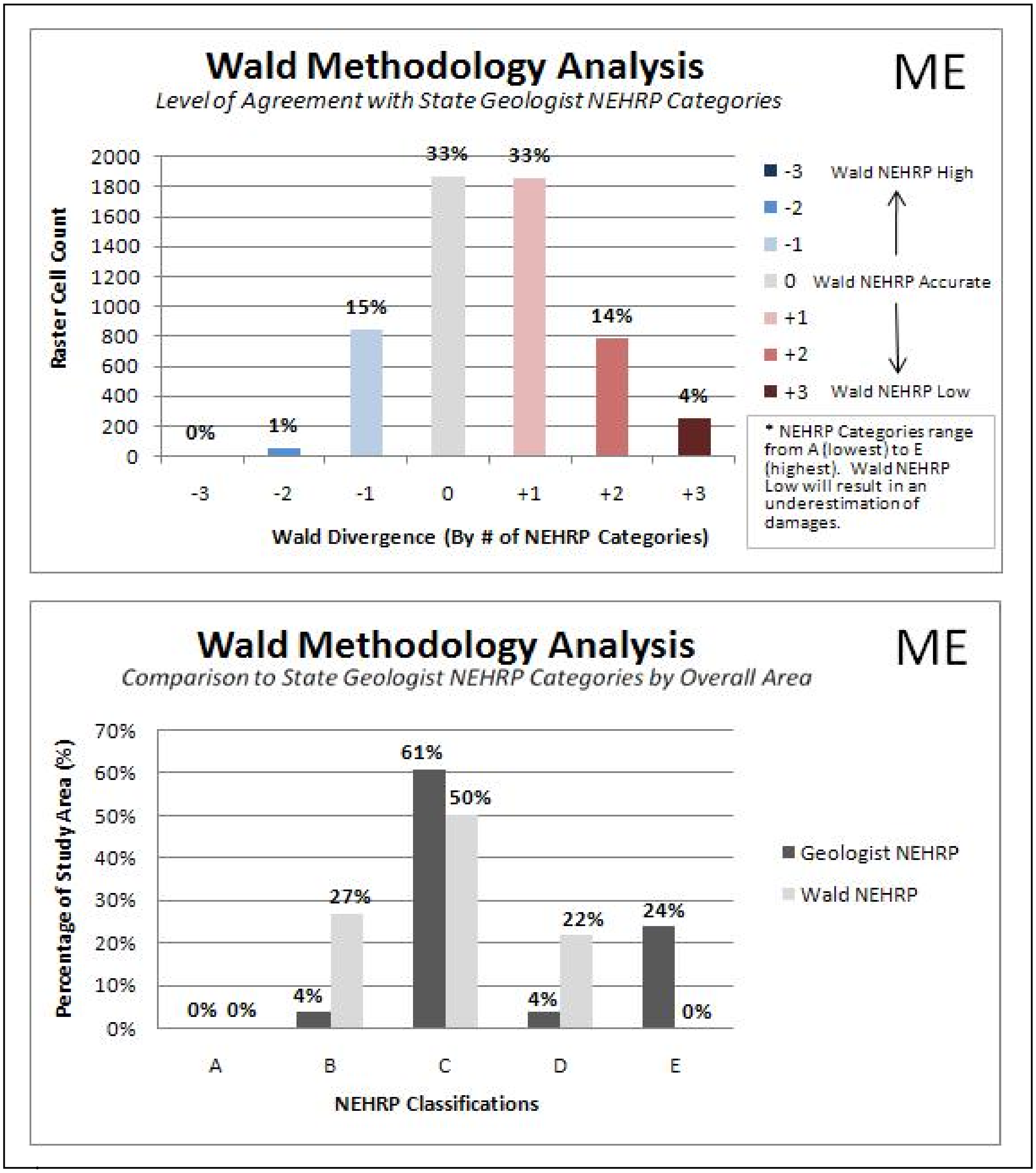

Figure 10: Maine Pilot Region Analysis Charts

The top graph quantifies (% study area) the Wald methodology's divergence from the State Geologist NEHRP categories by number and direction of NEHRP categories. Nonzero integers represent divergence, whereas zero indicates the percentage of pilot area where the Wald methodology agrees with State Geologist classification. The bottom graph is a side-by-side comparison of the area (%) occupied by each NEHRP category using both methodologies.

4.1.3 Massachusetts Pilot Region

As discussed in *Section 2.4: Geologic Setting of the Pilot Regions*, the Connecticut River Valley is characterized by a wide variety of surficial materials types. Figure 11, which contains a compilation of the three key GIS-compatible maps described above for the Connecticut Pilot Region, illustrates this variation quite clearly. While the State Geologist provided surficial materials dataset includes regions of all five NEHRP site classes in significant percentages by total land area, the *Wald Methodology* generated map is again limited primarily to NEHRP categories B, C and D. As such, the *Wald Methodology* significant underestimates the presence of A soils (Very Hard Rock) and E soils (Softest Soils) in the region.

Beyond the absence of Categories A and E in the *Wald Methodology* generated map, Figure 11 reveals that the Wald method captures the thin till deposits on sedimentary bedrock and is within one classification unit in the flatter Connecticut Valley bottomlands as well as in some of the flatter and larger sand and gravel delta deposits. The *Wald Methodology* is also within one classification unit in the uplands where thin till lies over igneous and metamorphic bedrock. The greatest areas of spatial disagreement (areas where Wald units diverge by two or more classifications units is in the Connecticut Valley bottom where most deposits are underlain by varved lacustrine deposits of Lake Hitchcock; areas where the greatest population and structures reside. The other area of disagreement occurs in alluvial deposits along upland streams and rivers.

The analysis charts (Figure 12), when taken together with the spatial analysis in Figure 11, reveal a number of key findings for the Massachusetts Pilot Region. In 5% of the total study area, the *Wald Methodology* is in exact agreement with the local surficial materials data. In 63% of the study area, the *Wald Methodology* is within one NEHRP category of the local surficial materials assessed NEHRP value (i.e., if local value is assessed at “C” soils, Wald estimates either B, C, or D 63% of the time). Importantly, in 27% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an underestimation of damages in HAZUS-MH (i.e., Wald’s estimated NEHRP Category too low in a scheme where A, “very hard rock,” is defined as lowest, and E, “soft soils,” is defined as highest). In 11% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an overestimation of damages in HAZUS-MH.

With regards to individual surficial materials types, the *Wald Methodology* does not capture the significant areas of A and E soils in the Massachusetts Pilot Region. It also significantly overestimates the prevalence of B, C, and D soils.

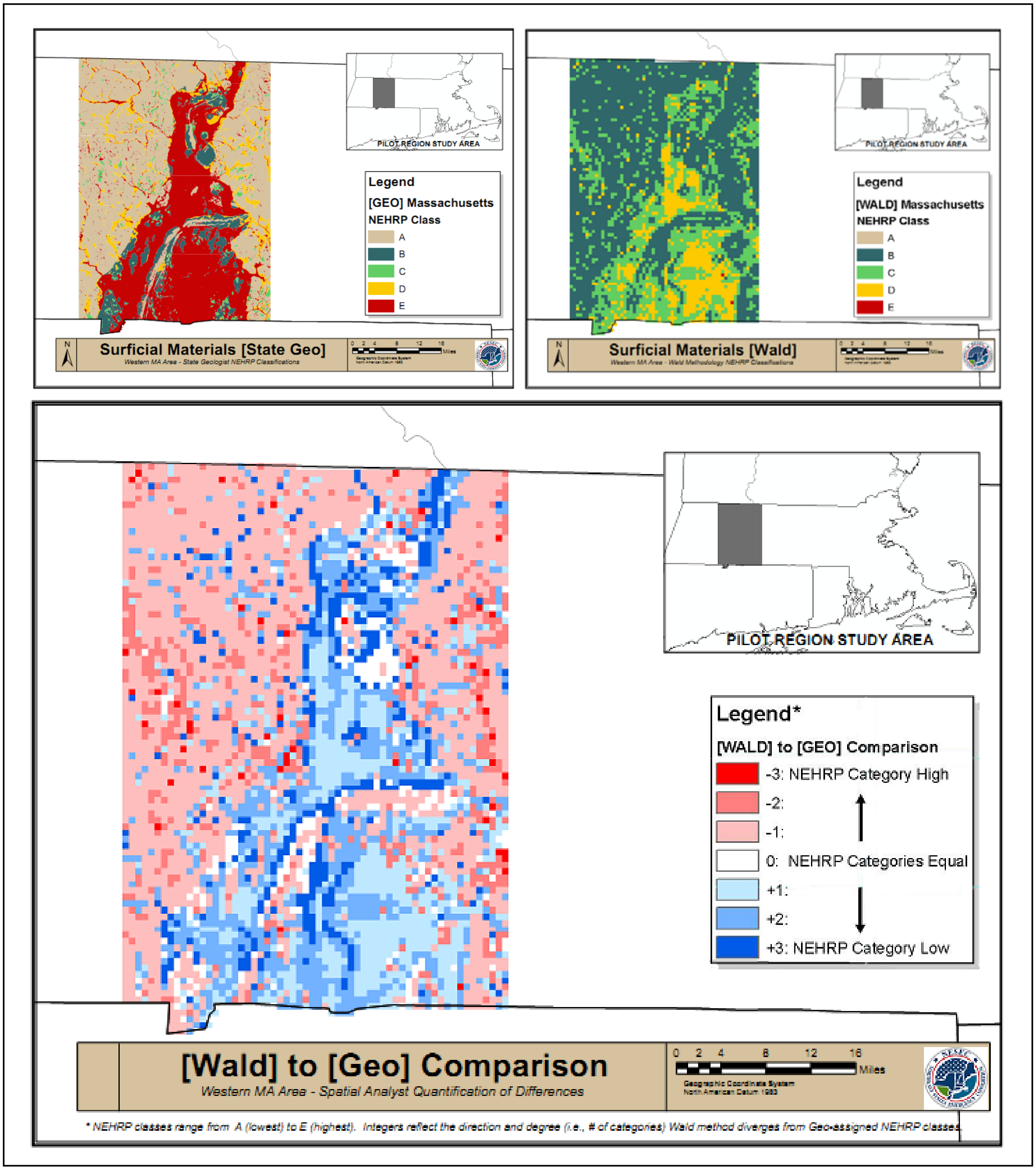

Figure 11: Massachusetts Pilot Region Map Bundle

Top (L) map illustrates NEHRP categorizations based on local surficial materials data. Top (R) map illustrates NEHRP categorizations based on Wald Methodology. The bottom map illustrates the Wald map's level of agreement with local soils data; more muted colors indicate areas of better agreement.

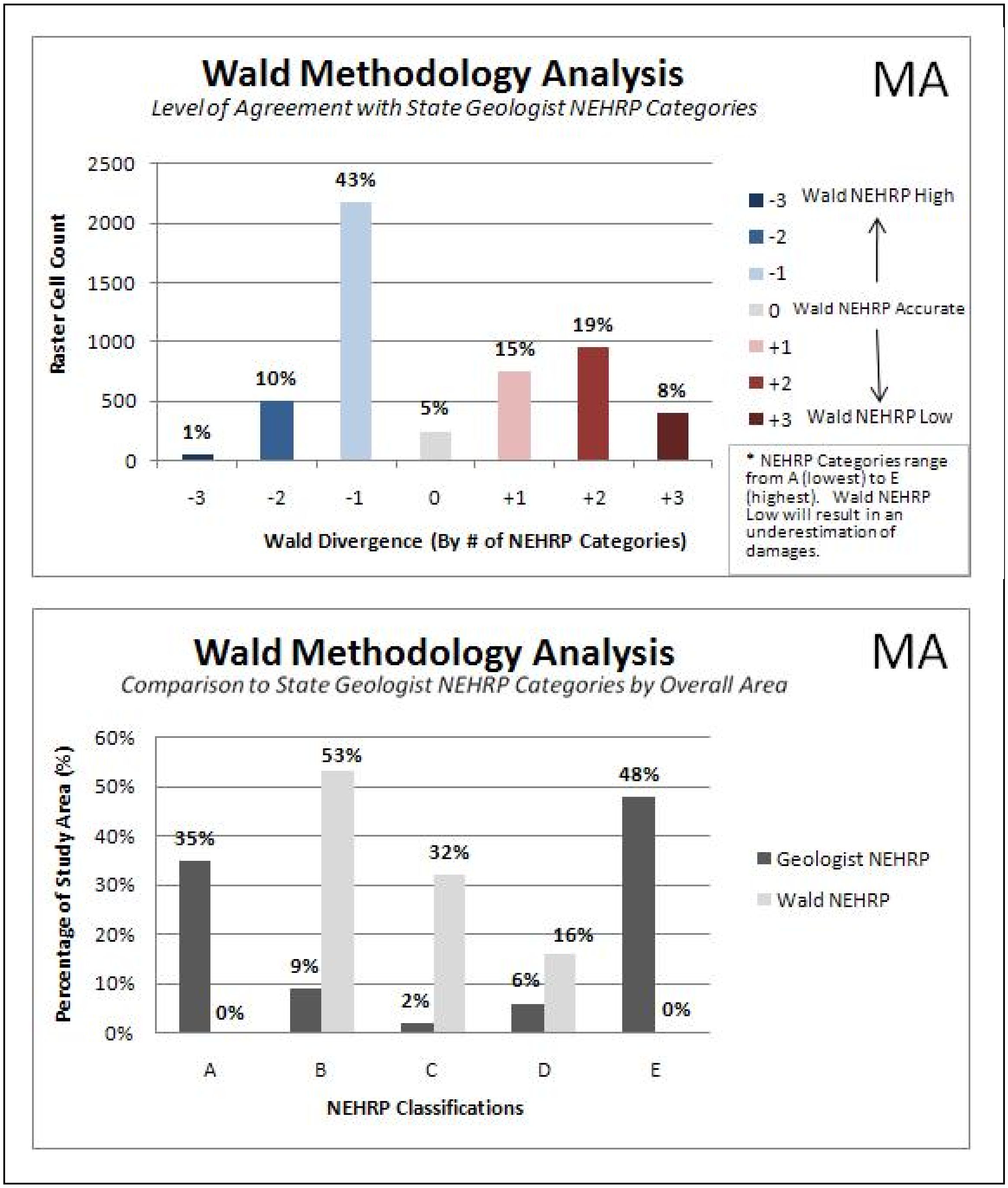

Figure 12: Massachusetts Pilot Region Analysis Charts

The top graph quantifies (% study area) the Wald Methodology's divergence from the State Geologist NEHRP categories by number and direction of NEHRP categories. Nonzero integers represent divergence, whereas zero indicates the percentage of pilot area where the Wald methodology agrees with State Geologist classification. The bottom graph is a side-by-side comparison of the area (%) occupied by each NEHRP category using both methodologies

4.1.4 Vermont Pilot Region

As discussed in *Section 2.5: Geologic Setting of the Pilot Regions*, Chittenden County is characterized by a wide variety of surficial materials types. Figure 13, which contains a compilation of the three key GIS-compatible maps described above for Chittenden County, illustrates this variation. While the State Geologist provided surficial materials dataset includes regions of all five NEHRP site classes in significant percentages by total land area, the *Wald Methodology* generated map is limited primarily to NEHRP categories B, C and D. As such, the *Wald Methodology* significantly underestimates the presence of A soils (Very Hard Rock) and E soils (Softest Soils) in the region; a result that is observed in all pilot regions.

Beyond the absence of Categories A and E in the *Wald Methodology* generated map – an issue that is common to all four pilot regions – Figure 13 reveals that the *Wald Methodology* captures fairly the eastern half of the County in the till covered and exposed bedrock portion of the study area. The Winooski River Valley that flows west through the upland area display a change from Wald when coded Surficial materials maps are employed. This is largely due to alluvium and lacustrine deposits in the valley bottom. In the Western lowlands, there are a number of areas that diverge from the Wald approach when surficial materials are coded using the Cadwell guidance. There are prominent areas that are coded as Class "E" due to lacustrine deposits of clay, silt, silty clay, clay, varved clay as well as marine clay exposures.

The analysis charts (Figure 14), when taken together with the spatial analysis illustrated in Figure 13, reveal the following results for the Vermont Pilot Region. In 47% of the total study area, the *Wald Methodology* is in exact agreement with the local surficial materials data. In 74% of the study area, the *Wald Methodology* is within one NEHRP category of the local surficial materials assessed NEHRP value (i.e., if local value is assessed at "C" soils, Wald estimates either B, C, or D 74% of the time). In 22% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an underestimation of damages in HAZUS-MH (i.e., Wald's estimated NEHRP Category too low in a scheme where A, "very hard rock," is defined as lowest, and E, "soft soils," is defined as highest). In 3% of the study area, the *Wald Methodology* is off by 2 or more categories in the direction that would result in an overestimation of damages in HAZUS-MH.

With regards to individual surficial materials types, the *Wald Methodology* does not capture the significant areas of A and E soils in the Vermont Pilot Region. Inspection of the spatial analysis map reveals that the source of the 47% of exact agreement between the *Wald Methodology* and surficial materials data is primarily due to agreement in the large swatch of B soils in the eastern two-thirds of Chittenden County. The *Wald Methodology* moderately overestimates the prevalence of B soils

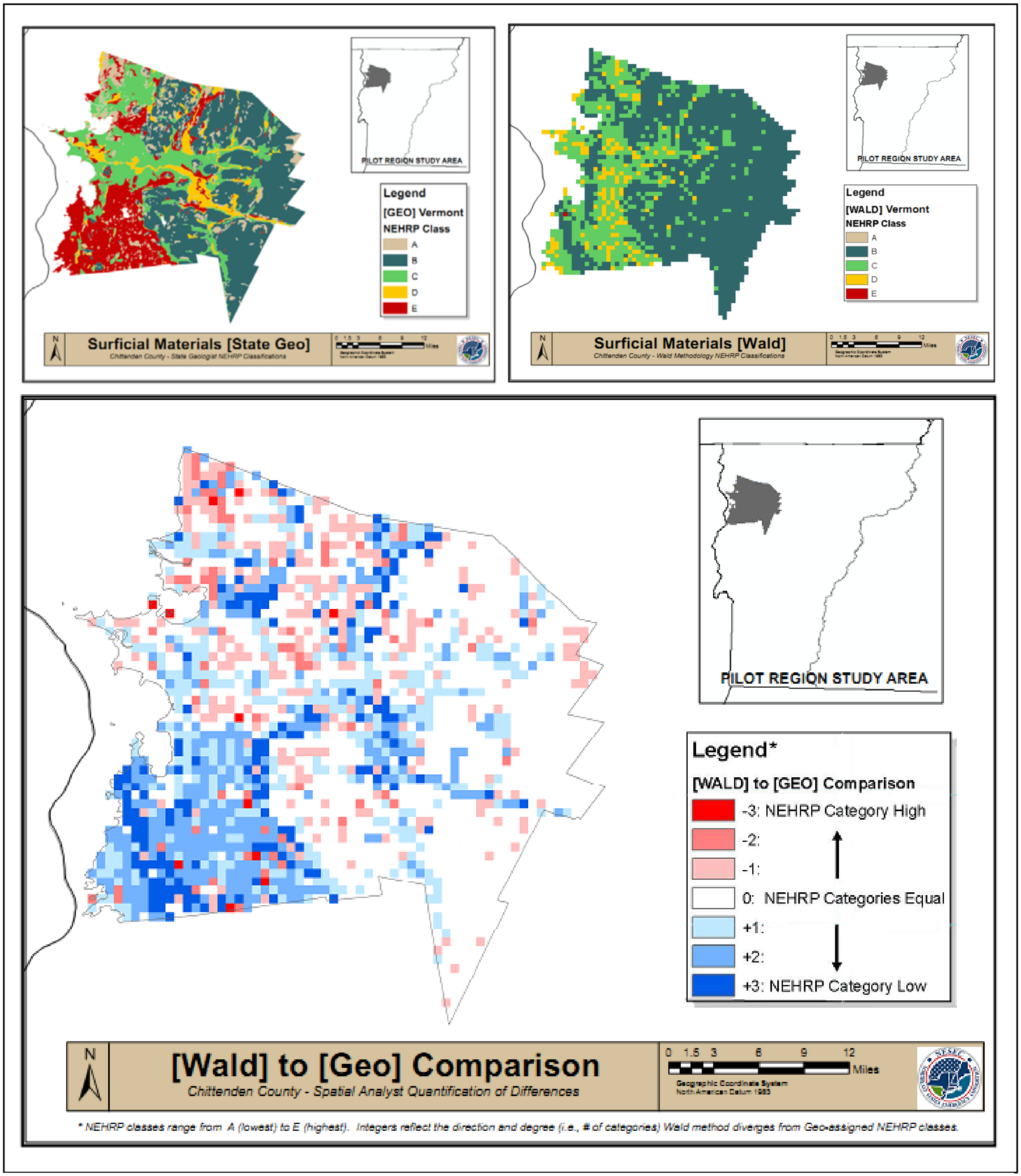

Figure 13: Vermont Pilot Region Map Bundle

Top (L) map illustrates NEHRP categorizations based on local surficial materials data. Top (R) map illustrates NEHRP categorizations based on Wald methodology. The bottom map illustrates the Wald map's level of agreement with local soils data; more muted colors indicate areas of better agreement.

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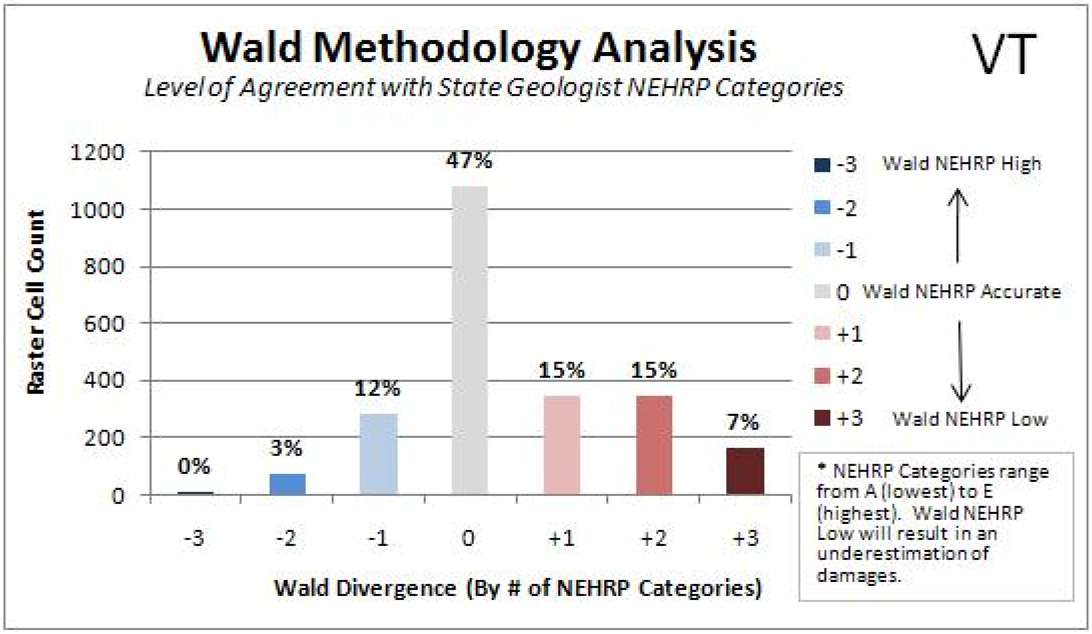

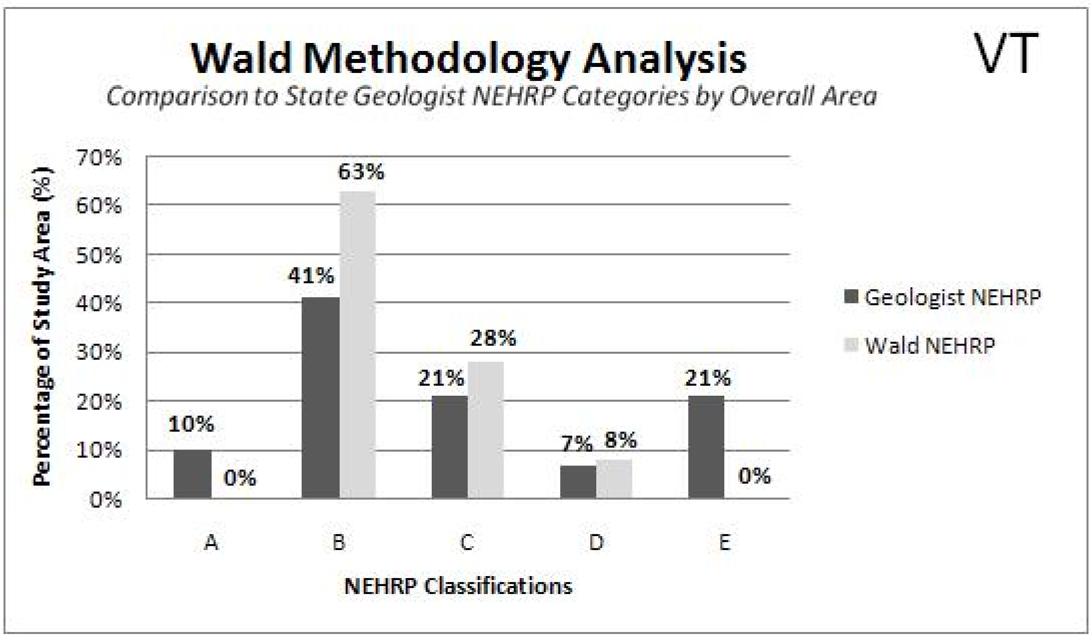

Figure 14: Analysis Charts for Vermont Pilot Region

The top graph quantifies (% study area) the Wald methodology's divergence from the State Geologist NEHRP categories by number and direction of NEHRP categories. Nonzero integers represent divergence, whereas zero indicates the percentage of pilot area where the Wald methodology agrees with State Geologist classification. The bottom graph is a side-by-side comparison of the area (%) occupied by each NEHRP category using both methodologies.

5.0 DISCUSSION

5.0.1 Wald Methodology and Soils

In order to analyze the validity of using the *Wald Methodology* to classify surficial geology for HAZUS-MH loss estimations in the Northeast, the authors of this study relied on the best available surficial materials information along with a methodology that served as an effective baseline for conversion of detailed surficial materials datasets into the five NEHRP categories. This allowed for a comparative analysis to be performed. While this process produced a fairly robust assessment indicating the lack of suitability of the *Wald Methodology* classifications for HAZUS-MH loss estimations in the Northeast, there are two main issues with this approach that must be acknowledged.

First and foremost, surficial materials mapping requires interpretation by geologists and the classification is ultimately based on professional judgment. This process is not standardized and judgments can vary between individual geologists. This was the case with the Cadwell methodology – the underlying approach utilized in this study that allowed for the conversion of surficial materials datasets into the five NEHRP categories. Second, the Cadwell approach is based upon studies conducted in Upstate New York. The extrapolation of this model to other states within the Northeast is not without its drawbacks, however, the previously mentioned professional discretion issued to state geologists allowed for modifications to these conversions to enhance accuracy. Ultimately, the Cadwell methodology is advantageous because it is an unbiased regional approach that is repeatable. While surficial maps provide the best resolution for planners, the geologists' interpretations – though useful – will remain in question without shear wave data to provide conclusive support.

5.0.2 Implications of Results for Emergency Managers

While the *Wald Methodology* captures broad geologic features (e.g., the Connecticut River Valley) and shows significant variation in site classifications, it largely misses the "extremes" of the NEHRP classification system – namely category A (i.e., hard rock) and category E (i.e., soft clays). These two categories are of particular interest to emergency managers, as knowing their location allows for a reasonable assessment of which areas will be of least and most concern, respectively, in the course of a seismic event.

When presented with the option of utilizing the default all D classification in HAZUS-MH or utilizing the *Wald Methodology*, emergency managers must decide whether it will beneficial to use a methodology which includes inaccurate variations that may underestimate risk and damage to some key areas while overestimating risk and damage to others. In nearly all cases, it can be expected that the default all-D classification will be preferred, despite its inability to illustrate "potential pockets" of damage.

6.0 CONCLUSION / RECOMMENDATIONS

The authors of this study have concluded that the *Wald Methodology* underestimates classifications of NEHRP category A (i.e., hard rock) and NEHRP category E (i.e., soft clays) in the Northeast region. These categories - the so-called "extremes" - are of particular interest to emergency managers as they can generally be expected to incur the least severe and most severe damages, respectively. As a result, the replacement of default NEHRP category D in HAZUS with the *Wald Methodology* would not be recommended, as it would be expected to underestimate risk and damages in some key areas of most concern while overestimating risk and damages in some areas of least concern. The authors of this study do not feel that this represents an improvement over the all-D classification that would produce a nearly uniform overestimation of risk and damage for all but the poorest soils (i.e., Category E -soft clays). For emergency management planning purposes it is better to slightly overestimate the damage and losses utilizing the default all-D Classification.

In order to truly provide accurate seismic risk information for emergency managers, the authors of this study feel that it is critical that further shear wave velocity studies be conducted. Minimally, these studies could provide validation of the Cadwell methodology, which could be adopted as the standard model for the conversion of already available surficial materials datasets to NEHRP maps for the inclusion in HAZUS-MH.

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