Liquefaction Susceptibility for the Auburn and Poverty Bay 7.5-minute Quadrangles, Washington

by Stephen P. Palmer,
Timothy J. Walsh,
Robert L. Logan, and
Wendy J. Gerstel

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-43
September 1995

Partially supported by the
Federal Emergency Management Agency,
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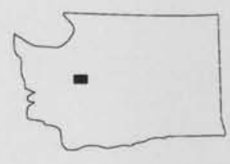
The information provided in this map cannot be substituted for a site-specific geotechnical investigation, which must be performed by qualified practitioners and is required to assess the potential for and consequent damage from soil liquefaction.



Location of quadrangles

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands
Kaleen Cottingham - Supervisor

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Liquefaction Susceptibility for the Auburn and Poverty Bay 7.5-minute Quadrangles, Washington

by Stephen P. Palmer, Timothy J. Walsh, Robert L. Logan, and Wendy J. Gerstel

SUMMARY

Liquefaction susceptibility maps are presented for the Auburn and Poverty Bay 7.5-minute topographic quadrangles*. These maps are based on analyses of 301 geotechnical borings obtained from the Washington State Department of Transportation, the King County Development and Environmental Services Department, and the City of Auburn. Three categories of geologic deposits found in the study area are assigned a susceptibility ranking determined through analysis of the geotechnical data, geological characterization, and historical reports of liquefaction during the 1949 magnitude 7.1 Olympia and 1965 magnitude 6.5 Seattle–Tacoma earthquakes.

These maps are intended to provide land-use planners, emergency-response personnel, geotechnical consultants, building developers and contractors, and private citizens with a qualitative assessment of the likelihood of soil liquefaction during an earthquake. The various data used in the liquefaction susceptibility assessment have been correlated with geological units mapped at 1:24,000 scale (1 in. equals 2,000 ft). Because of the regional nature of these maps (as determined by their 1:24,000 scale) only generalized areas more or less prone to liquefaction can be specified. These maps *cannot* be used to determine the presence or absence of liquefiable soils beneath any specific locality. Likewise, no estimate of the damage resulting from liquefaction is presented in this study; in many instances liquefaction may occur without causing significant ground displacement and consequent damage to structures.

These maps cannot be substituted for a site-specific geotechnical investigation, which must be performed by qualified practitioners and is required to assess the potential for liquefaction and consequent damage for a given project.

Category I deposits, comprising artificial fill and modified land and Holocene (younger than 10,000 years) alluvium, are ranked as having a high susceptibility to liquefaction. The courses of the White and Stuck Rivers immediately prior to the major diversion and realignment of these rivers in 1906 are shown on the Auburn quadrangle. In addition, abandoned channel segments of the White, Stuck, and Green Rivers are mapped in the study area. Although these riverine features already lie within Category I deposits, they *may* have a locally higher susceptibility to liquefaction, either because they have been filled during this century as a consequence of the development of the Duwamish valley or because they are topographically low areas that are likely to have a shallower ground-water table than the adjacent flood plain.

Category II deposits, ranked as having a moderate liquefaction susceptibility, consist of Holocene lacustrine (lake) and mass-wasting (downslope transport of soil and rock) deposits and late Pleistocene (older than 10,000 years) glaciolacustrine (glacial lake) deposits predominantly composed of sand. Twenty-one geotechnical borings are in this liquefaction category. Our geotechnical analysis indicates that some of these borings penetrated liquefiable soil. Also, possible liquefaction of Holocene lacustrine sediments near Big Soos Creek just north of the study area was reported during the 1949 Olympia earthquake.

Category III deposits include the Osceola Mudflow and all remaining Pleistocene sediments. Quantitative evaluation of geotechnical data obtained from the Pleistocene deposits indicates a low susceptibility to liquefaction. The historic record supports the low ranking assigned to Category III deposits, as there are no reported instances of liquefaction in these deposits during the 1949 and 1965 earthquakes. However, small, unmapped areas of fill soils occur throughout the area designated as Category III and may have a higher liquefaction susceptibility than the underlying native soils.

* This pamphlet accompanies the liquefaction susceptibility maps for the Auburn and Poverty Bay quadrangles.

INTRODUCTION

The Washington Department of Natural Resources, Division of Geology and Earth Resources Division (DGER), is actively investigating earthquake hazards statewide using funding from the National Earthquake Hazards Reduction Program initially provided through the U.S. Geological Survey and subsequently through the Federal Emergency Management Agency and the Washington State Department of Trade and Economic Development, Division of Emergency Management (now part of the Military Department). DGER has concentrated its technical program on mapping deposits in the Puget Sound region that are subject to seismically induced soil liquefaction.

The purpose of this report is to present maps showing liquefaction susceptibility in the Auburn and Poverty Bay 7.5-minute quadrangles. These maps encompass the alluvial valley along the lower reaches of the Green and White Rivers in the Duwamish valley and the adjacent glacial drift plains. The liquefaction susceptibility maps are adjacent to the Des Moines and Renton 7.5-minute quadrangles to the north, the Sumner and Puyallup 7.5-minute quadrangles to the south, and the Tacoma North 7.5-minute quadrangle to the west. Liquefaction susceptibility mapping has been published for these quadrangles by Palmer and others (1994), Dragovich and Pringle (1995), and Shannon & Wilson, Inc. (1993) (Fig. 1).

Liquefaction occurs when a water-saturated, granular (sandy) soil loses strength during vibratory shaking such as that generated by an earthquake. Below the ground-water table, the pore space among sand grains is filled with water. The weight of the overlying soil mass is ordinarily supported by grain-to-grain contact. Strong shaking during a large earthquake can disrupt the grain-to-grain contact, causing a decrease in the grain support. If strong shaking lasts long enough, the grain structure of a loose sandy soil may completely collapse. If the pore water cannot flow out of the collapsing pore space quickly, then the pore-water pressure must increase to account for the stresses imposed by the overlying soil mass. In the extreme case where the grain support is completely lost, the pore water must bear the entire weight of the overlying soil mass. At this point, the sandy soil is liquefied and will temporarily behave as a viscous fluid. The liquefied soil may then be subject to extreme lateral deformation because it does not provide much resistance to horizontal forces. This lateral spreading can cause tremendous damage to buildings and buried utilities subjected to these horizontal translations. Additionally, soil liquefaction can result in loss of bearing capacity for large structures, flotation of underground tanks and other buried structures, and foundation damage caused by differential vertical settlement.

These maps provide land-use planners, emergency-response personnel, geotechnical consultants, building developers and contractors, and private citizens with a qualitative assessment of the likelihood for soil liquefaction during an earthquake. These maps are meant only as a general guide to delineate areas prone to liquefaction. *These maps are not a substitute for a site-specific investigation to assess the potential for liquefaction and corresponding damage for any development project.* Because the liquefaction susceptibility categories have been delineated using 1:24,000-scale geological mapping, these maps cannot be used to determine the presence or absence of liquefiable soils beneath any specific locality, nor the potential for damage if liquefaction should occur. *Site-specific geotechnical investigations performed by qualified practitioners are required to make these determinations.*

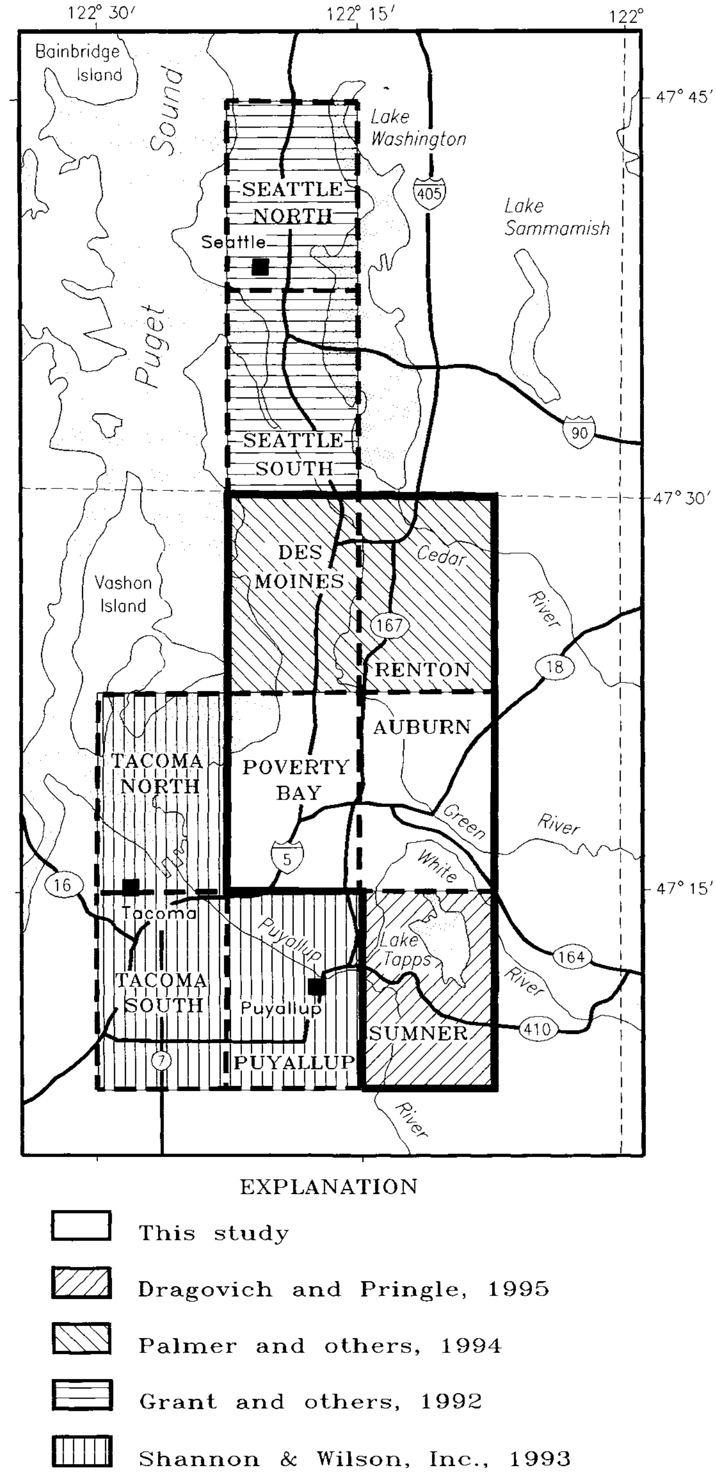


Figure 1. Location map showing the Poverty Bay and Auburn 7.5-minute quadrangles and adjacent quadrangles for which liquefaction studies have been completed.

GEOLOGY OF THE AUBURN AND POVERTY BAY QUADRANGLES

Geological mapping of the Auburn and Poverty Bay 7.5-minute quadrangles at 1:24,000 scale is provided by Mullineaux

(1965) and Waldron (1961). The oldest geological deposits exposed in the study area are Pleistocene glacial and nonglacial deposits that unconformably overlie Tertiary bedrock (Fig. 2, p. 4,5). The youngest of these glacial units was deposited during the Vashon Stade of the Fraser Glaciation (ca. 13,000 to 15,000 years ago). Vashon till, glaciofluvial, and glaciolacustrine deposits form a broad drift plain that occupies the lowland between the Olympic Mountains and the foothills of the Cascade Range. In the study area this drift plain stands a few hundred feet above the floor of the Duwamish valley, through which flow the Green and White Rivers.

Sedimentary deposits younger than the Vashon Drift are also present in the study area. Holocene lacustrine deposits mapped by Mullineaux (1965) and Waldron (1961) in low areas on the drift plain are primarily peat with some sand, silt, and clay. Thin, peaty lake deposits also have formed in depressions on the flood plain of the Duwamish River, although none is mapped in the study area. However, peaty lake deposits on the flood plain of the Puyallup River are mapped by Waldron (1961) in the southwest portion of the Poverty Bay quadrangle[1]. Osceola Mudflow deposits were mapped by Mullineaux (1965) in the southeast portion of the Auburn quadrangle. Holocene alluvial sand, silt, and gravel are found in the Duwamish valley, in the valleys occupied by the White and Green Rivers and Big Soos Creek, and at the mouths of several small drainages where they empty into the Duwamish valley or Puget Sound. Water-well data from the area immediately northwest of Auburn show that the mid-Holocene Osceola Mudflow (Luzier, 1969) lies at a depth of approximately 260 to 280 ft (79 to 85 m) below present-day sea level. These data indicate that the Duwamish valley was an embayment of Puget Sound at the time of deposition of the Osceola Mudflow. Thus the alluvial deposits overlying the Osceola Mudflow in the study area are no older than middle Holocene.

Waldron (1961) describes present-day beach deposits as consisting of gravel, sand, silt, and clay that are derived mostly from material in the adjoining bluffs, but also include some alluvium reworked by waves and littoral currents. Small alluvial fan deltas are common at the mouths of streams; many of the silt and clay beaches are adjacent to these fan deltas. However, these beach deposits are not shown on the geologic map of the Poverty Bay quadrangle as they are too small in area to be represented at 1:24,000 scale.

Mass-wasting deposits mapped by Mullineaux (1965) consist primarily of relatively thick and continuous landslide debris and colluvium and generally form wet, unstable ground. Waldron (1961) mapped four major landslides as mass-wasting deposits, which he described as heterogeneous landslide debris including both slumps and earthflow material. He notes that the products of mass wasting (small landslide deposits and colluvium) are common in the Poverty Bay quadrangle, but they were not included on his geologic map.

Before 1906, the White River bifurcated just before reaching the floor of the Duwamish valley, with the White River flowing northward into the Green River and the Stuck River flowing southward as a tributary of the Puyallup River (Willis and Smith, 1899; Luzier, 1969). After a flood in 1906 most of the flow was directed into the Stuck River, and subsequent engineering projects permanently diverted the north-flowing White River into the Stuck River (which was then renamed the White River). The city of Auburn has developed on the abandoned channel and adjacent flood plain of the pre-1906 White River. Figure 3 presents the current and historic names and courses of the major rivers that traverse the study area.

Modified and filled land is largely concentrated in alluvial valleys; it includes extensive fill along the pre-1906 course of the White River in the vicinity of Auburn, embankments constructed for railroad lines, roadways, and water impoundments, and foundation pads for buildings. However, several small areas of modified and filled land occur at scattered locations on the drift plain in both quadrangles.

Figure 2. Generalized geologic maps of the Poverty Bay and Auburn quadrangles are presented on the following two pages. Asterisks are approximate locations of individual boreholes; filled triangles are clusters of closely spaced boreholes (number of boreholes superscripted); squares are the approximate locations of the centers of various communities.

EXPLANATION

af	Artificial fill and modified land, undifferentiated
Qa	Quaternary alluvium; stratified clay, silt, sand, and gravel
Qm	Quaternary mass-wasting deposits; includes colluvium, slump-earthflow, debris avalanche, and talus deposits
Ql	Lacustrine deposits; organic and mineral sediments chiefly deposited in closed depressions
Qo	Osceola Mudflow; volcanic rock fragments (largely Mount Rainier provenance) in clayey, sandy matrix; deposited about 5,000 years ago (radiocarbon years)
Qis	Glaciolacustrine deposits, chiefly sand
Qic	Glaciolacustrine deposits, chiefly silt and clay

LIQUEFACTION SUSCEPTIBILITY MAPS FOR THE AUBURN AND POVERTY BAY QUADRANGLES

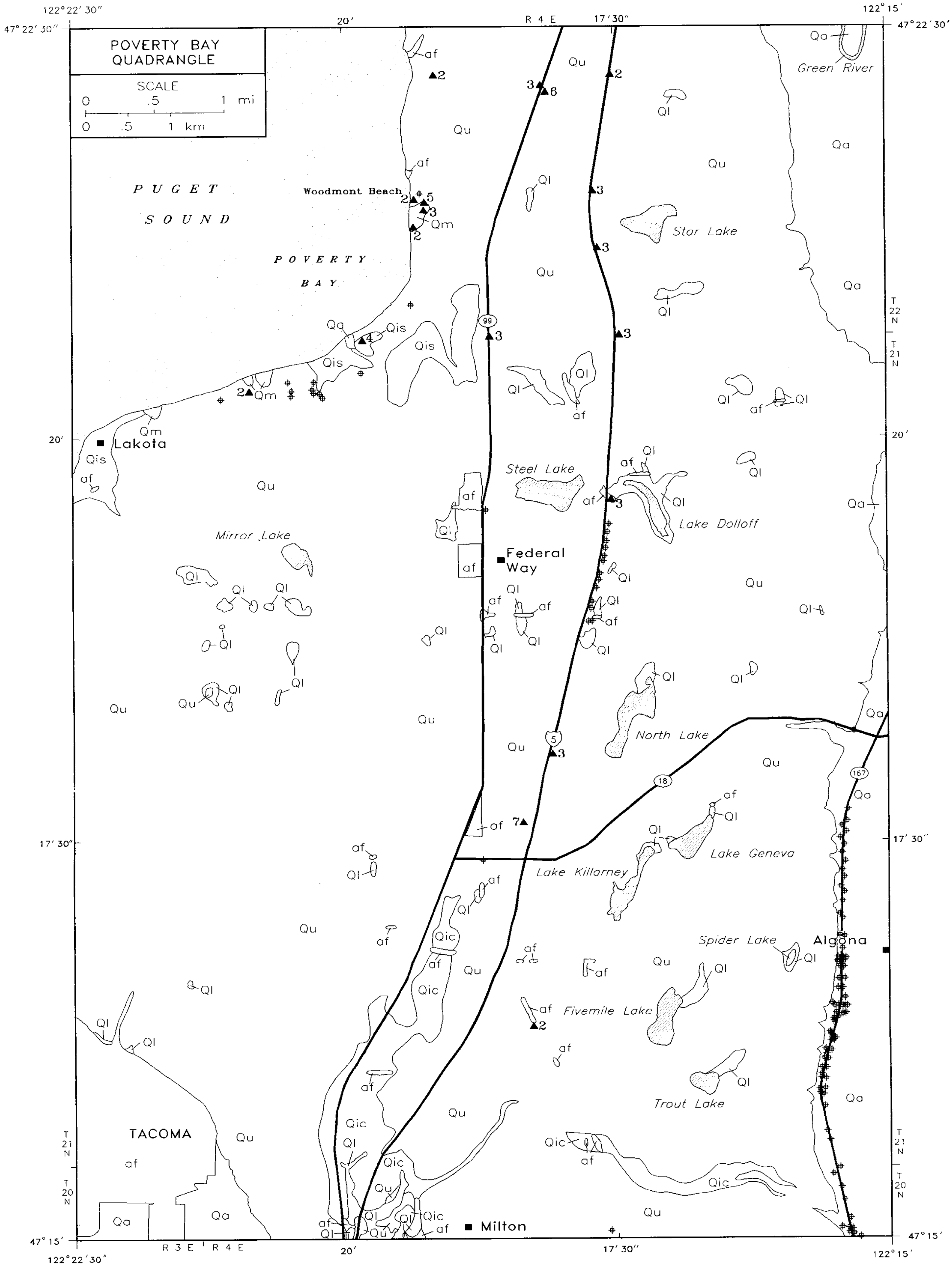
We have generalized the geological map units of Mullineaux (1965) and Waldron (1961) into three categories of deposits on the basis of their engineering and geological characteristics:

- *Category I:* artificial fill and modified land and Holocene alluvium[2];
- *Category II:* Holocene lacustrine and mass-wasting deposits and late Pleistocene glaciolacustrine deposits composed chiefly of sand;
- *Category III:* all other Pleistocene glacial and nonglacial deposits and the mid-Holocene Osceola Mudflow.

Table 1 lists the three liquefaction categories used in this study and the corresponding map units of Mullineaux (1965) and Waldron (1961) for the Auburn and Poverty Bay quadrangles. Plates 1 and 2 show the distribution of the three categories on the basis of Mullineaux's mapping in the Auburn quadrangle and Waldron's mapping in the Poverty Bay quadrangle. The geologic contacts mapped by Mullineaux (1965) and

[1] In our liquefaction evaluation we have considered these peaty lake deposits as now being areas of artificial fill and modified land.

[2] Holocene lacustrine deposits mapped by Waldron (1961) on the flood plain of the Puyallup River have been included in this category (see footnote 1).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Green River
Star Lake
Steel Lake
Lake Dolloff
Mirror Lake
Federal Way
Lakota
North Lake
Lake Geneva
Lake Killarney
Spider Lake
Algona
Fivemile Lake
Trout Lake
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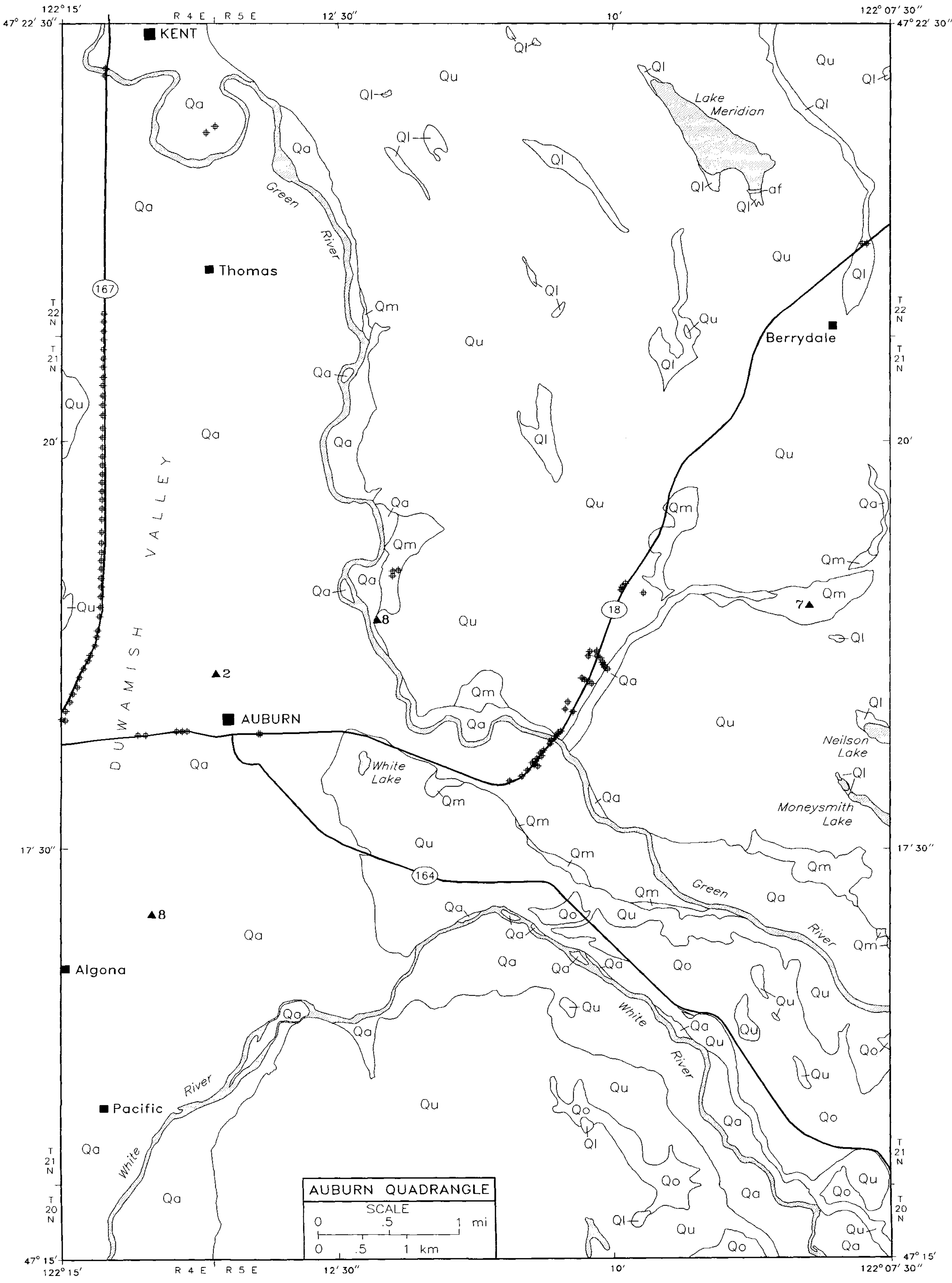
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White Lake
Neilson Lake
Moneysmith Lake
Green River
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T 21 N
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17′ 30″
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AUBURN QUADRANGLE
SCALE
0 .5 1 mi
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Waldron (1961) were not field checked during this study. The historic courses of the Stuck and White Rivers were taken from Willis and Smith (1899) and are shown on Plate 1.

U.S. Army Corps of Engineers (USACE) 1944-vintage aerial photo mosaics of the Duwamish valley were reviewed in this study to map abandoned channels of the Green, White, and Stuck Rivers in the Duwamish valley. The traces of abandoned channels observed on these photo mosaics were transferred to Plates 1 and 2. An example of an USACE aerial photo mosaic (showing the area north of the city of Auburn) is given in Figure 4. We attempted further mapping using 1976-vintage 1:24,000-scale stereo air photos (Washington Department of Natural Resources Flight Index Symbol NW-C-76). However, agricultural, residential, and commercial development of the Duwamish valley between 1944 and 1976 has obscured many of the abandoned channels observable on the USACE aerial photo mosaics.

Two types of abandoned channels are mapped in Plates 1 and 2. The hatchured features mark the trace of clearly identifiable abandoned channels that generally do not appear to contain intermittent streams or support riparian vegetation. The dot-and-dash lines denote drainages and streams that appear to be continuations or parts of abandoned river channels. These abandoned channel features were not commonly observed on the aerial mosaics in the vicinity of Auburn, either because of urban development, or possibly because channel morphology of the Green River and the White and Stuck Rivers differs. While there are not adequate quantitative data to demonstrate that the abandoned channels mapped in this study have a higher liquefaction susceptibility than other Category I deposits, they are shown because they are likely to have a shallower water table than nearby flood-plain deposits.

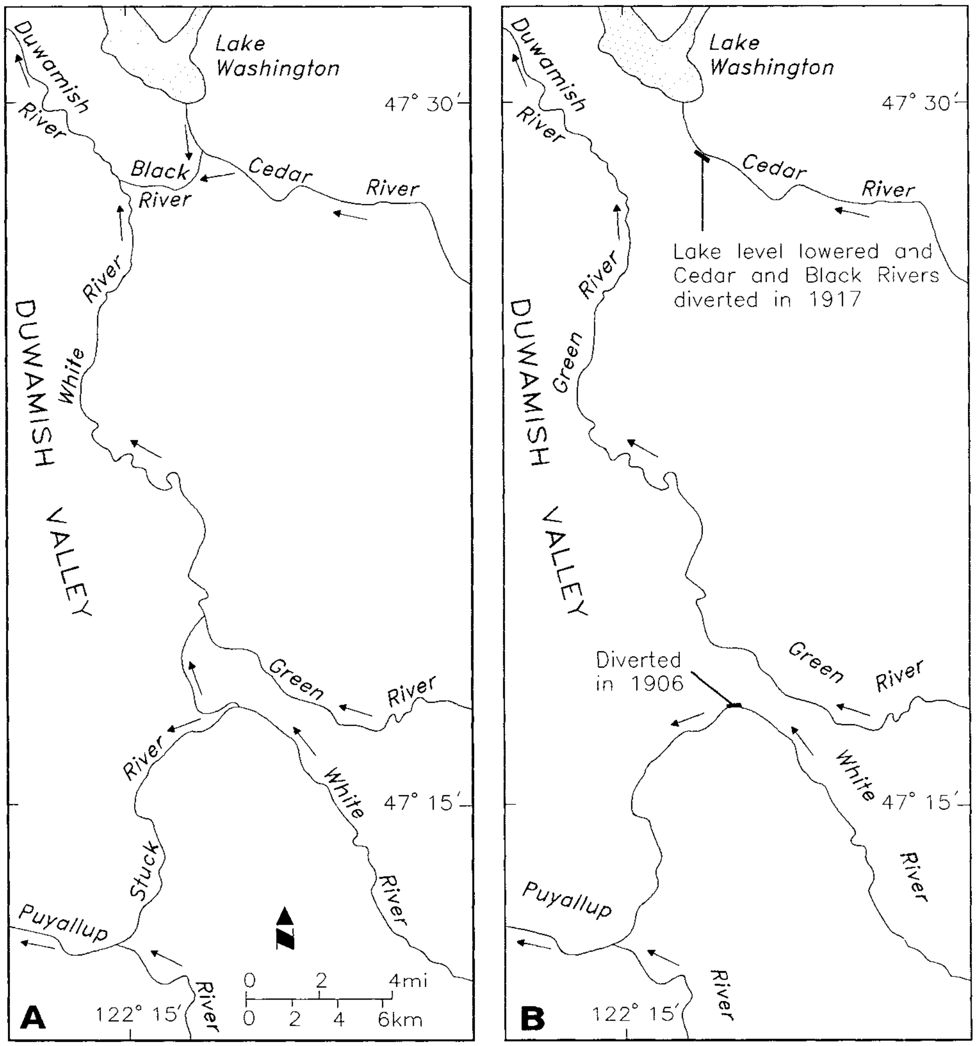

Figure 3. Historic (A) and current (B) waterways in the Duwamish valley (modified from Luzier, 1969).

Table 1. The three liquefaction categories used in this study and the corresponding map units of Mullineaux (1965) and Waldron (1961)

Category	Geologic description	Map units in the Auburn quadrangle (Mullineaux, 1965)	Map units in the Poverty Bay quadrangle (Waldron, 1961)
I	artificial fill and modified land	af,afm	af,afm
	Holocene alluvium	Qaw,Qag,Qas	Qa
II	Holocene lacustrine deposits	Qlp,Qlm,Qlc	Qpm,Qlc
	mass-wasting deposits	Qmc,Qms	Qm
	late Pleistocene glaciolacustrine deposits	(none)	Qis,Qic
III	Osceola Mudflow	Qom	(none)
	Vashon Stade glacial deposits;	Qpo,Qpv,Qpa,Qik, Qit,Qiv,Qg,Qgt,Qsa	Qit,Qik,Qie, Qgt,Qg,Qsr,Qsa
	other Pleistocene glacial and nonglacial deposits	Qss,Qpy,Qst,Qu	Qss,Qpy,Qst,Qu

METHODOLOGY USED TO EVALUATE LIQUEFACTION SUSCEPTIBILITY

The analysis of liquefaction susceptibility in the Auburn and Poverty Bay quadrangles follows the methodology of Palmer and others (1994) in their study of the Des Moines and Renton 7.5-minute quadrangles. Our approach is also similar to that used by Grant and others (1992) and Shannon & Wilson, Inc. (1993). We estimate the potential for soil liquefaction using the field evaluation methodology developed by Seed and Idriss (1971) and modified by Seed and others (1983, 1985). This field evaluation procedure uses Standard Penetration Test

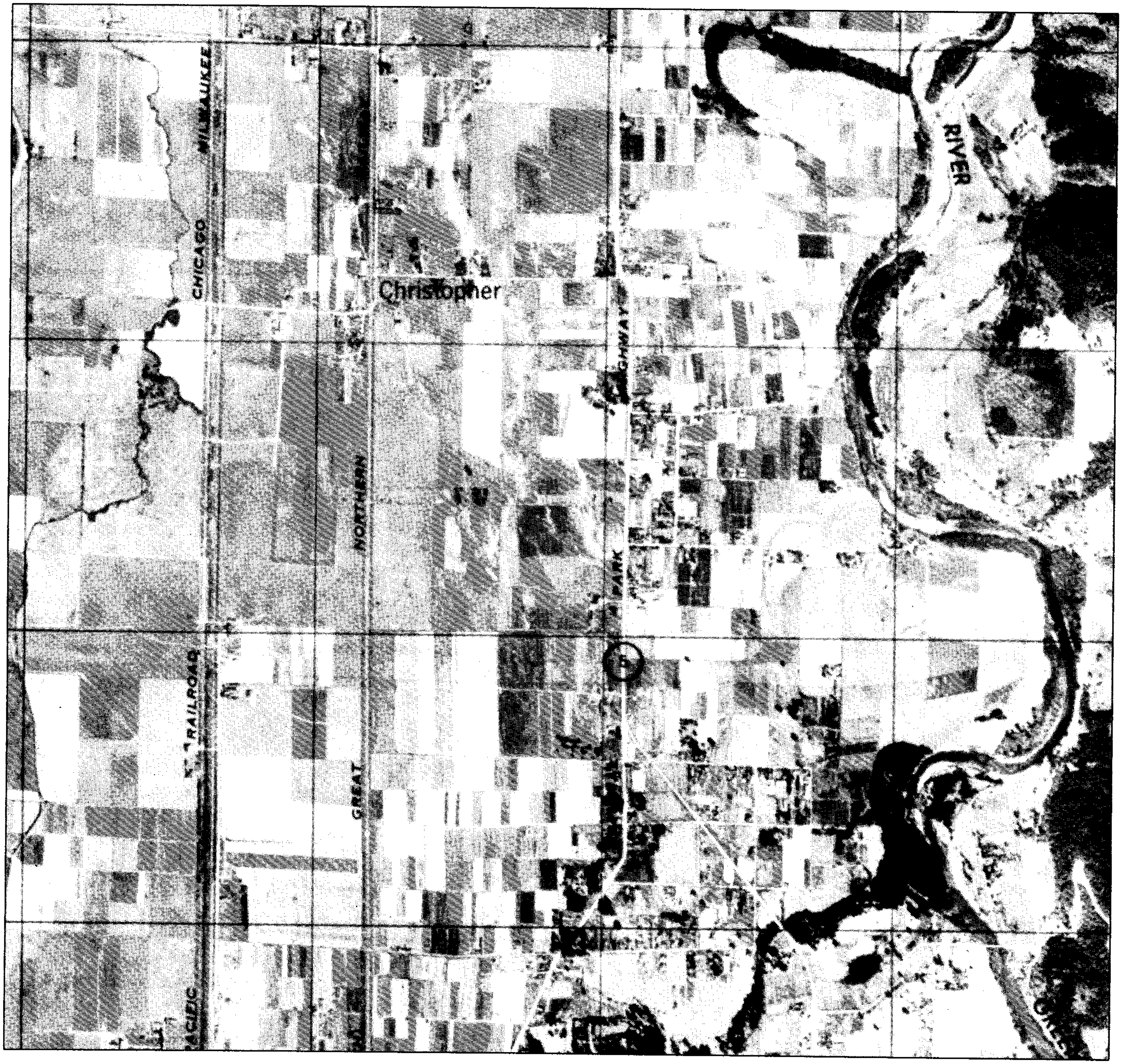

Figure 4. A portion of the U.S. Army Corps of Engineers aerial photo mosaic from the area of the Duwamish valley near liquefaction site 103 north of the city of Auburn (see Plate 1). The light-colored north-trending linear features in the central part of the figure are the abandoned channels mapped near site 103 on Plate 1. The north-trending stream on the left side of the figure is mapped on Plate 1 as a drainage or stream that may be an abandoned course of the White or Green River.

(SPT) N-values (ASTM D 1586-84[3]), sample descriptions, grain-size analyses, and measured ground-water depths obtained from geotechnical borings to estimate the factor of safety for a hypothetical earthquake with a specified magnitude and peak ground acceleration (PGA).

The SPT N-values and other data are obtained from sampled depths in a geotechnical boring so that the thicknesses

[3] American Society for Testing and Materials (ASTM), 1991, D 1586-84, Standard method for penetration test and split-barrel sampling of soils. *In* Annual book of ASTM standards, v. 04.08, Soil and rock; dimension stone; geosynthetics, p. 232-236.

Table 2. Conversion of Unified Soil Classification System (USCS) soil class to fines fraction used as input to the liquefaction susceptibility analysis

USCS soil class	Fines fraction (percent)
SP	5
SM	30
SP–SM	15
SW–SM	20

and depths of individual liquefiable soil units and the total thickness of liquefiable material in that boring can be estimated. The procedure used in this study characterizes the liquefaction susceptibility of various Quaternary deposits through the cumulative frequency histogram of the aggregate thickness of liquefiable material penetrated in the borings. This is equivalent to the thickness criteria used by Grant and others (1992) and Shannon & Wilson, Inc. (1993).

The Quaternary units in the study area are grouped into three categories on the basis of their geological and engineering characteristics. The liquefaction susceptibility of each category is quantified from borings drilled only in geologic units that are included in that category. The three liquefaction categories used in this study (Categories I, II, and III) were discussed in the preceding section.

This study is primarily concerned with evaluating liquefaction that would have potential to cause noticeable effects at the ground surface. A relationship presented by Ishihara (1985) suggests that for PGAs of 0.30 g or less, liquefaction that occurs at depths greater than approximately 40 ft (12 m) will probably not cause noticeable effects or damage at the surface. Thus, this study limits the evaluation of liquefaction to only the upper 40 ft (12 m) of the borings. Many of the borings used in this study are less than 40 ft (12 m) deep; the average depth of all borings is 41.7 ft (12.6 m). Also, restricting the evaluation to these shallow depths allows a more direct comparison to historic reports of liquefaction.

The field evaluation methodology requires an estimate of the fines fraction (the fraction of a sample that passes a 200-mesh sieve). We used measured grain-size distribution data to provide this parameter. If measured data were not available, we estimated the fines fraction from the soil category assigned using the Unified Soil Classification System (ASTM D 2487-90[4]) and the conversions given in Table 2. We restrict the liquefaction analysis to sandy soils containing 40 percent or less fines. This is less conservative than Seed and others' (1983, 1985) method, as they allow liquefaction of sandy soils with as much as 50 percent fines. We also do not investigate the possibility of liquefaction of soils classified as silts even though liquefaction of native silt soils has been observed in past earthquakes (for example, Ying Kou City [Arulanandan and others, 1986] and the San Fernando Juvenile Hall [Bennett,1989]).

Cumulative frequency histograms for Category I, II, and III deposits were made for a hypothetical earthquake of magnitude 7.3 (M_w 7.3) that produces a PGA of either 0.15 g or 0.30 g. This is consistent with the scenario earthquakes used by Grant and others (1992) and Shannon & Wilson, Inc., (1993) in evaluating liquefaction susceptibility in the Seattle and Tacoma areas. The scenario earthquakes used in this study are intended to represent a major earthquake similar to the 1949 Olympia event. We consider the M_w 7.3 scenario earthquake to be at an intermediate depth (30 to 37 mi, or 48 to 60 km) located within the subducting Juan de Fuca plate; this is termed an intraplate earthquake. The two values of PGA used in the scenario earthquakes are expected to bracket the range of damaging ground motions that would arise from a M_w 7.3 intraplate event. The 0.30 g PGA corresponds closely to the PGA measured in downtown Olympia during the 1949 earthquake.

However, recent studies indicate that other earthquake sources have the potential to generate more severe ground motions than the scenario earthquakes chosen for this study. The potential for great (M_w 8 or larger) thrust earthquakes to occur on the Cascadia subduction zone has been recognized (Atwater, 1987; Weaver and Shedlock, 1991; Atwater and others, 1995). Also, evidence for a major earthquake (M_w 7 to 7.5) on the Seattle fault about 1,000 years ago was recently presented (Bucknam and others, 1992; Atwater and Moore, 1992; Jacoby and others, 1992). The projected trace of this west-trending fault is located approximately 15 mi (24 km) north of the northern boundary of the study area. However, the Seattle fault is south-dipping, so that the main area of energy release during an earthquake on this fault could be closer to the study area.

Ground motion simulation studies for a M_w 8.0 to 8.5 subduction zone earthquake were presented by Cohee and others (1991) and Wong and others (1993). These studies suggest that the PGAs in the Puget Sound region resulting from such an earthquake would be reasonably bounded by the 0.15 to 0.30 g range of the scenario earthquakes used in this study. However, the duration of strong ground shaking for a subduction zone event would be significantly longer than for the M_w 7.3 event considered in this study. The longer duration of shaking would result in more numerous instances of liquefaction and more ground displacement and consequent damage. A major earthquake (M_w 7.0) on the Seattle fault would result in PGAs that would likely exceed 0.30 g, particularly in the northern portion of the study area. This intensity of shaking would likely produce more numerous and severe occurrences of liquefaction than would be expected for the scenario events used in this study.

The evaluation of liquefaction susceptibility presented in this study is nonconservative because we did not consider liquefaction of sandy or silty soils containing more than 40 percent fines. Also, our choice of scenario earthquakes does not necessarily represent the most severe ground motions that can occur in the study area. However, our methodology provides a quantitative basis for assessing the relative liquefaction susceptibility of each of the three liquefaction hazard categories distinguished in the study area that is applicable regardless of the choice of earthquake sources. Furthermore, our results can be compared to those of Grant and others (1992) and Shannon & Wilson, Inc., (1993) to obtain a perspective on the relative liquefaction hazard regionally.

GEOTECHNICAL BORING DATA USED IN EVALUATION OF LIQUEFACTION SUSCEPTIBILITY

The geotechnical boring data used in this study were obtained from the Washington State Department of Transportation, the King County Development and Environmental Services Department, and the City of Auburn. Of the total of 301 borings obtained from these agencies or their consultants, 181 are located in the Duwamish valley in Category I deposits. The locations of the geotechnical borings used in this study are shown in Figure 2. The majority of the Category I borings fall along State Route 167 in the Poverty Bay quadrangle and

[4] American Society for Testing and Materials (ASTM), 1991, D 2487-90, Standard test method for classification of soils for engineering purposes. *In* Annual book of ASTM standards, v. 04.08, Soil and rock; dimension stone; geosynthetics, p. 309-319.

along State Route 18 in the Auburn quadrangle. We obtained 21 borings logs in deposits classified as Category II. Most of these borings are located adjacent to Puget Sound in the Poverty Bay quadrangle. The majority of the 99 borings drilled in Category III deposits are located in the Poverty Bay quadrangle along highway alignments (Interstate 5 and State Route 99). The sparsity of data on the drift plain in the eastern portion of the Auburn quadrangle reflects the absence of engineering projects in this area requiring extensive subsurface investigation.

The maximum depth of these 301 borings is 170.8 ft (51.8 m). Information from boreholes that were less than 9 ft (2.7 m) deep was not included in the analysis. One hundred thirty-two and 169 borings are located in the Auburn and Poverty Bay quadrangles, respectively. Sixty-two of the borings in the Auburn quadrangle were from the original database generated by Palmer (1992). All boring logs included sample descriptions, SPT N-values, and a general description of drilling and sampling procedures; most boring logs or reports recorded measured depth to ground water, accessory geotechnical data (such as grain-size analyses), and a site plan showing boring locations.

Seed and others (1984) note that variation in drilling methods and sampling procedures used in geotechnical borings can significantly affect the measured SPT N-values. They suggest that the ideal drilling and sampling practice for obtaining SPT N-values for evaluating liquefaction susceptibility is as follows:

- 4- to 5-in.(10.2-12.7 cm) -diameter rotary boring drilled using an upward-directed flow of bentonite mud (typically a tri-cone bit configuration);
- a sampling tube with 2.00-in. (5.08 cm) O.D. and 1.38-in. (3.50 cm) I.D. without a liner;
- AW drill rods for depths less than 50 ft (15.2 m), and N, BW, or NW rods for greater depths;
- 30 to 40 blows per minute delivered to the sampler;
- SPT N-value measured between 6 in. (15.2 cm) and 18 in. (45.7 cm.) penetration of the sampler at the bottom of the hole; and
- 2,520 in.-lb (2903 kg-cm) energy delivered to the sampler (60% of theoretical maximum).

The energy delivered to the sampler is typically not measured, but it has been shown to depend on the type of hammer and size of the drill rods used in the penetration testing. In the United States, the most commonly used hammer configuration is a rope and pulley system using a safety hammer (Seed and others, 1984). AW drill rods are often used in shallow geotechnical borings drilled in the Puget Sound region. Consequently, SPT N-values obtained from these borings would follow this detail of the recommended practice of Seed and others (1984). Use of a rope and pulley safety hammer system with AW rods would ideally result in a 60 percent transfer of energy to the sampler at depths less than 50 ft (15.2 m) (Seed and others, 1984), which would satisfy their recommended parameters.

The N-values reported in many borings drilled since the mid-1980s by the Washington State Department of Transportation (WSDOT) were obtained using a variety of automatic trip hammers. Recent measurements performed on two WSDOT trip hammers indicated approximately 70 percent efficiency in energy transfer to the drill rods (American Society of Civil Engineers Seattle Section Geotechnical Group, 1995). However, many of the boring logs obtained from WSDOT files predate the use of the automatic trip hammer, and many recent WSDOT boring logs do not document the type of hammer (rope and cathead safety versus trip hammer) used in the SPT testing. Measurements of hammer efficiency made as part of the 1995 ASCE Seattle Section Geotechnical Group spring seminar on *in-situ* testing for seismic evaluation demonstrated that an assumption of approximately 60 percent efficiency is only appropriate for carefully conducted SPT testing using a rope and cathead safety hammer or an automatic trip hammer (American Society of Civil Engineers Seattle Section Geotechnical Group, 1995). As a minimum criterion, measurement of the SPT-N value in all borings used in this study adhered to ASTM D1586-84. We have treated SPT blow counts from all data sources as if the hammer efficiency were 60 percent. This may lead to a biased estimate of the calculated factors of safety, but by treating all borings in the same manner this bias should have little effect on our comparison of the relative liquefaction hazard of the various liquefaction categories.

The most significant departure from the recommended procedures of Seed and others (1984) is the regular use of hollow-stem augers instead of rotary methods in drilling geotechnical borings in the Puget Sound region. A standard auger has an 8-in. (20.4 cm) O.D. and a 4-in. (10.2 cm) I.D. and drills a hole larger than the 4- to 5-in. (10.2 to 12.7 cm) optimal size. Water, rather than bentonite mud, is often used as the drilling fluid, if fluid is used at all during drilling. However, Seed and others (1988) have shown that the type of fluid (drilling mud or water) does not affect the SPT blow counts.

Shannon & Wilson, Inc. (1990) suggested that SPT N-values measured in borings drilled using hollow-stem augers are consistently lower than those measured in rotary-drilled borings. The certainty of this observation is obscured by the mixed use of safety- and donut-type hammers in their study. Shannon & Wilson, Inc. (1993) drilled paired rotary and hollow-stem auger borings with the same drill rig at three sites in the Puyallup valley and reported no significant bias in measuring SPT N-values with the type of drilling method. Only a small number of borings in this study's data set are known to have been drilled using rotary methods. For the majority of the available borings either the method of drilling was not reported or they were drilled using hollow-stem augers. Thus, this study ignores any possible bias introduced into SPT N-values measured in hollow-stem auger borings on pragmatic grounds: it would not be possible to perform a defensible evaluation of liquefaction susceptibility using only the sparse data set provided by rotary-drilled borings.

HISTORIC LIQUEFACTION

The two largest earthquakes in recent historic times in the Puget Sound region are the 1949 surface wave magnitude (M_S) 7.1 Olympia and the 1965 M_S 6.5 Seattle–Tacoma earthquakes. The study area was exposed to Mercalli Modified Intensity VIII and VII shaking in the 1949 and 1965 events, respectively (Murphy and Ulrich, 1951; Roberts and Ulrich, 1951; von Hake and Cloud, 1967). Sites of ground failures caused by liquefaction in the study area have been reported by Hopper (1981) and Chleborad and Schuster (1990). Three sites

Table 3. Descriptions of selected ground failures in the Auburn and Poverty Bay 7.5-minute quadrangles (excerpted from table 2 of Chleborad and Schuster, 1990). Location numbers correspond to ground-failure location numbers on Plate 1. Location accuracy: A, available information allows accurate relocation; B, available information allows relocation to within a kilometer. Quotations referenced as "written commun., 1949", or "written commun., 1965", are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colorado

Loc. no.	Failure type (year of earthquake)	Reference municipality or geographic location; County	Location accuracy	Quotation and (or) comment
100	ground crack (49) sand boils (49) misc. effects (49)	Pacific, Wash. (south, near county line); King and Pierce Counties	A	"Beginning in the south side of Pacific (Pacific City) and running almost straight south for a ½ mile [0.8 km] into Pierce County, a fissure opened up, out of which at various points water boiled out (according to one observer * * * to a height of 2 feet [0.6 m]. Several inches of water were on the surface before the action stopped. The water carried with it a considerable amount of very fine sand, * * *." (Ralph Pommert, written commun., 1949). "The ground out here is peat and sand, and very pliable. The water bubbled in one place * * * approximately 1 ft [0.3 m] out of ground. Bubbled on all of our land out here and pushed up various types of soil. A very large crack on place next to ours * * * crack runs NW to SW. Imagine it was much deeper than it is now for soil and silt washed in. On next place to above a large crack * * * in berry patch. Their strawberries sank several inches. At trunks of trees, fence posts, all bubbled and soil washed up. Water lines broke." (Margaret E. Farr, written commun., 1949).
	sand boils (65)	Pacific, Wash. (south, near county line); King and Pierce Counties	A	"Among the strange things that came along with the earthquake Thursday was one out on Roy Road, on the way to Auburn, when a housewife saw a field near her home develop its own sprinkler irrigation system. * * * As it spouted out it brought with it a foamy sand which was in piles all over the two fields." (Sumner News-Index, 5/6/65, p.1). The sand boils occurred just SW of the intersection of 2nd Street East and Valentine Road. (Mrs. Palmer Johnson, personal commun., 1988)
101	sand boils (49)	Auburn, Wash.; King County	A	Co-workers reported seeing numerous water-sand geysers in fields adjacent to the shop at the north end of the Auburn General Depot [at the time of the 1949 quake]. (Larry Lunderg, personal commun., 1988).
103	ejection of ground water (65)	Auburn, Wash. (north side); King County	B	[Photo caption] "GROUND SEEPAGE—Jerry Keesee, city sewage plant superintendent, * * * checks seriousness of seepage around manhole on line leading into plant in North Auburn. Keesee said later it appeared to be relief point for ground water—not sewage—and that there was no apparent break in the line." (Auburn Globe-News, 5/5/65, p. 2-1).

where liquefaction occurred are identified by the reference number used in Chleborad and Schuster (1990) and are shown on Plate 1. Table 3 reproduces the information given for the sites identified in Chleborad and Schuster (1990).

All of the historic liquefaction sites are located in the Duwamish valley in Holocene alluvium (Category I deposits). Site 100 presented clear evidence for widespread liquefaction during both the 1949 and 1965 earthquakes, mostly in the form of sand blows and ground cracking. Reports from multiple observers lend high credibility to the evidence. The report of broken water lines during the 1949 event suggests that lateral spreading might have occurred. The strong evidence of liquefaction, including numerous reported sand blows at site 101, is based on the report of only one observer, but the description of the sand blows seems quite reliable. At site 103, vertical seepage of ground-water around a sewer manhole was observed, but no apparent nearby breaks in the sewer line were reported. The observation of the phenomenon was reported by the sewage plant superintendent and verifiable by a photograph published in a local newspaper. The ground-water seepage was likely the result of liquefaction of fill surrounding the utility installation and (or) of the underlying native soils.

LIQUEFACTION ANALYSIS

Figure 5 is a cumulative frequency histogram for each scenario earthquake showing the percentage of the total borings located in Category I deposits that equal or exceed an aggregate thickness of liquefiable soils expressed as a percentage of the total boring depth. The aggregate thickness is the sum of the thicknesses of all soil units that would liquefy at the magnitude and PGA value chosen for the scenario earthquake. Figure 5 shows the histograms for the two scenario earthquakes used in this study (a M_W 7.3 earthquake that produces a PGA of 0.15 g or 0.30 g). The abscissa of the histograms measures the aggregate thickness of liquefiable material in a boring (expressed as a percentage of the depth of the boring). For borings drilled deeper than 40 ft (12.1 m), only the upper 40 ft (12.1 m) were analyzed for susceptibility to liquefaction. The ordinate delineates the percentage of the total number of borings that contain a percentage of liquefiable material greater than the abscissa value.

Figure 6 presents the cumulative frequency histograms for Category I deposits in the study area and in the Des Moines and Renton quadrangles (Palmer and others, 1994). These cumulative frequency histograms are generally comparable. The histograms developed for the 0.15 g PGA indicate that the Category I deposits in the study area are somewhat more liquefiable than those in the Renton and Des Moines quadrangles. For the 0.30 g PGA event, the histograms indicate that Category I deposits in the Renton and Des Moines quadrangles have a larger percentage of borings with significant thicknesses (greater than 25 percent aggregate thickness) of liquefiable soils than Category I deposits found in the study area. Because these differences are small and inconsistent, we conclude that there is no significant difference in the liquefaction susceptibility of the Holocene alluvium found in the Auburn and Poverty Bay quadrangles and that found to the north in the Renton and Des Moines quadrangles.

The southwesternmost part of the area shown in Plate 2, which includes part of the city of Tacoma, is shown entirely as Category I. We did not analyze borehole data acquired in this area. Instead, we adopted the Category I ranking given this area by Shannon & Wilson, Inc. (1993). An independent analysis by HartCrowser (1986) also indicates that the soils in this area have a significant liquefaction susceptibility.

We show this area on Figure 2, Poverty Bay quadrangle, as consisting entirely of units af and Qa. Waldron (1961) shows large areas of peat and muck (unit Qpm), but Hart-Crowser and Associates, Inc. (1974) document emplacement of fill in most (though not all) of these areas. We have chosen to show all of it as fill because industrial development precludes detailed examination and because the peats are underlain by alluvial deposits of the Puyallup River, which are highly susceptible to liquefaction (Shannon & Wilson, Inc., 1993). Holocene peats developed in closed depressions on the glacial drift plain are classified as Category II as previously discussed.

Table 4 presents the thickness criteria used by Shannon & Wilson, Inc., (1993) to rank the relative liquefaction susceptibility of the various soil units in their study area. Figure 5 shows that 38 percent of the borings drilled in Category I deposits in the Auburn and Poverty Bay quadrangles had at least 1 ft (0.3 m) of liquefiable material for the 0.15 g earthquake, and 30 percent had at least 10 ft (3 m) of liquefiable soils for the 0.30 g event. We use a total boring depth of 40 ft (12.1 m) to convert the aggregate thickness, expressed as a percentage, to an aggregate thickness expressed in feet. Using the criteria given in Table 4, Category I deposits in the study area fall in the middle range of the moderate rating.

A second method of ranking the liquefaction susceptibility of a soil deposit is presented by Youd and Perkins (1987). They calculate relative susceptibility to liquefaction using the following expression:

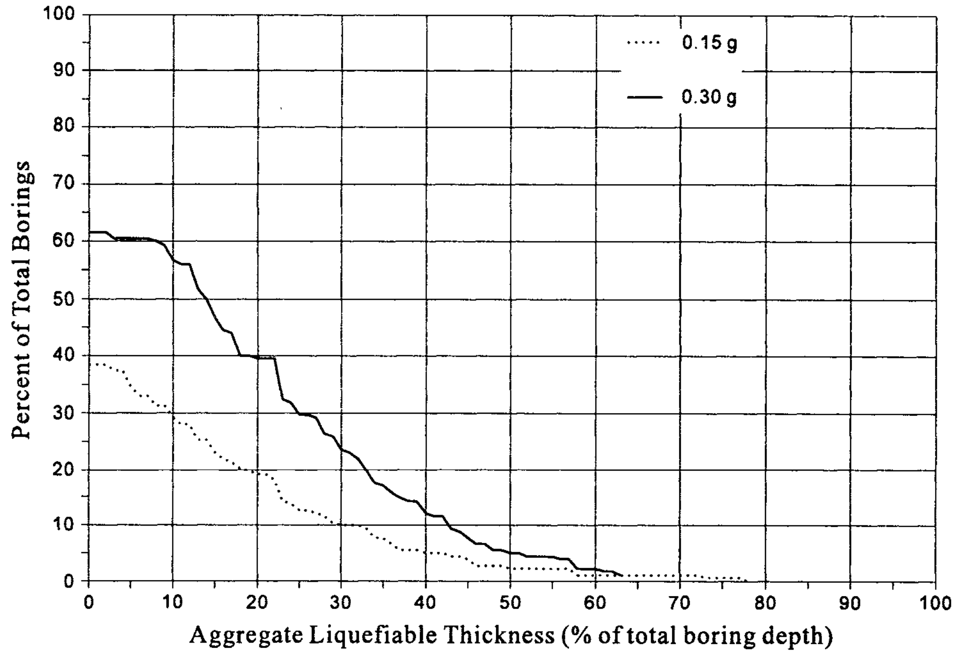

Figure 5. Cumulative frequency histograms for Category I deposits, M_w 7.3 event, Auburn and Poverty Bay quadrangles.

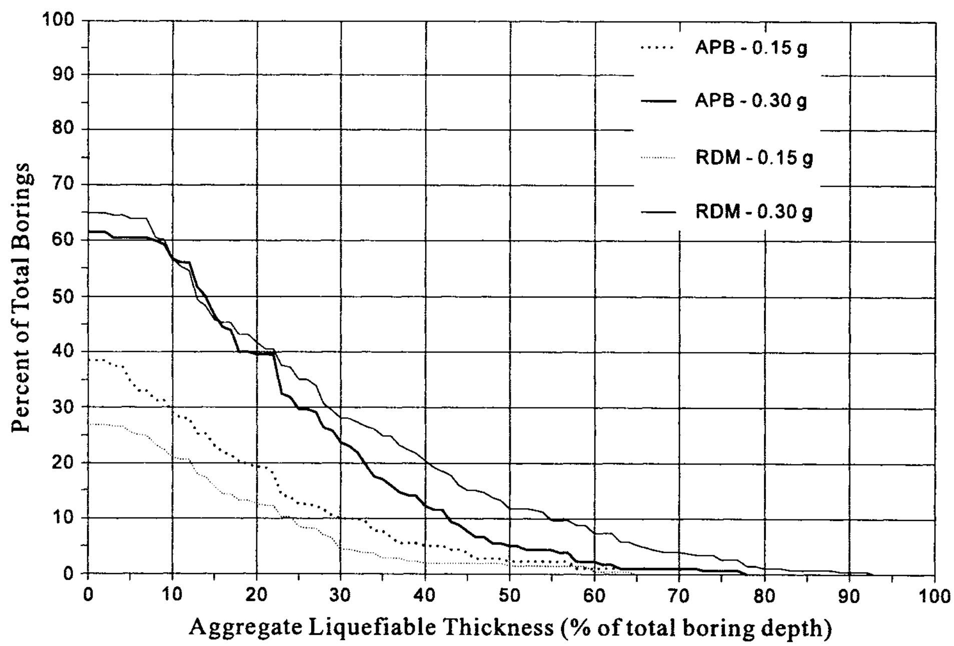

Figure 6. Comparison of cumulative frequency histograms for Category I deposits, M_w 7.3 event, for the Des Moines and Renton quadrangles (RDM) (Palmer and others, 1994) and for this study (APB).

Relative susceptibility = [(A x B x C)/10] x 100, where,

A = percent of sandy soils expressed as a decimal fraction;

B = percent of these soils that are liquefiable if saturated, expressed as a decimal fraction;

C = percent of these soils that are saturated, expressed as a decimal fraction.

Their hazard rating scheme is based on the relative susceptibility and is summarized in Table 5.

Youd and Perkins (1987) evaluated and mapped the liquefaction susceptibility of soil deposits found in San Mateo County, California, using the field evaluation methodology of

Seed and others (1983, 1985). In their liquefaction analysis, they used a scenario earthquake with a magnitude of 6.5 that produces a PGA of 0.20 g (Youd and others, 1975)[5]. We calculated factors of safety for a number of soil profiles using both the scenario earthquake of Youd and Perkins (1987) and the magnitude 7.3 earthquake producing a PGA of 0.15 g used in our study. We found that for a variety of subsurface conditions in which liquefaction is marginal (that is, the factor of safety is near unity), this study's 0.15 g scenario earthquake yielded factors of safety from 10 to 15 percent higher (see footnote 5) than those calculated using Youd and Perkins' (1987) scenario event. Because we have used a less severe earthquake to evaluate liquefaction susceptibility in the study area than that used by Youd and Perkins (1987), our results are not directly comparable to theirs.

Inspection of Youd and Perkins' expression for computing relative susceptibility shows that this value can be obtained by integrating the 0.15 g cumulative frequency histogram (after conversion of percentages to their equivalent decimal values) and multiplying the result by 10. This calculation yields a relative susceptibility of 0.89 for Category I deposits in the Auburn and Poverty Bay quadrangles. This relative susceptibility falls at the upper end of a moderate hazard using the Youd and Perkins (1987) ranking criteria (Table 5). We did not rigorously account for the differences in calculated factors of safety resulting from the different scenario earthquakes used in this study and in Youd and Perkins (1987). However, we do know that a more severe scenario earthquake will result in a greater amount of liquefaction (for example, compare the 0.15 g and 0.30 g cumulative frequency histograms shown in Fig. 5), and that Youd and Perkins (1987) used a more severe scenario event in their liquefaction susceptibility analysis. Consequently the relative susceptibility calculated from our analysis (0.89) somewhat underestimates the value we would have obtained if we had used earthquake magnitudes and PGAs comparable to those used by Youd and Perkins (1987). By using comparable parameters we would have calculated a relative susceptibility that would likely place the Category I deposits in the Auburn and Poverty Bay quadrangles near the lower end of a high hazard rating.

Ideally, all liquefaction susceptibility maps should use the same criteria when rating the severity of the liquefaction hazard. However, the rating system developed by Grant and others (1992) would consider all Category I deposits in the study area as having a moderate hazard, which to us seems contradicted by the numerous historic observations of liquefaction. Their only high liquefaction hazard is located in the 6.1 mi^2 (16.9 km^2) of fill areas of the Seattle North and Seattle South quadrangles in which a total of 26 instances of liquefaction was reported during the 1949 and 1965 earthquakes (W. J. Perkins, Shannon & Wilson, Inc., written commun., 1994). Other Holocene deposits in Grant and others' (1992) study area where liquefaction was also reported were assigned a moderate rating.

[5] Youd and others (1975) use 10 cycles of strong shaking to characterize the magnitude 6.5 scenario earthquake. Seed and others (1983) use 10 cycles of strong shaking to characterize an earthquake magnitude of 6.75. Factors of safety calculated for these two magnitude levels will differ by approximately 5 percent, with the larger magnitude earthquake producing a smaller factor of safety.

Table 4. Criteria used by Shannon & Wilson, Inc. (1993) for rating the hazard due to liquefaction based on analysis of geotechnical boring data in the Tacoma area

Percentage of borings in a geographic location with thickness of liquefied sediment ≥: (a) 3.05 m (10 ft) for a 0.30 g event, and (b) 0.305 m (1 ft) for a 0.15 g event	Hazard rating
>50	High
25–50	Moderate
1–25	Low
<1	Very low

Table 5. Relative liquefaction susceptibility and associated hazard rating from Youd and Perkins (1987)

Relative susceptibility	Hazard rating
1.0 to 10.0	High
0.1 to 1.0	Moderate
0.01 to 0.1	Low

All the historical liquefaction in our study area occurred in Category I deposits. The two methods of ranking liquefaction susceptibility discussed previously indicate that Category I deposits rank from the mid-range of the moderate hazard to possibly the lower end of the high hazard rating. The cumulative frequency histograms indicate that liquefaction could be expected to occur at a number of sites within Category I deposits, an observation supported by the historical record. We have chosen to rank the Category I deposits in the Auburn and Poverty Bay quadrangles as having a high liquefaction susceptibility on the basis of the historical record and the relative liquefaction susceptibility and associated hazard rating obtained using the criteria of Youd and Perkins (1987). *The high hazard rating does not indicate that any specific locality within a Category I deposit is underlain by liquefiable soils. The presence or absence of liquefiable material can only be determined by a site-specific geotechnical investigation performed by a qualified practitioner.*

Abandoned channels mapped in Plates 1 and 2 *may* represent areas of locally higher liquefaction susceptibility. At least five of the historic liquefaction sites in the Duwamish and upper Puyallup valleys are near abandoned channels (this study; Palmer and others, 1994; Dragovich and Pringle, 1995). Many of these abandoned channels are low points in the local topography and would consequently have higher ground-water tables than the adjacent flood plain. The presence of a shallower ground-water table would increase the liquefaction susceptibility of the loose, near-surface sandy soils commonly found in the Duwamish and Puyallup valleys. Also, many of these abandoned channels were filled during the urbanization of the area in the early part of this century, and this nonengineered fill may be more liquefiable than the underlying native soils. Either of these factors could result in a locally higher susceptibility to liquefaction within these abandoned channels.

Category II deposits include Holocene mass-wasting and lacustrine deposits and late Pleistocene glaciolacustrine sediments predominantly composed of sand. We obtained data for 21 borings that penetrated these deposits. Figure 7 shows the cumulative frequency histograms derived from these 21 geotechnical borings. Seventeen percent of the borings had at least 1 ft (0.3 m) of liquefiable material for the 0.15 g earthquake, and 23.5 percent had at least 10 ft (3 m) of liquefiable soils for the 0.30 g event. We use a total boring depth of 40 ft (12.1 m) to convert the aggregate thickness, expressed as a percentage, to an aggregate thickness expressed in feet. Using the criteria given in Table 4, Category II deposits in the study area fall in the upper range of the low-hazard rating. The relative susceptibility of Category II deposits is 0.49, which falls in the mid-range of the moderate hazard of Youd and Perkins (1987).

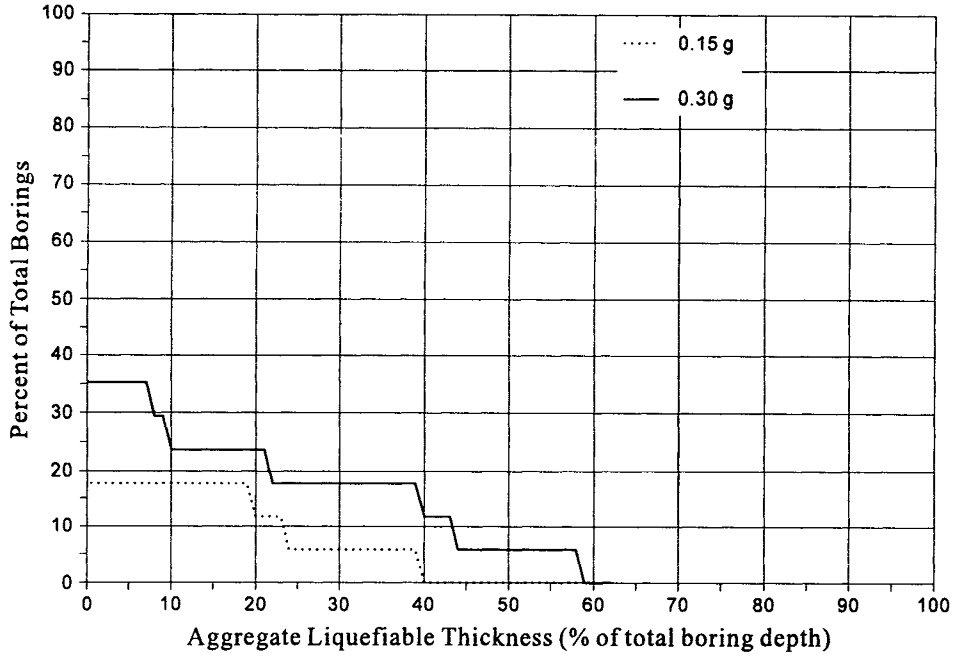

Figure 7. Cumulative frequency histogram for Category II deposits, M_w 7.3 event, Auburn and Poverty Bay quadrangles.

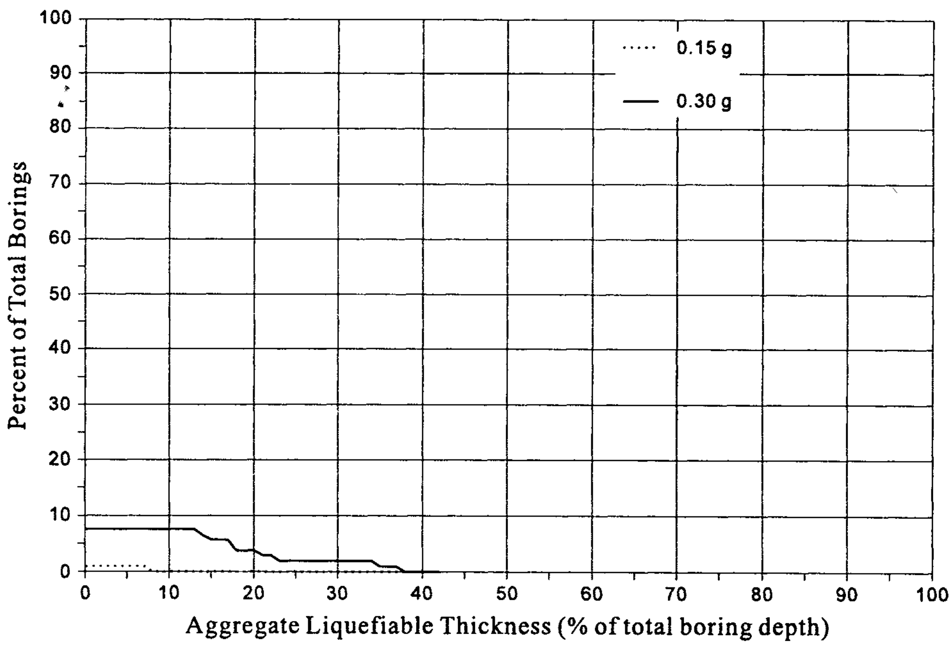

Figure 8. Cumulative frequency histogram for Category III deposits, M_w 7.3 event, Auburn and Poverty Bay quadrangles.

Waldron (1961) mapped two late Pleistocene glaciolacustrine units (Qis and Qic, Table 1 and Figure 2, p. 4) in the Poverty Bay quadrangle. Unit Qis is composed of light-brown, fine to medium sand with lenses of coarse sand to pebbles; it was interpreted by Waldron as having been deposited in ice marginal lakes of the Vashon Stade glaciation. This glaciolacustrine unit forms sloping terraces at two elevations, approximately 100 ft (30 m) and 300 ft (91 m). Analysis of four geotechnical borings located in these sandy glaciolacustrine deposits indicates that some sections are susceptible to liquefaction. The description of these deposits is very similar to that of a late Pleistocene glaciolacustrine unit that underlies an extensive terrace in the Olympia area (Gerstel and Palmer, 1993). In the Olympia area these sands are commonly loose to medium dense, and, when saturated, can be capable of liquefying (Palmer, unpublished data). Consequently, we have assigned the late Pleistocene glaciolacustrine unit Qis to Category II.

Waldron (1961) described the late Pleistocene glaciolacustrine unit Qic as a well to poorly bedded silt and clay with scattered sections of sand and gravel that are interpreted as either being ice-rafted sediments or exposures of kames against which the glaciolacustrine silt and clay was deposited. Because unit Qic is composed predominantly of silt and clay soils (which are typically not susceptible to liquefaction) we have assigned this unit to Category III.

Mullineaux (1965) mapped only thick and continuous colluvial deposits in the Auburn quadrangle. These typically occur on the lower parts of steep slopes and primarily consist of landslide debris and slope wash, and their composition reflects the diversity of their source deposits. Waldron (1961) mapped only four large landslides as mass-wasting deposits on the Poverty Bay quadrangle, although he noted that the products of mass wasting (colluvium) mantle nearly all the valley walls. Landslides and ground cracks were reported in mass-wasting deposits during the 1949 and 1965 earthquakes at many locations in the Puget Sound region (Chleborad and Schuster, 1990), and liquefaction may have been a factor in some of these ground failures. Without a thorough geotechnical investigation we cannot ascertain if an earthquake-induced slope failure resulted from soil liquefaction or the additional dynamic load imposed by strong ground shaking. Our analysis of geotechnical boring data obtained in mass-wasting deposits in the study area indicates that some sections of these deposits could liquefy. Consequently, we assign this map unit to Category II.

Holocene lacustrine deposits are primarily composed of peat and silt (Mullineaux, 1965; Waldron, 1961) and would typically be considered as having a low liquefaction susceptibility. However, there was one possible instance of liquefaction in this type of deposit in the Big Soos Creek drainage during the 1949 earthquake (Chleborad and Schuster, 1990; Palmer and others, 1994). This suggests that these deposits could liquefy. On this basis we assign this map unit to Category II.

Figure 8 presents the cumulative frequency histograms for Category III deposits; 99 borings drilled in Vashon and older glacial and nonglacial deposits were available for constructing these histograms. These deposits are typically quite dense and provide excellent foundation stability (Mullineaux, 1970). No boring data were available for the Osceola Mudflow in its outcrop area, where it is described as having fair to good foundation stability (Mullineaux, 1970). Crandell (1963) indicates that the upper 10 to 12 ft (3–4 m) of the weathered mudflow is oxidized and cemented and that it provides sufficient bearing capacity for light construction. However, below this weathered zone the mudflow becomes highly unstable when disturbed and near its liquid limit. The uncertainty in the seismic response of the unweathered portion of the Osceola Mudflow is discussed by Palmer (1995). Lacking more detailed information on the dynamic behavior of the Osceola Mudflow, we have assigned this unit to Category III. The relative susceptibility for Category III deposits is 0.007, which falls below the low liquefaction hazard rating of Youd and Perkins (1987). This category also has a very low ranking using the thickness criteria of Shannon & Wilson, Inc. (1993). No instances of liquefaction were observed in Category III deposits during the 1949 and 1965 Puget Sound earthquakes. The geologic descriptions, geotechnical analyses, and historical record indicate that Category III deposits have little susceptibility to liquefaction, and we assign them a low rating. However, unmapped areas of fill located within areas shown as Category III deposits could have a significantly higher liquefaction susceptibility. Thus, the presence or absence of liquefiable soils at a given location within the Category III map area can only be determined by a site-specific geotechnical investigation performed by a qualified practitioner.

CONCLUSIONS

Table 6 summarizes this study's ranking of the liquefaction susceptibility in the Auburn and Poverty Bay quadrangles. Category I deposits are composed of artificial fill and modified land or Holocene alluvium. They are ranked as having high liquefaction susceptibility. Category II deposits include late Pleistocene glaciolacustrine deposits predominantly composed of sand and Holocene mass-wasting deposits and lacustrine sediments. Our analysis of 21 geotechnical borings penetrating Category II deposits indicates that they contain sections of potentially liquefiable soils. The late Pleistocene sandy glaciolacustrine deposits in the study area are quite similar to potentially liquefiable glaciolacustrine sediments found near Olympia. Some of the numerous ground failures (cracking, slumping, etc.) in colluvium during the 1949 and 1965 earthquakes may have been the result of liquefaction, but no definitive evidence supporting liquefaction as the primary cause of these failures is available. Descriptions of Holocene lacustrine deposits indicate that they are composed of peaty and silty soils that generally have a low susceptibility to liquefaction. An equivocal historical example of liquefaction in a Holocene lacustrine deposit directly north of the study area indicates that liquefiable material might be present in these lake deposits. From this information we assign Category II deposits as having a moderate liquefaction susceptibility. Areas underlain by the Osceola Mudflow and the remaining Pleistocene glacial and nonglacial deposits (Category III deposits) have been assessed as having low liquefaction susceptibility.

Table 6. Ranking of the liquefaction hazard susceptibility for the three liquefaction categories defined in the Auburn and Poverty Bay quadrangles

Liquefaction category	Hazard rating
I	High
II	Moderate
III	Low

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WASHINGTON STATE DEPARTMENT OF Natural Resources
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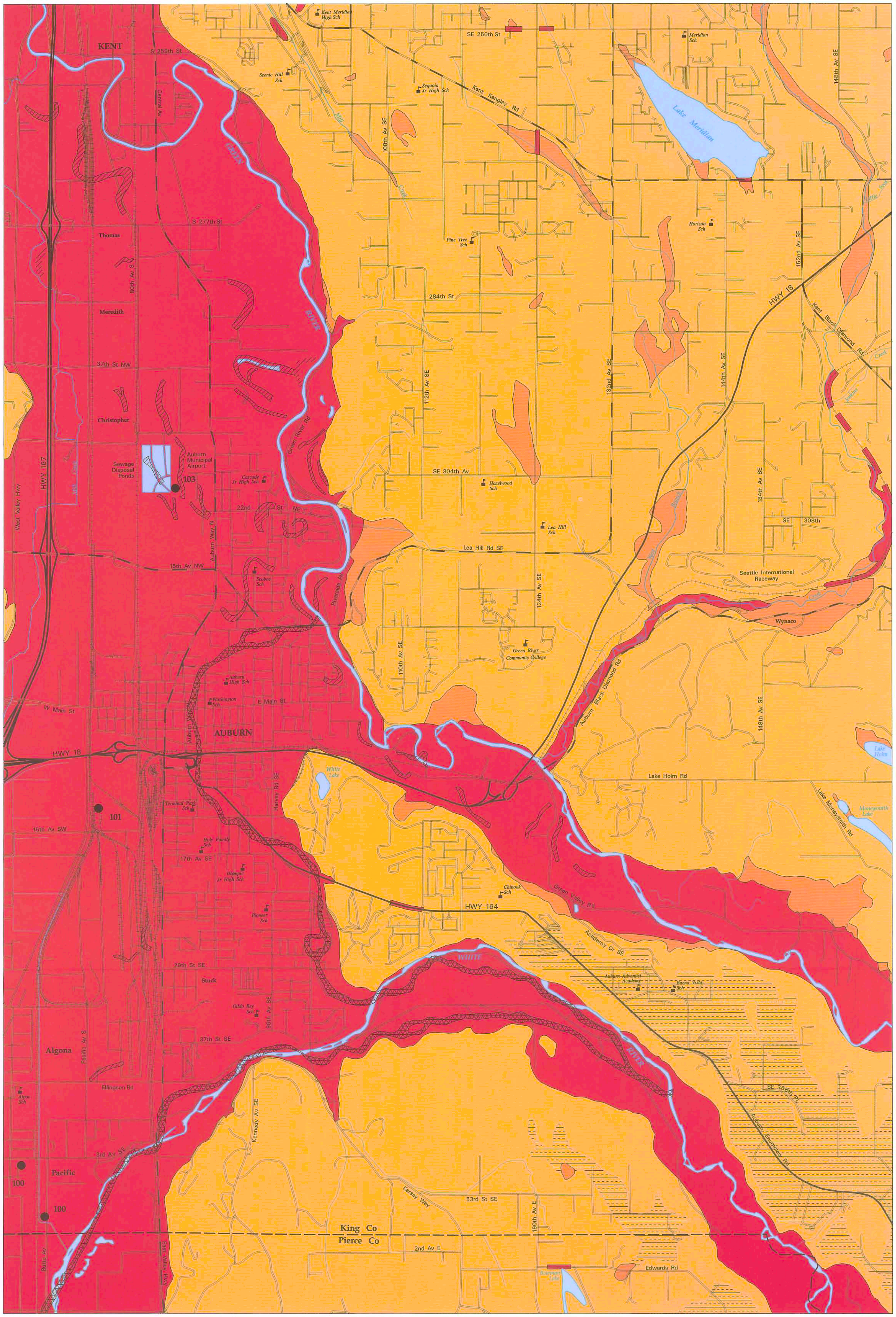
GM-43

LIQUEFACTION SUSCEPTIBILITY FOR THE AUBURN AND POVERTY BAY 7.5-MINUTE QUADRANGLES, WASHINGTON
PLATE 1 OF 2



LIQUEFACTION SUSCEPTIBILITY FOR THE AUBURN QUADRANGLE, WASHINGTON

by

Stephen P. Palmer, Timothy J. Walsh, Robert L. Logan, and Wendy J. Gerstel

1995

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EXPLANATION

CATEGORY I includes artificial fill and modified land and Holocene alluvium.
LIQUEFACTION SUSCEPTIBILITY: HIGH

CATEGORY II includes Holocene lacustrine and mass-wasting deposits and late Pleistocene sandy glaciolacustine sediments.
LIQUEFACTION SUSCEPTIBILITY: MODERATE

CATEGORY III includes all other Pleistocene glacial and nonglacial deposits and the Osceola Mudflow.
LIQUEFACTION SUSCEPTIBILITY: LOW

Major open water features.

Contacts between liquefaction susceptibility categories based on geologic map units derived from Mullineaux (1965).

Historic liquefaction sites identified by the corresponding reference number in Chleborad and Schuster (1990). Table 3 reproduces the quotations and comments given for the sites in Table 2 of Chleborad and Schuster (1990).

Pre-1906 courses of the White and Stuck Rivers as mapped by Willis and Smith (1899).

Osceola Mudflow deposits.

Abandoned channels of the Green, White or Stuck Rivers that generally do not appear to contain intermittent streams or support riparian vegetation.

Drainages and streams that appear to be abandoned channels of the Green, White, or Stuck Rivers.

This map is meant only as a general guide to delineate areas prone to liquefaction. This map is not a substitute for site-specific investigation to assess the potential for liquefaction for any development project. Because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geologic mapping, this map cannot be used to determine the presence or absence of liquifiable soils beneath any specific locality. This determination requires a site-specific geotechnical investigation performed by qualified practitioners.

This project was partially supported by the Federal Emergency Management Agency, the Washington Division of Emergency Management, and the U.S. Geological Survey.

SCALE 1:24,000

0 0.5 1 1.5 2
MILES

Lambert Conformal projection
1927 North American Datum
Washington coordinate system, south zone
Base map information from the Washington Department of Natural Resources, Geographic Information System - 1995
Cartographic design and production by Carl F. T. Harris
Washington Division of Geology and Earth Resources

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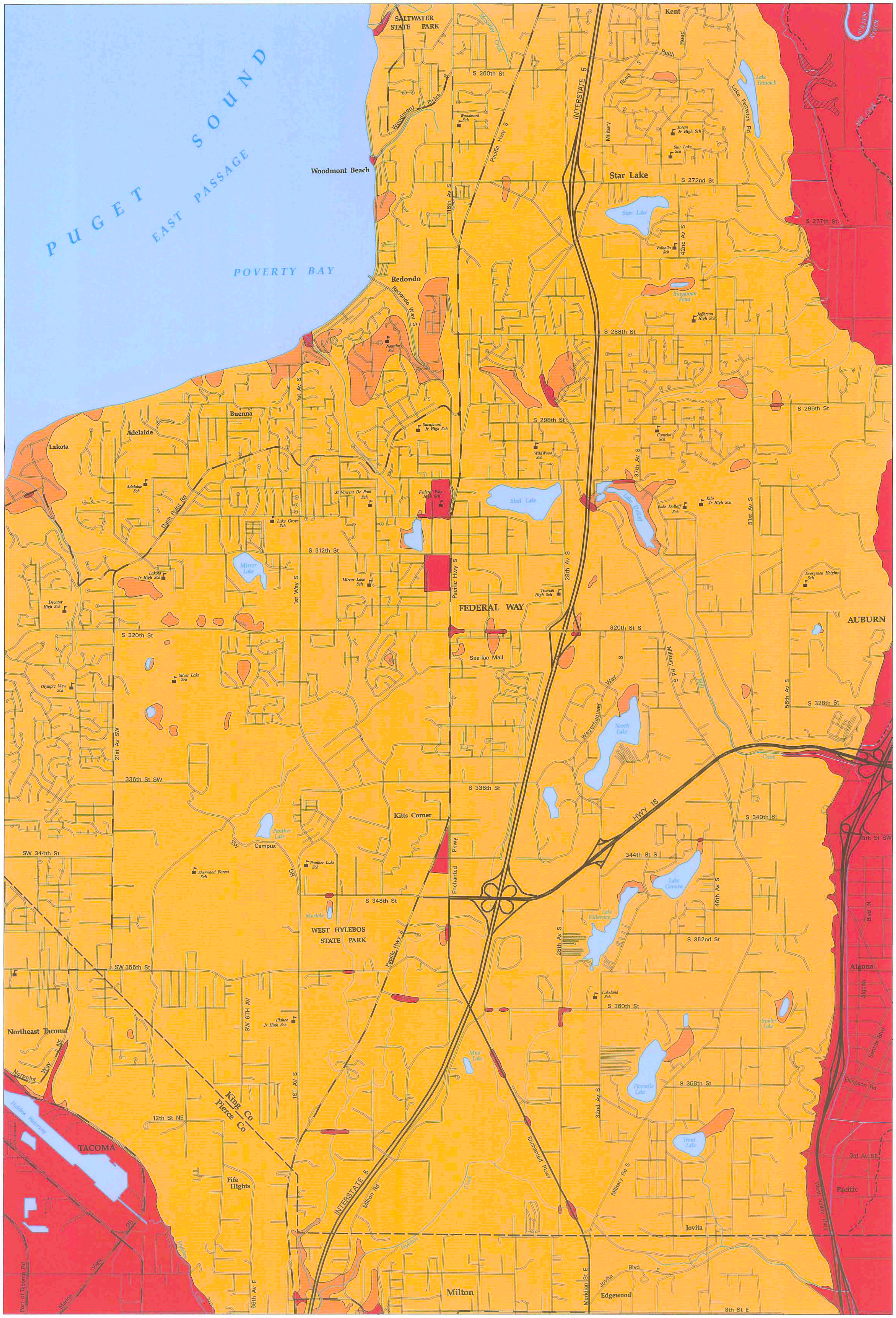
LIQUEFACTION SUSCEPTIBILITY FOR THE AUBURN AND
POVERTY BAY 7.5-MINUTE QUADRANGLES, WASHINGTON
PLATE 2 OF 2



LIQUEFACTION SUSCEPTIBILITY FOR THE POVERTY BAY QUADRANGLE, WASHINGTON

by

Stephen P. Palmer, Timothy J. Walsh,
Robert L. Logan, and Wendy J. Gerstel

1995

N

EXPLANATION

CATEGORY I includes artificial fill and modified land and Holocene alluvium.
LIQUEFACTION SUSCEPTIBILITY: HIGH

CATEGORY II includes Holocene lacustrine and mass-wasting deposits and late Pleistocene sandy glaciolacustine sediments.
LIQUEFACTION SUSCEPTIBILITY: MODERATE

CATEGORY III includes all other Pleistocene glacial and nonglacial deposits.
LIQUEFACTION SUSCEPTIBILITY: LOW

Major open water features.

Contacts between liquefaction susceptibility categories based on geologic map units derived from Waldron (1961).

Abandoned channels of the Green River that generally do not appear to contain intermittent streams or support riparian vegetation.

Drainages and streams that appear to be abandoned channels of the Green, White or Stuck Rivers.

This map is meant only as a general guide to delineate areas prone to liquefaction. This map is not a substitute for site-specific investigation to assess the potential for liquefaction for any development project. Because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geologic mapping, this map cannot be used to determine the presence or absence of liquifiable soils beneath any specific locality. This determination requires a site-specific geotechnical investigation performed by qualified practitioners.

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