FINAL TECHNICAL REPORT
Award Number: G11AP20124 and G11AP20125

Title: "Liquefaction Hazard Maps for the St. Louis Area Earthquake Hazards Mapping Project: Collaborative Research with the Missouri University of Science and Technology and the University of Memphis"

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April 1, 2011 – March 31, 2012

Submitted: July 10, 2012

"Research supported by the U.S. Geological Survey (USGS), Department of Interior, under USGS award numbers G11AP20124 and G11AP20125. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government."

Abstract

The St. Louis Area Earthquake Hazards Mapping Project (SLAEHMP) is a key part of the U.S. Geological Survey's (USGS) Earthquake Hazards Program, which seeks to reduce the Nation's risk from earthquake hazards. The greater St. Louis, MO area has the highest earthquake risk of any metropolitan area in the eastern U.S. because metropolitan St. Louis is near the New Madrid seismic zone and has a much larger population and infrastructure than Memphis (FEMA, 2008). This final report is for the completion of liquefaction hazard maps for the 17 eastern-most SLAEHMP study-area quadrangles for the St. Louis area. Previously, USGS NEHRP grants and Missouri University of Science and Technology (MST) funding in support of SLAEHMP have only produced liquefaction susceptibility and potential maps. Pearce and Baldwin (2008) focused only on mapping floodplain areas, based on national seismic hazard estimates (Frankel et al., 2002), while Chung and Rogers (2011) proposed using a new mapping methodology based on calculated values of the Liquefaction Potential Index (LPI). As part of this NEHRP funded research, credible liquefaction hazard maps have been generated using the voluminous library of subsurface data currently available. This requires the generation of liquefaction cumulative probability curves for SLAEHMP using the approach of Romero-Huddock and Rix (2005). These curves are needed for generating liquefaction earthquake-scenario and probabilistic hazard maps using the approach of Cramer et al. (2008). The needed surficial geologic mapping and depth to water table information for all Illinois quadrangles and for 9 Missouri quadrangles was complete under USGS NEHRP grant and cooperative agreement funding. The SLAEHMP scenario and probabilistic seismic hazard maps and major river channel model that form the basis of the proposed liquefaction hazard maps have been completed under a cooperative agreement with the USGS (G10AC00224). As part of the work reported here, the liquefaction hazard calculation computer programs used to generate the Memphis liquefaction hazard maps have been updated from the 2002 to the 2008 USGS national seismic hazard model to remain compatible with the seismic hazard maps being generated for SLAEHMP. These computer programs were then used to generate probabilistic and scenario liquefaction hazard maps for the 17 easternmost SLAEHMP quadrangles using the corresponding seismic hazard maps and the liquefaction cumulative probability curves generated under these grants. This work is a key element in SLAEHMP efforts to produce seismic and liquefaction hazard maps for the St. Louis area and liquefaction hazard maps have been a highly regarded and sought after product of the Memphis hazard mapping project, more than the urban seismic hazard maps upon which they are based.

Study Area

The whole SLAEHMP study area encompasses > 4,400 km^2 (29 USGS 7.5-minute quadrangles – Figure 1) in the greater St. Louis area, Missouri and Illinois. The St. Louis area includes four major rivers (Mississippi, Missouri, Illinois, and Meramec Rivers) and Mill, Piasa, and Cahokia Creeks. This region is setting on Quaternary deposits, which consist of: 1) Holocene alluvial deposits in the river valley floodplains and 2) Pleistocene loess and/or glacial till deposits mantling dissected uplands. The uplands in the Missouri side are deeply incised, while those on the Illinois side are more gently rolling. These Quaternary sediments overlie Paleozoic strata, mostly Pennsylvanian shales and Mississippian limestones, with some older Paleozoic rocks.

Liquefaction cumulative potential curves were generated for the whole SLAEHMP study area. But for this report, liquefaction hazard maps were generated for only the easternmost 17 quadrangles shown in Figure 1. For the remaining westernmost 12 quadrangles, geologic mapping is not complete, but should be finished by June 2013.

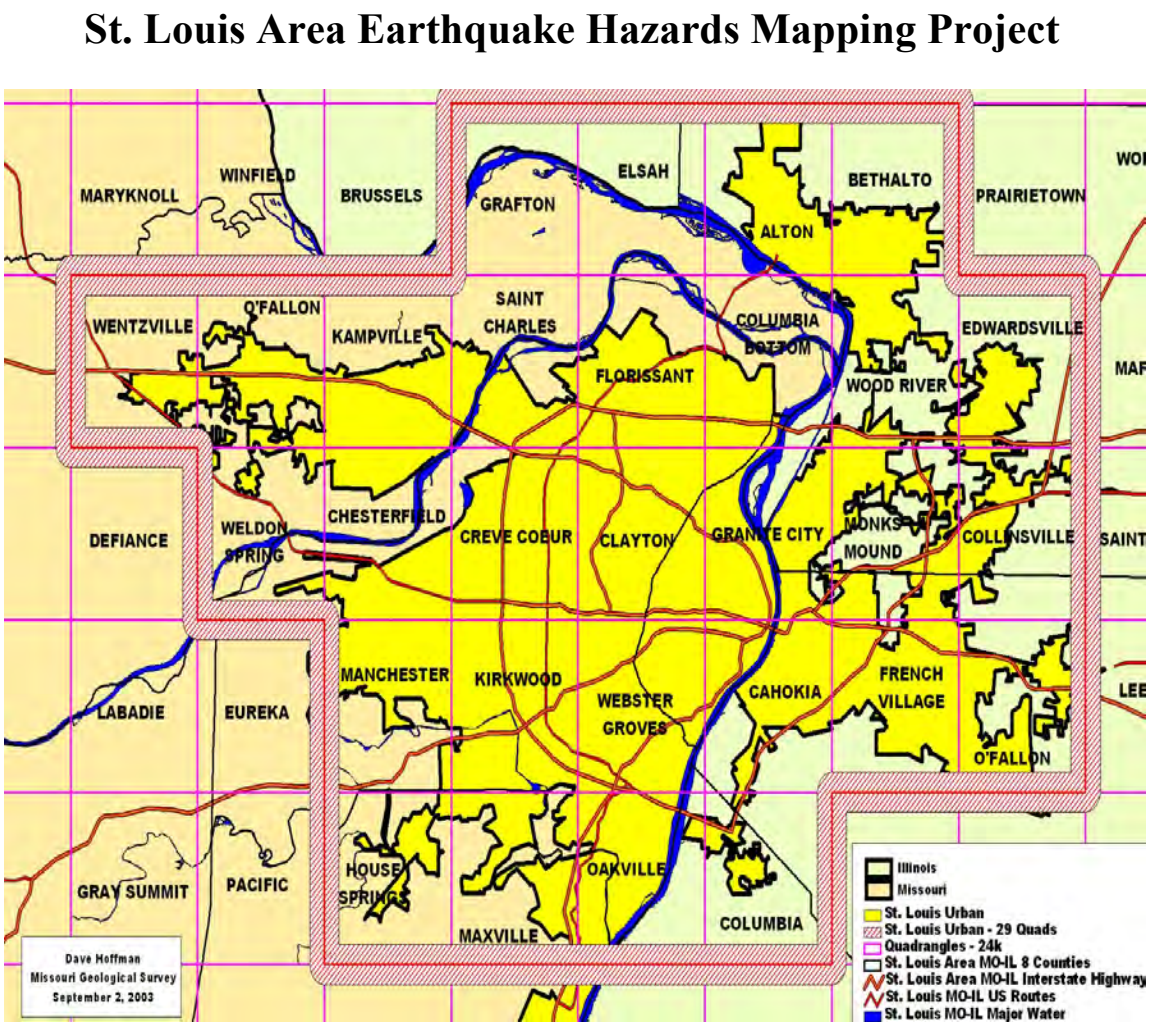

Figure 1. SLAEHMP study area.

LPI based Liquefaction Cumulative Potential Curves for SLAEHMP

Liquefaction Potential Index

The liquefaction potential index (LPI; Iwasaki et al., 1978 and 1982) has been increasingly applied to evaluate liquefaction risk, world-wide (Holzer et al. 2005; Papathanassiou 2008; Hayati and Andrus 2008; Haase et al. 2011). Its risk criteria (zero to minor liquefaction risk when LPI < 5; severe liquefaction risk when LPI > 15) generally correlate well with liquefaction case histories (Iwasaki et al. 1982; Toprak and Holzer 2003).

Exceeding LPI value of 15 represents the median figure extracted from post-quake evaluations of liquefied sites over the past half-century (Iwasaki et al. 1978 and 1982). Recently, Toprak and Holzer (2003) related LPIs with ground damage for the 1989 Loma Prieta Earthquake, and they found that LPI > 12 were associated with more than 50 % of ground cracking as severe hazards and LPI > 5 for sand boils as moderate hazards. Exceeding LPI values of 12 as the lower limit of severe liquefaction should be adopted if a conservative estimate is sought, as is typical of planning documents. Thus exceeding LPI values of 12 was adopted as the lower limit of severe liquefaction in this report.

Cumulative Frequency Distributions

Holzer et al. (2006) grouped 202 cone penetration test-based liquefaction potential index (LPI) values in surficial geologic units along the margins of San Francisco Bay (140 km^2), California. Cumulative frequency distributions of LPI > 5 for surficial geologic units were then analyzed. The percentage of LPI > 5 were interpreted as the probability to estimate surface manifestations of liquefaction at a random location.

This method estimates the threshold PGA for specific LPI values and its probability, for a scenario earthquake magnitude (e.g., Mw = 7.5). Cramer et al. (2008) modified the approach to map liquefaction hazards in the Memphis area (six 7.5-minute quadrangles, 950 km^2). They adjusted the PGA values with various earthquake magnitudes, by applying correction factors termed 'magnitude scaling factors' (MSF).

Groundwater Depth

The depth of the groundwater table is a controlling factor for assessing liquefaction potential, because liquefaction only occurs in saturated soils. High groundwater levels increase the liquefaction potential and increase the LPI values. Liquefaction seldom occurs where the groundwater table is deeper than 12 m below ground surface (Youd, 1973). To demonstrate the effect of water table depth on liquefaction probability, Holzer et al. (2011) showed that the liquefaction probabilities decrease significantly, for groundwater table depths of 1.5 m to 5 m.

Previous probabilistic liquefaction hazard maps (Holzer et al., 2006, Cramer et al., 2008) have been prepared using scenario earthquakes and groundwater levels for an entire study area (e.g., 1.5 m depth for San Francisco Bay; 6 m depth for Memphis). Such blanket assumptions tend to oversimplify liquefaction probability of regional areas. For example, the St. Louis metro area is situated on contrasting geomorphic settings: alluvial floodplains and dissected loess-covered

uplands, which exhibit different groundwater depths. The depths-to-groundwater in the uplands are highly variable, ranging from 1 m to 30 m or more (Pearce and Baldwin 2008; Chung and Rogers, 2011 and 2012).

To determine the liquefaction potential curves under the most likely conditions, we considered high and normal water table scenarios for both geomorphic provinces (lowlands and uplands), then calculated the liquefaction probabilities for LPI > 5 (moderate) and >12 (severe liquefaction hazard) at the differing seismic demand of PGA/MSF. Information from the Illinois State Geological Survey (Bauer, 2012) in both the lowlands of the Mississippi flood plain and the uplands provided the estimates for high and normal water table depths used in this study. In the lowlands water table depths of 0.5m and 2.0m were used for the high and normal depths. In the uplands water table depths of 1.0m and 4.0 m were used.

Data

The input data for mapping liquefaction hazard in this study consists of the following components:

- Surficial geologic map: The Quaternary surficial geologic maps (Figure 2 and Table 1) were collected from: 1) the USGS (Schultz, 1993), and 2) the Illinois Geological Survey (ISGS; Grimley and Phillips, 2006; and Grimley, 2009). Different map units and mapping techniques have traditionally been employed by Missouri (depositional models) and Illinois (formational models). These were unified and simplified for this study, based on sediment types and genesis (Chung and Rogers, 2010; Chung and Rogers, 2011).

- SPT profiles: The logs of 1,923 engineering boreholes (Figure 2 and Table 1) including soil descriptions, respective thickness, and SPT (standard penetration test) blow counts, with sampling intervals of 0.76 m to 1.5 m were utilized in this study. These were collected from the Missouri Division of Geology and Land Survey (MODGLS; Palmer et al., 2006), the ISGS, and the USGS (Conor Watkins 2011, personal communication). These SPT profiles were used to calculate the LPI values.

- Assumed depth-to-groundwater (DTW): DTW estimates were based on data gleaned from monitoring wells (USGS, 2011), engineering boreholes (Chung and Rogers, 2012), and local experience (Robert Bauer, 2011, personal communication; Brad Mitchell 2011, personal communication, Bauer, 2012). After review by the SLAEHMP Technical Working Group (TWG) we assumed two depths-to-groundwater scenarios for each landform:

    - High level: 0.5 m (95th percentile) for floodplains and 1.0 m (95th percentile) for uplands;
    - Normal level: 2.0 m (the median) for the floodplains and 4.0 m (the mode) for uplands.

The curves of liquefaction probability were established for both assumed water table depths and for floodplains and uplands.

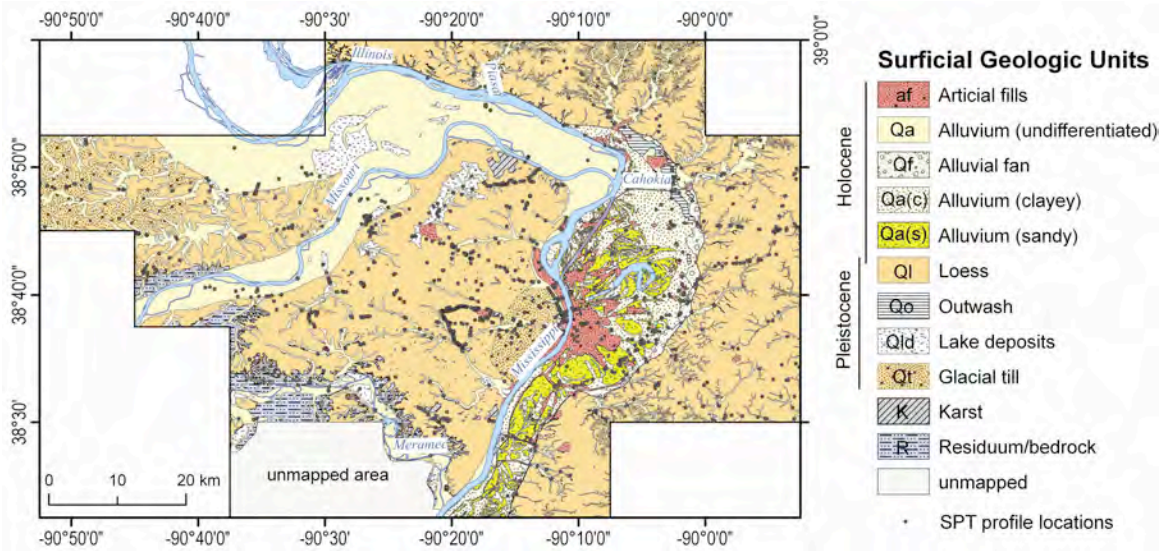

Figure 2. Simplified surficial geology map of the St. Louis area (modified from Schultz 1993; Grimley and Phillips, 2006; and Grimley, 2009), with overlay showing the locations of engineering borings used to assess liquefaction probability.

Table 1. Surficial Geologic Units and Distributions of Engineering Borings

Landform	Geologic Unit	Symbol	Materials	Number of Boreholes
Low-lying floodplains	Artificial fills	af	Various soil or rock types	150
	Alluvium	Qa	Silt loam	439
	Alluvial fan	Qf	Silt loam	17
	Alluvium (clayey facies)	Qa (C)	Silty to silty clay loam	74
	Alluvium (sandy facies)	Qa (S)	Very fine to medium sand	38
	Glacial outwash	Qo	Medium to coarse sand	8
	Lake deposits	Qld	Silty clay loam	120
Uplands	Artificial fill	af	Various soil or rock types	14
	Loess	Ql	Silt to silt loam	959
	Till	Qt	Mixed of clay, gravel, and rock fragment	87
	Residuum	R	Clay, silt and sand with rock fragments derived from the underlying bedrock	17

LPI Calculation

Following the approach of Romero-Huddock and Rix (2005) the simplified SPT-based procedure of Seed and Idriss (1971) and liquefaction resistance curve of Seed et al. (1985) were applied to evaluate the critical PGA/MSF sufficient to exceed LPI's of 5 (moderate) and 12 (severe liquefaction effects).

MSF: among various proposed equations of a magnitude scaling factor (MSF), we employed the MSF suggested by Youd et al. (2001):

$$MSF = 10^{2.24}/Mw^{2.56}$$

where Mw is moment magnitude.

PGA/MSF: 45 combinations of PGA (0.10g, 0.15g, 0.20g, 0.25g, 0.30g, 0.35g, 0.40g, 0.45g, 0.50g) and Mw (6.0, 6.5, 7.0, 7.5, 8.0) were used to calculate LPI values for each of the surficial geologic units shown in Table 1.

Liquefaction Probability Curves

Figures 3 and 4 present the probability of exceeding LPI's of 5 and 12, for high and normal groundwater levels, for the floodplain and upland geomorphic provinces, respectively. The liquefaction probability, as a function of the PGA/MSF, was fitted with a four-parameter Weibull's model, using SigmaPlot software (2006):

$$p = \begin{cases} 1 - e^{-\left(\frac{x - xo + b\ln 2^{1/c}}{b}\right)^c} & for x > x_0 - b\ln 2^{\frac{1}{c}} \\ 0 & for x \le x_0 - b\ln 2^{\frac{1}{c}} \end{cases}$$

where a*p = the liquefaction probability (LPI >5 or >12), x = PGA/MSF, a, b, c, and x_0 = fitted coefficients.

The Weibull cumulative probability model is suitable for analyzing the failure probability of composites or layered materials under a given stress (Weibull, 1951; Jibson et al., 2000). This model produces the most versatile sigmoid curve, and is sufficiently flexible to accommodate most data sets. Regression analyses for Weibull's model are presented in Figures 3 and 4, and the data is summarized in Table A1.

Updating Liquefaction Computer Codes

The approach used by Cramer et al. (2008) for producing liquefaction hazard maps for Memphis, TN has been applied to generating liquefaction hazard maps for SLAEHMP. The computer programs used to generate liquefaction hazard maps were updated from the 2002 to the 2008 USGS national seismic hazard model (Petersen et al., 2008) to remain compatible with the seismic hazard maps being generated for SLAEHMP. This involved not only updating map generation programs to the 2008 hazard model, but also transferring the national map codes to the University of Memphis High Performance Computing (HPC) facility. The HPC is needed to calculate both the site amplification distributions and the probabilistic liquefaction hazard in a reasonable time period (days instead of months) due to the 0.005-degree (~500 m) grid used and the number of quadrangles (17) included in the calculations.

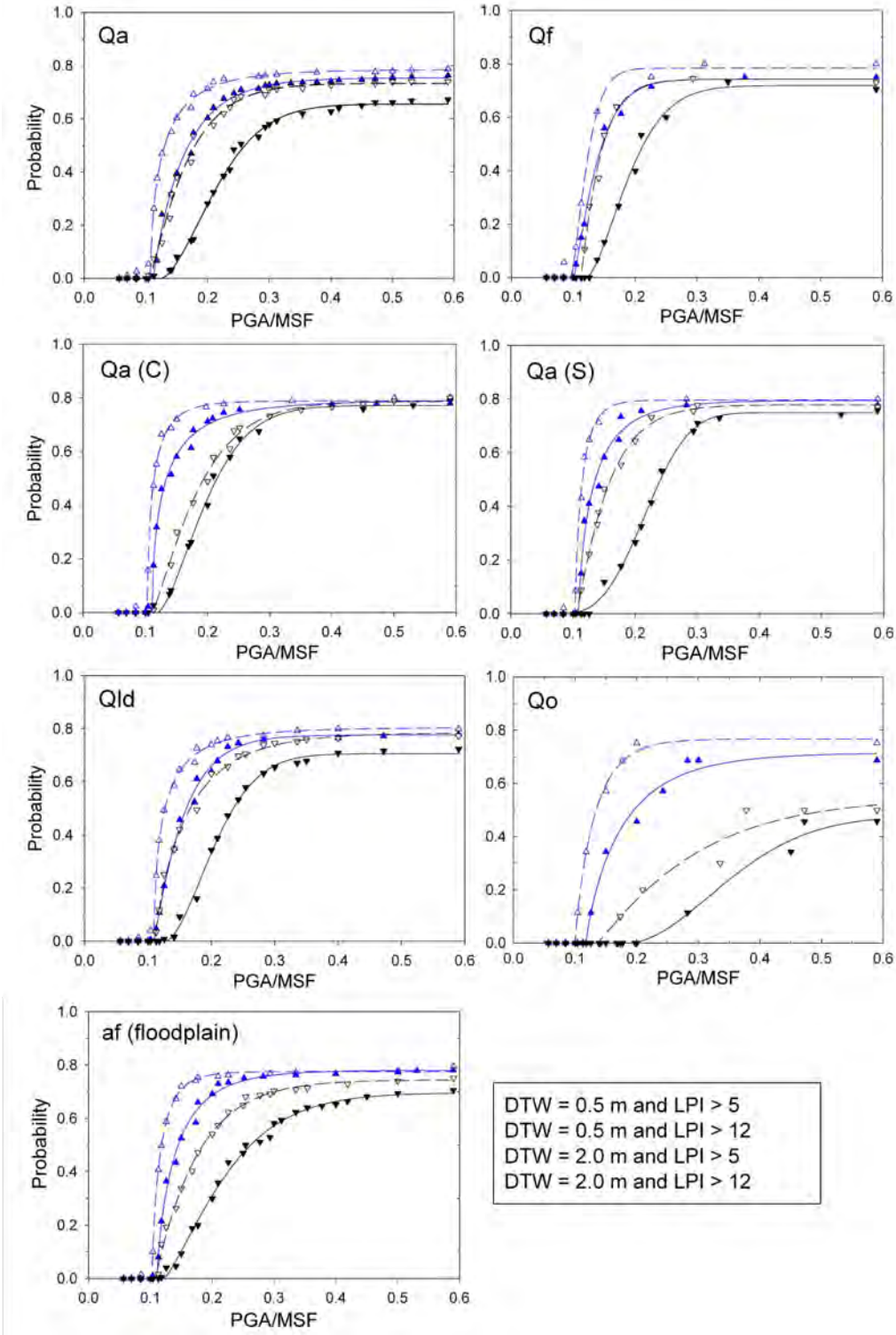

Figure 3. Curves of liquefaction probability of LPI > 5 (open) and LPI >12 (filled) for surficial geologic units, floodplains within St. Louis area. DWT = depth-to-groundwater (blue – 0.5m, black – 2.0m); Qa = alluvium; Qf = alluvial fan; Qa(C) = clayey alluvium; Qa(S) = sandy alluvium; Qld = lake deposits; Qo = glacial outwash; af = artificial fills.

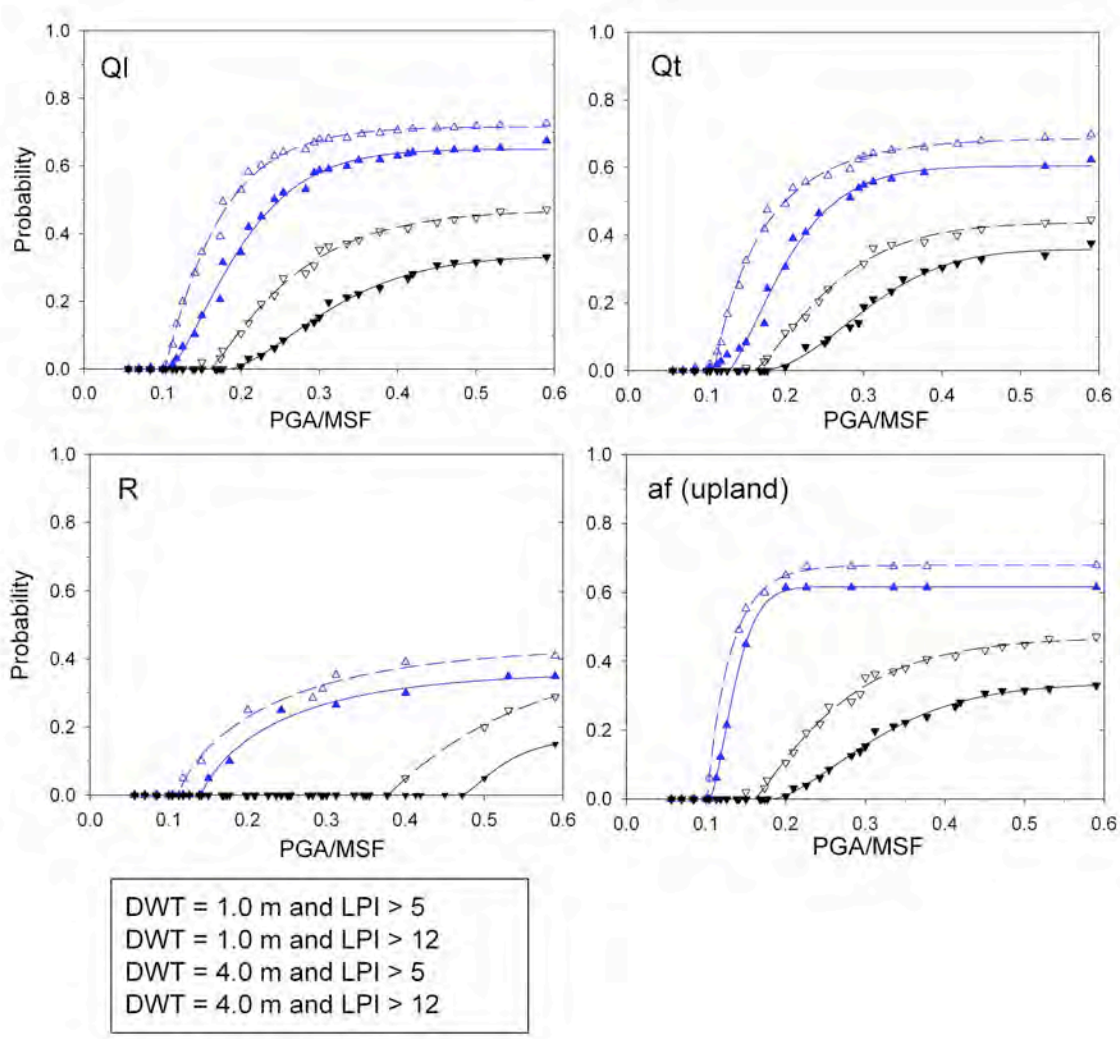

Figure 4. Curves of liquefaction probability of LPI > 5 (open) and LPI > 12 (filled) for surficial geologic units, uplands within St. Louis area. DWT = depth-to-groundwater (blue – 1.0m, black – 4.0m); Ql = loess; Qt = till; R = residuum; af = artificial fills.

The approach of Cramer et al. (2008) uses the liquefaction cumulative potential curves generated in the previous section. Note that the liquefaction cumulative probability curves are a function of magnitude and hence are used inside the hazard integral to calculate probabilistic liquefaction hazard maps as indicated in the following equation from Cramer et al. (2008):

$$P(P_{LPI>n} > Po) = \Sigma_i \, \alpha_i \int_M \int_R f_i(M) \, f_i(R) \, P(P_{LPI>n} > Po \mid A > Ao, M) \, P(A > Ao \mid M, R) \, dR \, dM$$

where $P(P_{LPI>n} > Po)$ is the liquefaction hazard curve for LPI>n, α_i is the rate of source i, M and R are magnitude and distance, $f_i(M)$ and $f_i(R)$ are the ith source magnitude and distance distribution functions, $P(P_{LPI>n} > Po \mid A > Ao, M)$ is the liquefaction cumulative probability curve for the site and LPI>n, and $P(A > Ao \mid M, R)$ is the site-specific attenuation relation. The site-specific attenuation relation is generated using the approach of Cramer (2003,2005).

St. Louis Scenario and Probabilistic Liquefaction Hazard Maps

The generation of final liquefaction hazard maps requires the use of a GIS, guided by the surface geology map, to piece together liquefaction hazard maps for each surface soil type into a scenario or probabilistic liquefaction hazard map. Figures 5 and 6 show the detailed surface geology maps for Illinois and Missouri, respectively, used to generate the liquefaction hazard maps. With the assistance of Illinois and Missouri geologists, surface geology units in Figures 5 and 6 were related to the simplified surface geology units of Figure 2 and Table 1 to assign the appropriate liquefaction cumulative potential curves to the detailed surface geology. In Figure 6, the two unmapped surface geology polygons at the south end of the map were assigned as Ql (loess) for the western polygon and Qa (alluvium) for the eastern polygon in the Mississippi flood plain, as confirmed by Missouri geologists providing the information.

Scenario liquefaction hazard maps have been generated by taking SLAEHMP scenario median peak ground acceleration (PGA) hazard maps that include the effects of local geology and applying the median liquefaction cumulative potential curve for the scenario magnitude. At each grid point, the median PGA scaled by the magnitude scaling factor is used to select the probability of exceeding LPI 5 or 12 from the curve for the surface geology at that grid point. SLAEHMP scenario PGA maps available are for (1) a M7.5 earthquake on the northeast arm of the New Madrid seismic zone, (2) a M6.0 40 km east of St. Louis near the Shoal Creek, IL paleoliquefaction feature, (3) a M6.0 50 km SSW of St. Louis near Sainte Genevieve, MO, (4) a M5.8 beneath downtown St. Louis, and (5) a M7.1 near Vincennes, IN.

Once the liquefaction hazard maps for a given scenario or probability of exceedance for each LPI exceedance level, surface geology type, and depth to water table (DTW - high or normal) have been calculated, the two depth to water table alternatives are combined using a weighted average. The SLAEHMP technical working group (TWG) discussed the weighting to be used in combining high and normal water table alternative maps. After reviewing the water table evidence of Bauer (2012), the TWG weighted the flood plain high DTW map 1.0 and the normal DTW map 0.0, as the reliable evidence in Bauer (2012) showed the flood plain water tables to fluctuate between 0.5 to 1.0 m and rarely fall below 1.0 m. For the uplands, the high and normal DTW maps were weighted equally (0.5 each). Thus for the flood plain surface geologies, only the 0.5 m DTW map was used, while for the uplands the 1.0m and 4.0 m maps were averaged together.

An example scenario liquefaction hazard map for the M7.5 New Madrid scenario is shown in Figure 7 for LPI>5 and LPI>12 along with its PGA scenario hazard map. Scenario liquefaction hazard maps for the remaining SLAEHMP earthquake scenarios are shown in Figures 8-10, except the Vincennes, IN scenario, which has no significant liquefaction hazard in the SLAEHMP study area.

Probabilistic liquefaction hazard maps have also been generated for LPI>5 and LPI>12. Again these maps were generated according to the method of Cramer et al. (2008), as briefly described above. Figures 11-13 present the 10%, 5%, and 2% in 50-year liquefaction hazard maps along with their accompanying PGA probabilistic seismic hazard maps. The high PGA on the 2%-in-

50-year maps near the Mississippi River north of downtown St. Louis and to the southwest of Mosenthein Island is due to a shallow bedrock shelf.

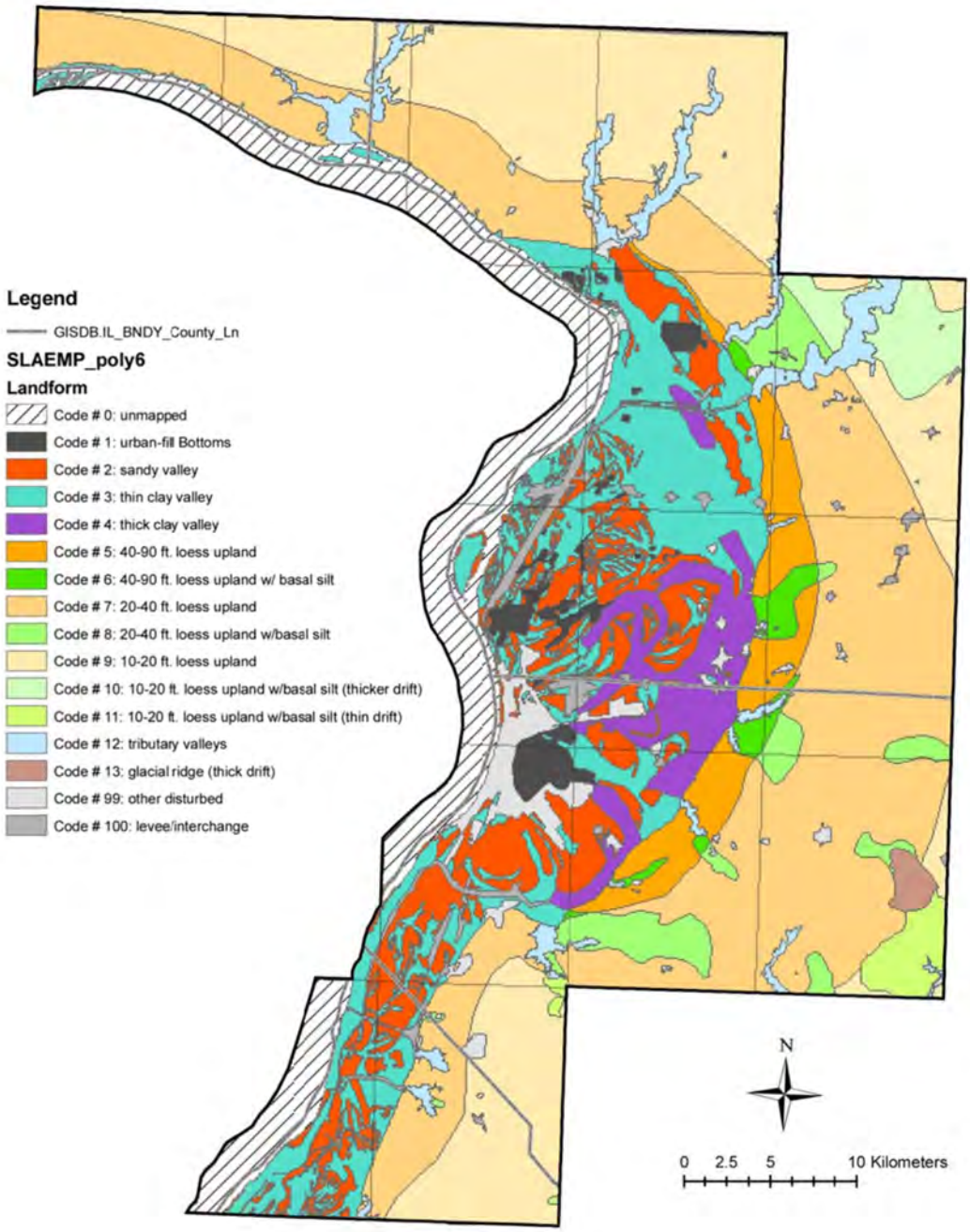

Figure 5. Illinois detailed surface geology map.

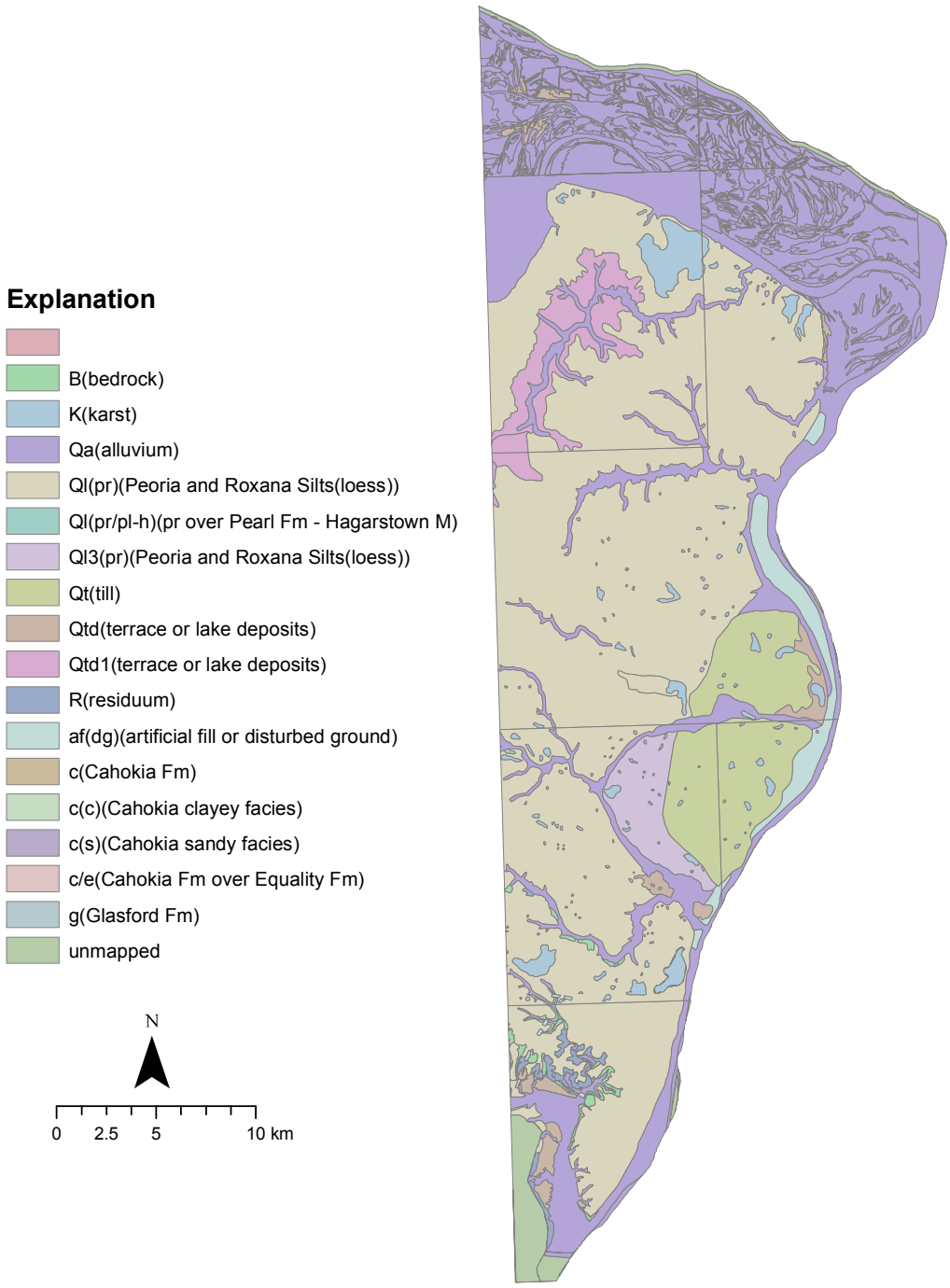

Figure 6. Missouri detailed surface geology map.

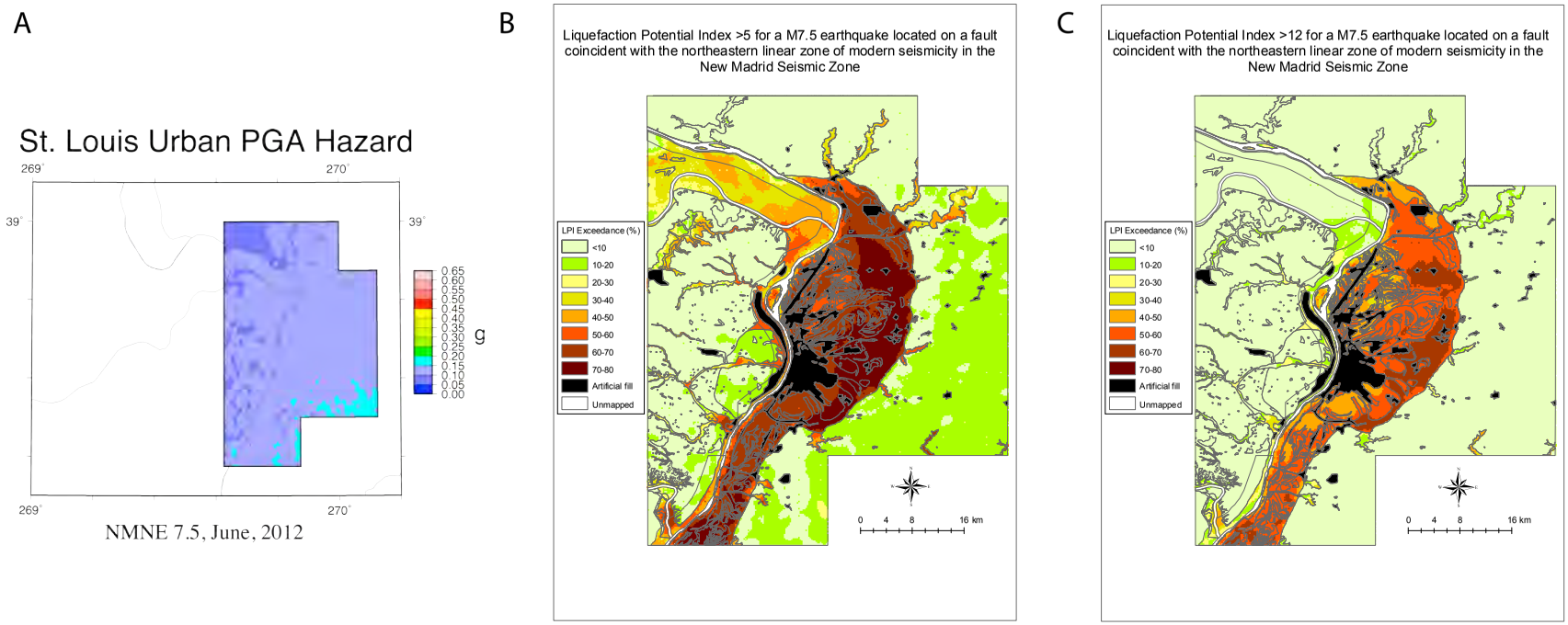

Figure 7. (A) PGA, (B) LPI>5, and (C) LPI>12 ground motion / liquefaction hazard maps for a scenario M7.5 earthquake on the NE segment of the New Madrid seismic zone.

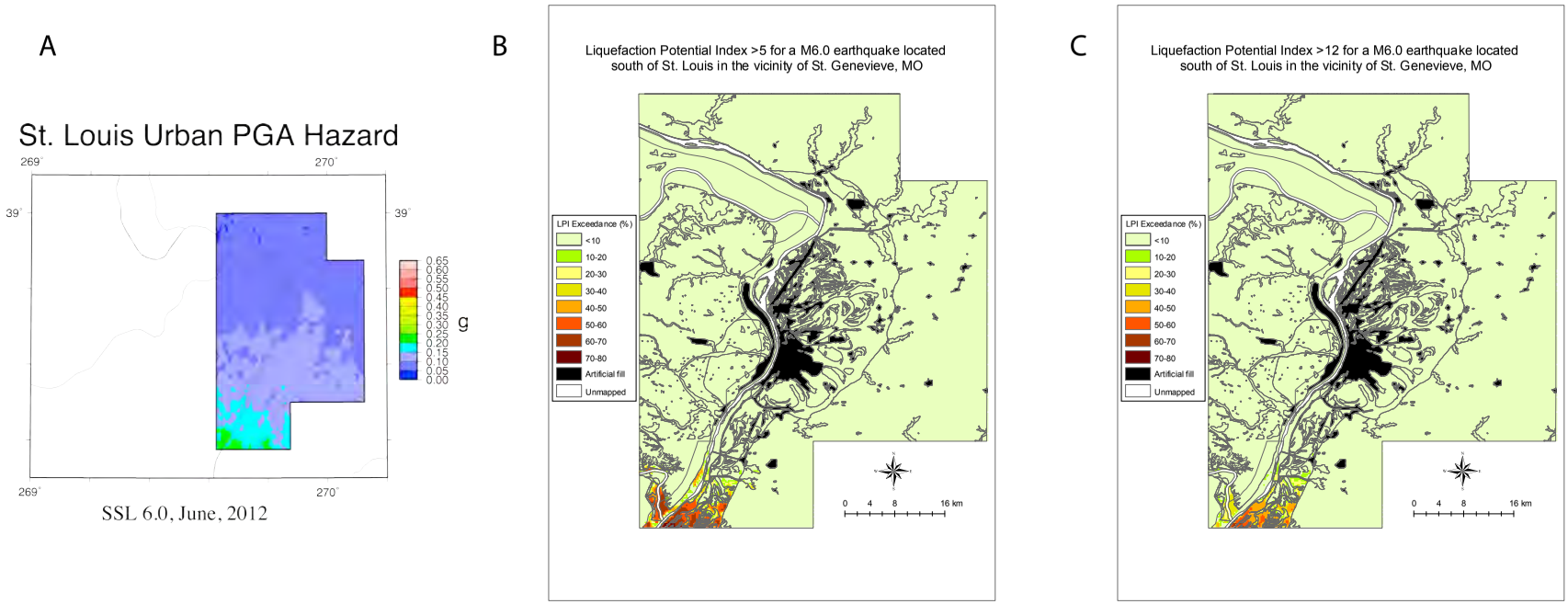

Figure 8. (A) PGA, (B) LPI>5, and (C) LPI>12 ground motion / liquefaction hazard maps for a scenario M6.0 earthquake south of St. Louis near Ste. Genevieve, MO.

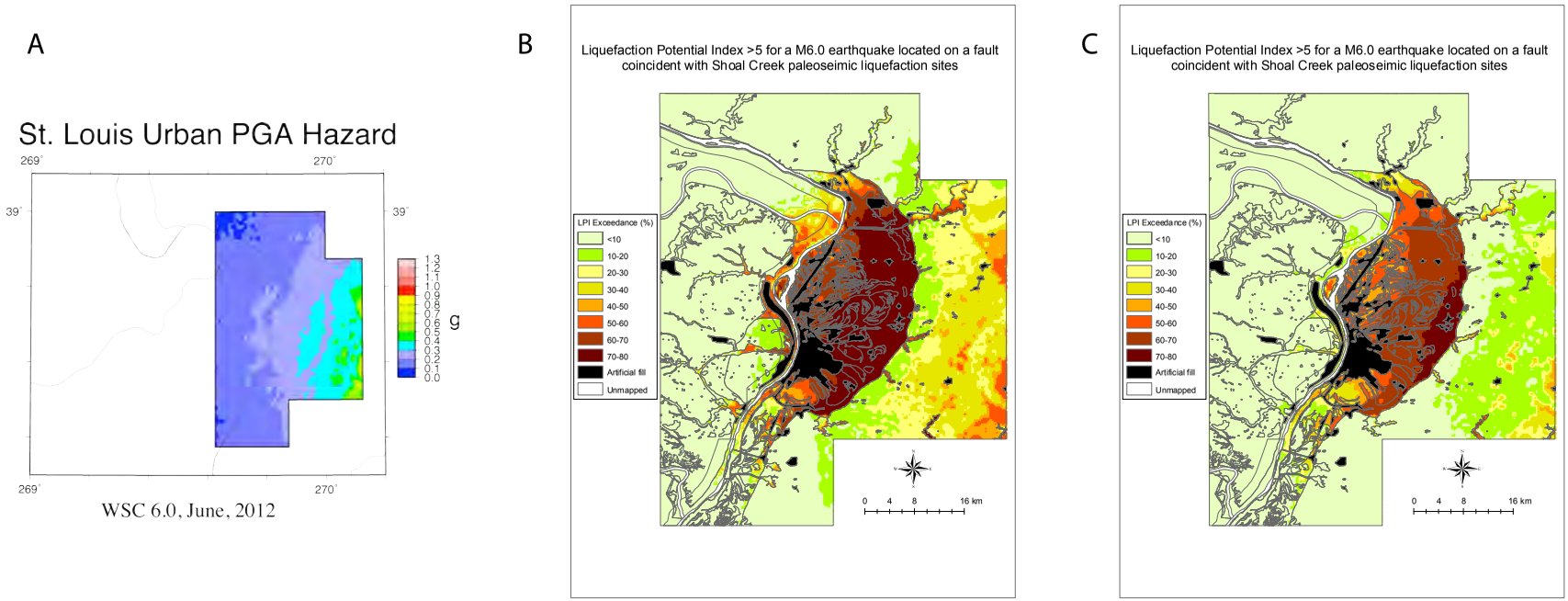

Figure 9. (A) PGA, (B) LPI>5, and (C) LPI>12 ground motion / liquefaction hazard maps for a scenario M6.0 earthquake near the Shoal Creek paleoliquefaction site.

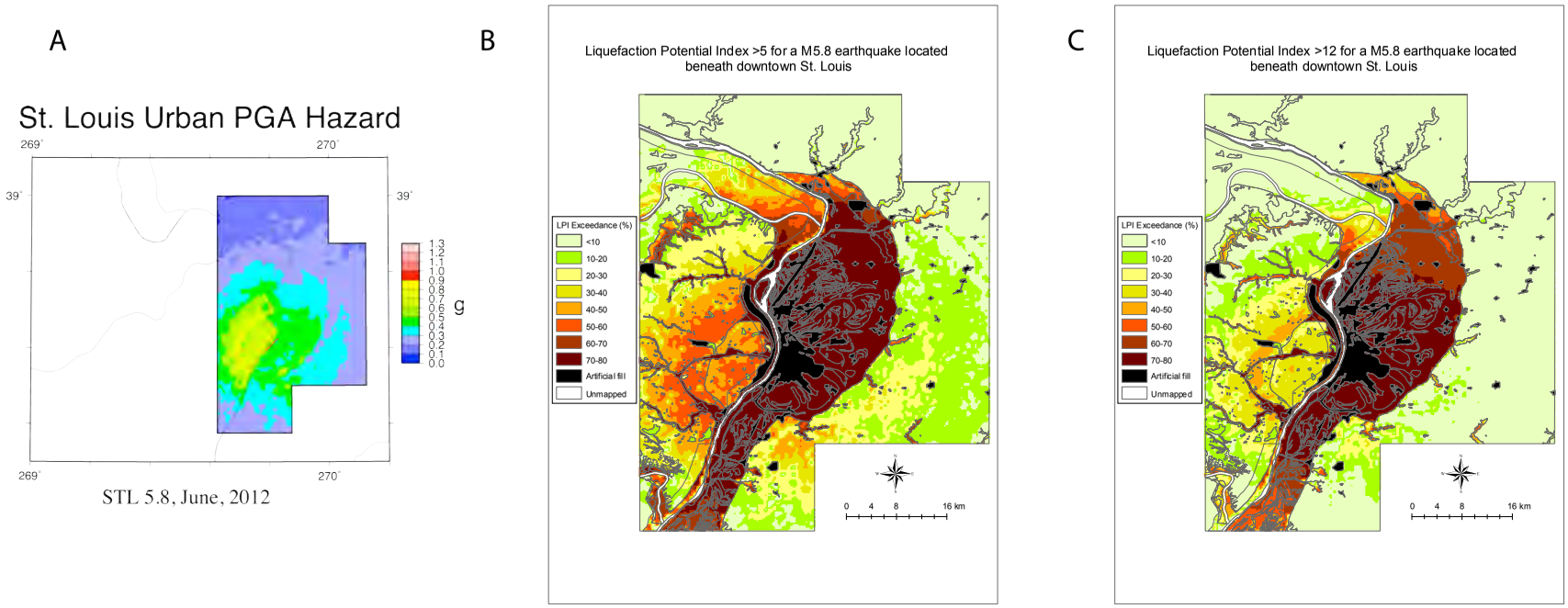

Figure 10. (A) PGA, (B) LPI>5, (C) LPI>12 ground motion / liquefaction hazard maps for a scenario M5.8 earthquake beneath St. Louis. Red line on PGA map is the fault rupture location.

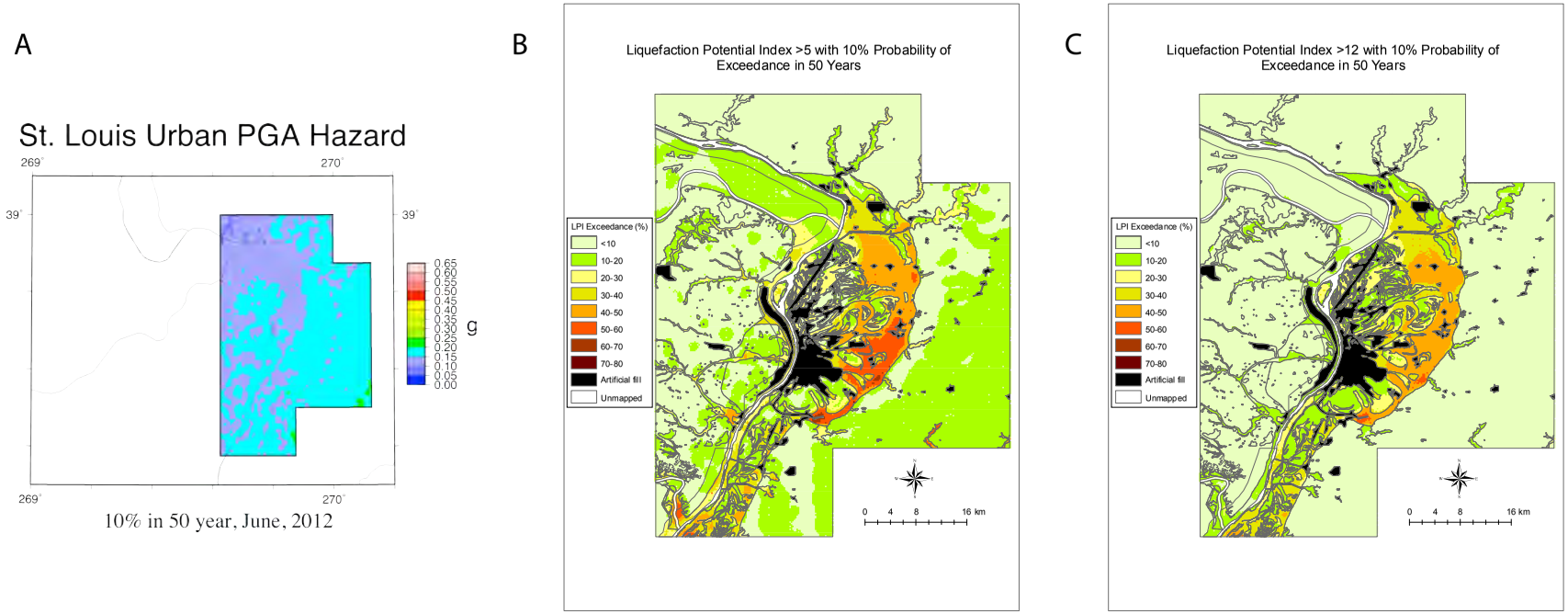

Figure 11. (A) PGA, (B) LPI>5, and (C) LPI>12 ground motion / liquefaction probabilistic hazard maps for 10% in 50 year exceedance.

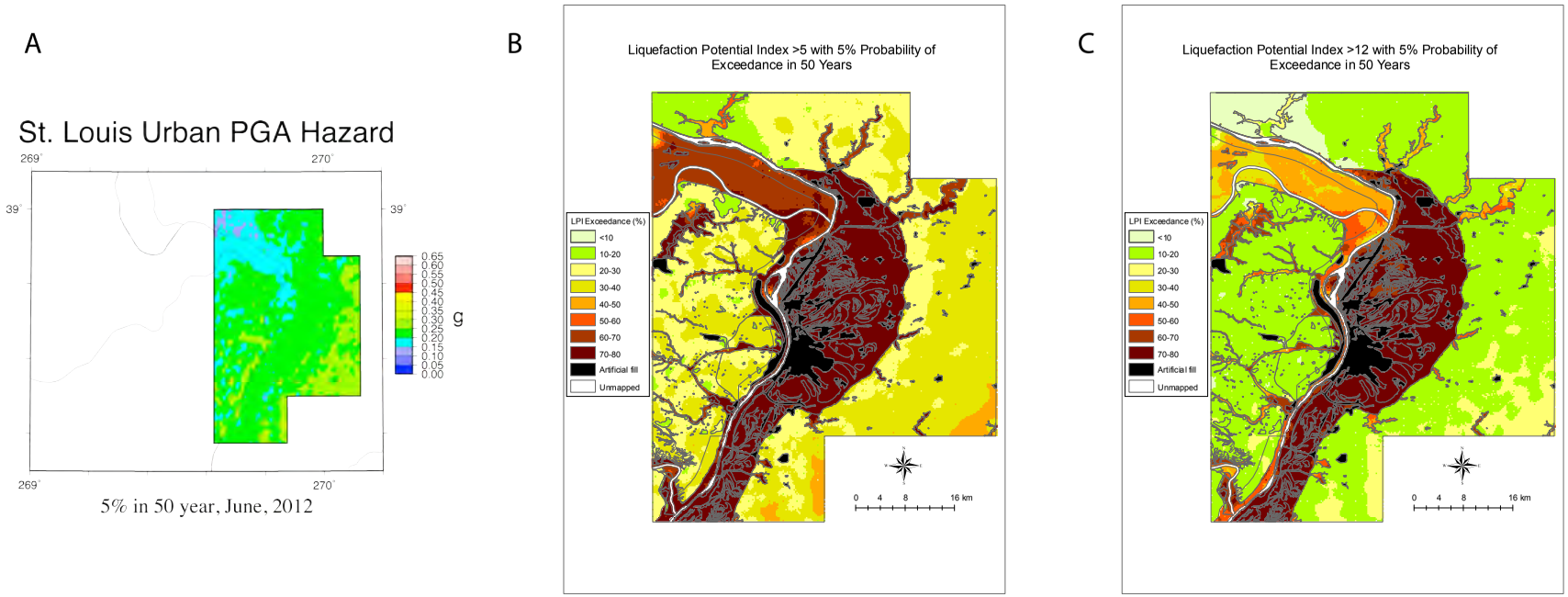

Figure 12. (A) PGA, (B) LPI>5, (C) LPI>12 ground motion / liquefaction probabilistic hazard maps for 5% in 50 year exceedance.

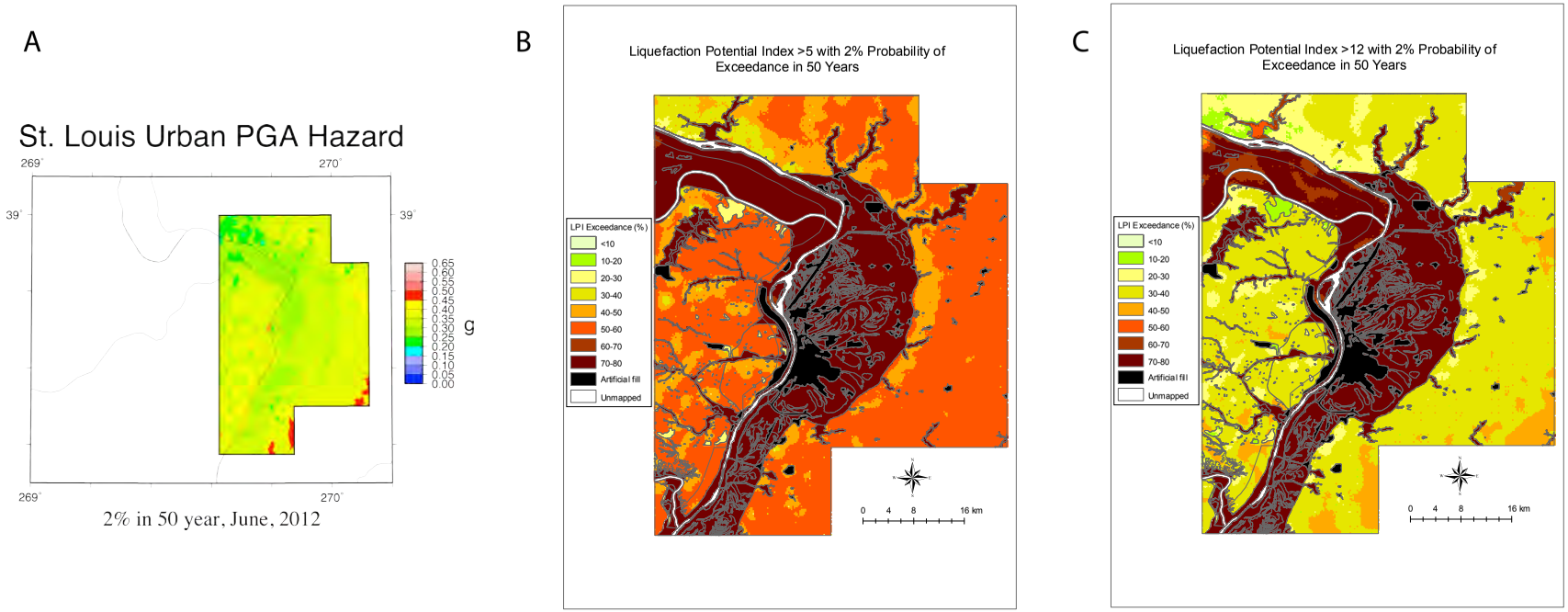

Figure 13. (A) PGA, (B) LPI>5, and (C) LPI>12 ground motion / liquefaction probabilistic hazard maps for 2% in 50 year exceedance.

An alternative interpretation of the LPI>5 liquefaction hazard maps is that they represent the percent area that will liquefy in the indicated surface geology formation during the scenario event or, in the case of the probabilistic maps, with the stated probability of being exceeded. LPI>5 is the threshold for the onset of liquefaction per our introductory discussion. Areas showing a probability for LPI exceeding 5 of less than 10% have very low likelihood of liquefaction effects at the surface. Probability of LPI>5 between 10% and 40% should have a low likelihood of liquefaction. For a probability of LPI>5 between 40% and 60%, the likelihood of liquefaction is moderate. It is severe for probabilities of LPI>5 exceeding 60%.

Remaining Issue

There is one remaining issue with the geology that needs to be resolved by the Mo DGLS and that is the possible division of the Quaternary alluvial (Qa) mapped unit into an uplands and lowlands component. The lowlands portion of the mapped Qa unit generally has depth to bedrock exceeding 20 m, while the uplands portion has a depth to bedrock less than 20 m, with a small amount of overlap. The problem is related to the Mo DGLS reference Vs profiles for the lowlands or Mississippi alluvial flood plain. The Missouri reference Vs profiles generally are not well constrained below 10 m, while the Illinois reference profiles are well constrained to 50 - 70 m (Figures 14-16).

In Figures 7-13 there is a decided shift to lower probability of exceedance in the liquefaction hazard maps for the Missouri portions of the Mississippi flood plain compared to the Illinois portions of the Mississippi flood plain. This is in part due to the PGA ground motions tailing off with distance from the source such that the transition from liquefaction to no liquefaction occurs in the vicinity of the state boundary in the Mississippi flood plain, and is a real effect of liquefaction potential based on peak ground acceleration and magnitude dependent duration of shaking. But it is also influenced to some extent by the choice of reference Vs profile governing the estimated PGA at those sites.

In the initial liquefaction hazard maps, the Mo DGLS lowlands reference Vs profiles did not cause as much amplification and hence lower PGA in the flood plains and a much stronger contrast in liquefaction hazard across the Mississippi river. Table 2 shows the PGA estimates for a test site at 38.875N, 90.25W with depth to bedrock of 38.7 and 10.0 m for the Missouri and Illinois lowlands reference Vs profiles. The Missouri-profile 38.7m estimates are consistently up to 70% of the Illinois-profile estimates (test run 1-3, 6-8), except for the Qa comparisons where the Missouri-profile estimate is 15% higher than the Illinois-profile estimate (test run 4-5). For a 10.0 m depth to bedrock the Qa PGA comparisons are similarly high ($\geq$0.120g). Based on these results, the liquefaction hazard maps shown in this report substituted the Illinois Qac and Qas profiles (IL-3 and IL-2, respectively) for the Missouri profiles. The Qa profile on the Missouri side was not changed because the Illinois profile (IL-12) estimated lower hazard and the IL-12 profile is for uplands tributary alluvial deposits, not lowlands alluvial deposits.

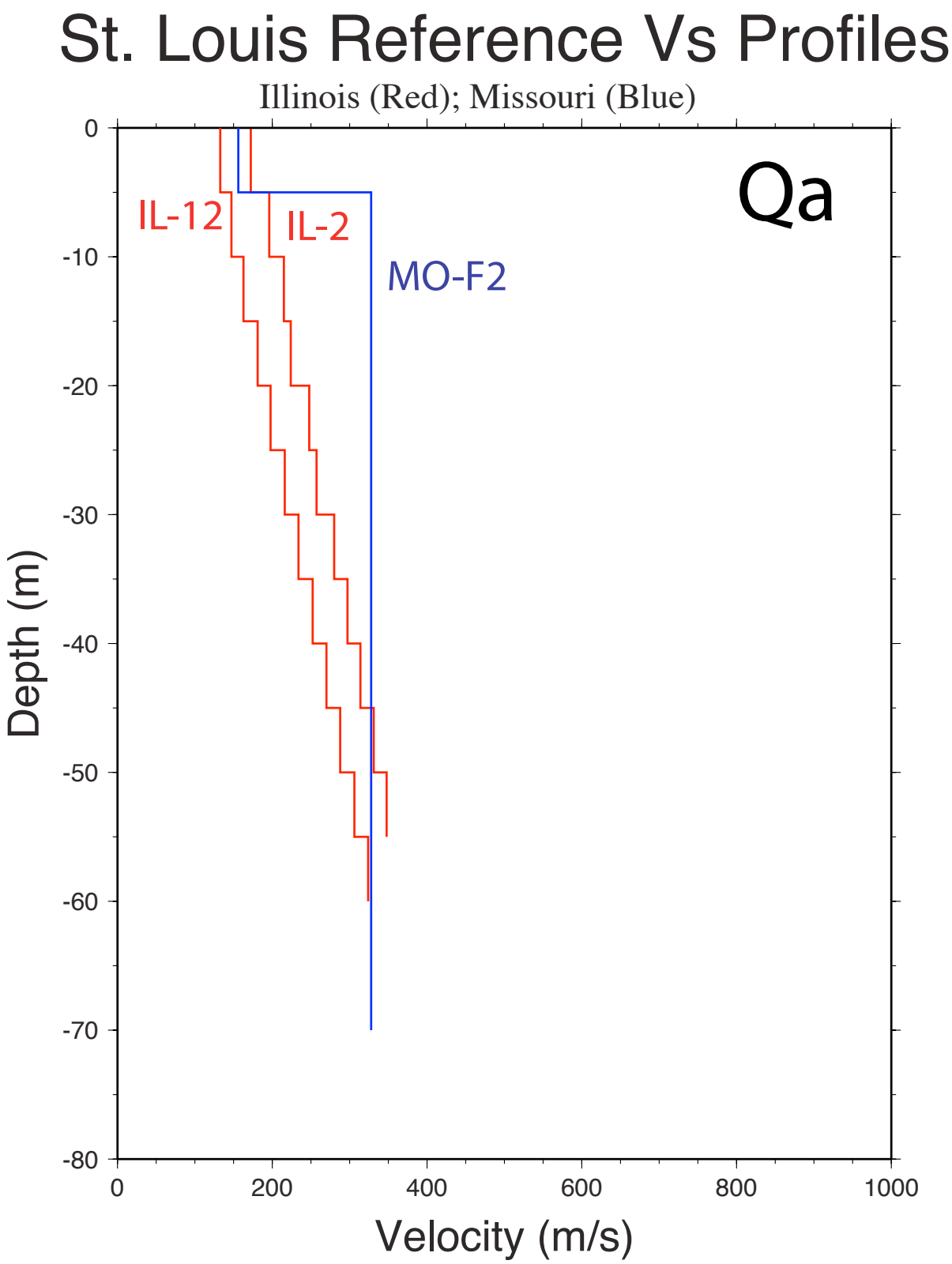

Figure 14. Comparison of Qa reference Vs profiles: IL-2 is ISGS sandy valley profile, IL-22 is ISGS tributary valleys profile, and MO-F2 is MoDGLS alluvium profile.

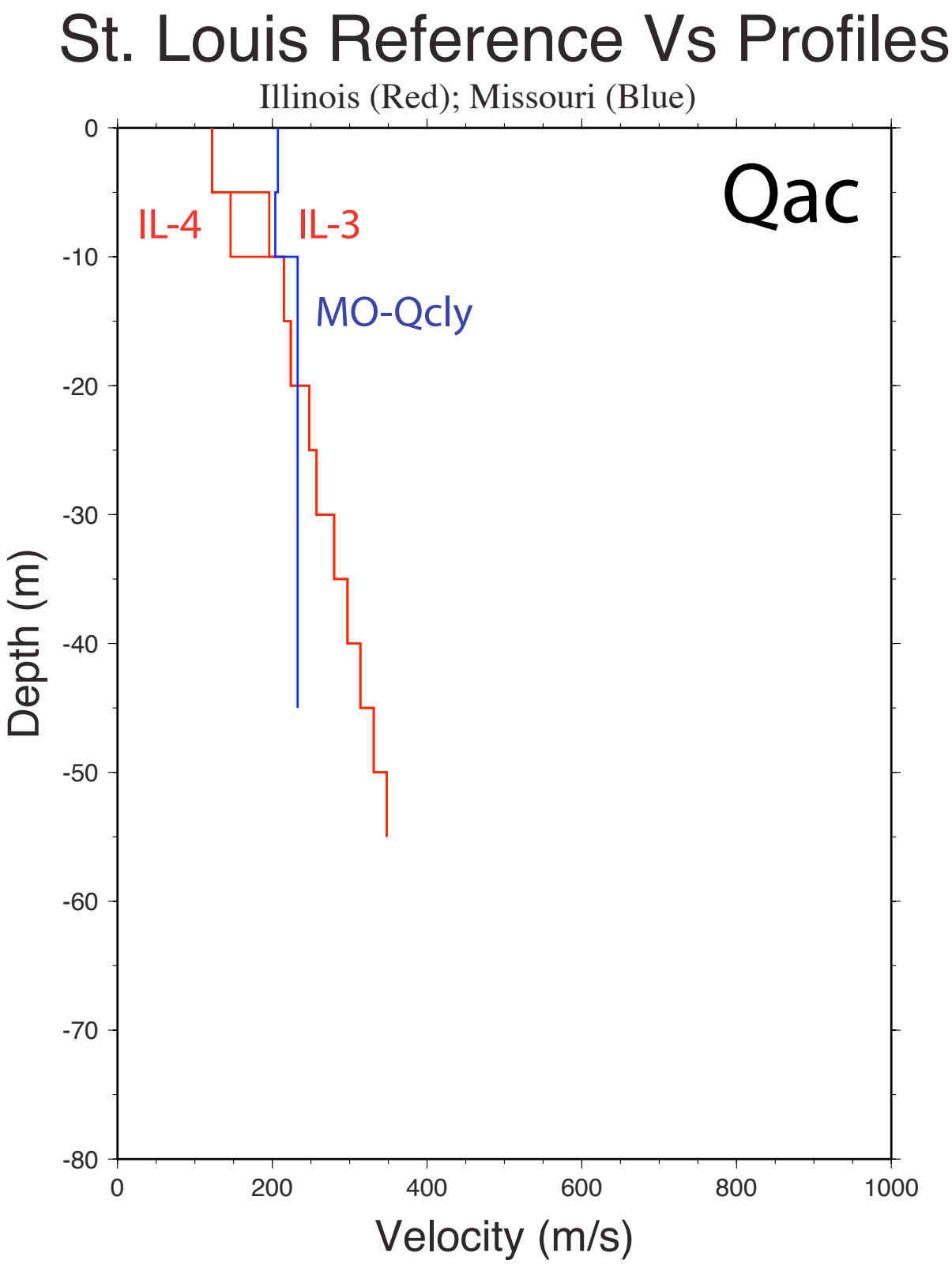

Figure 15. Comparison Qac reference Vs profiles: IL-3 is ISGS thin clay valley profile, IL-4 is ISGS thick clay valley profile, and MO-Qcly is MoDGLS clayey-alluvium profile.

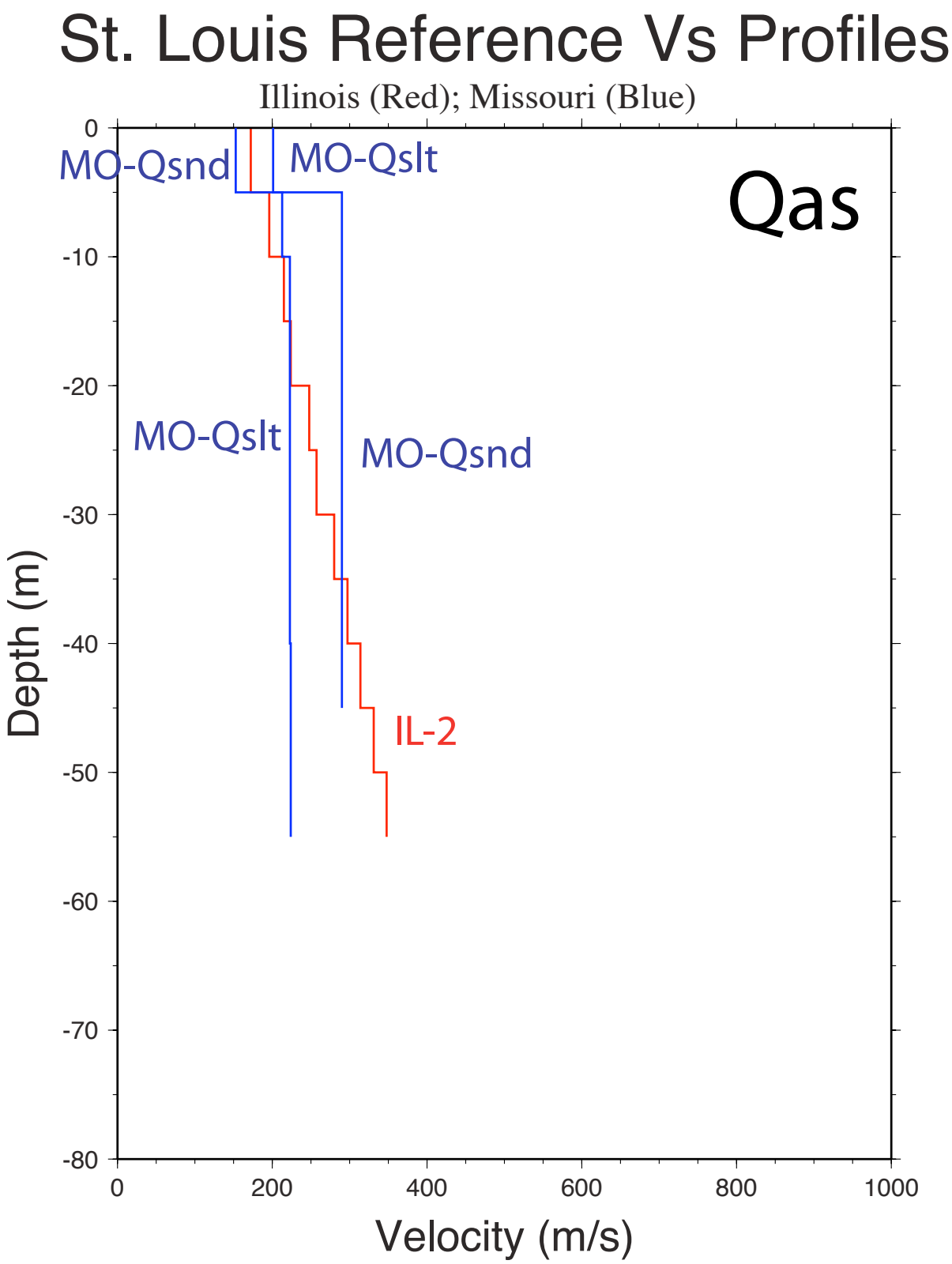

Figure 16. Comparison Qas reference Vs profiles: IL-2 is ISGS sandy valley profile, MO-Qslt is MoDGLS silty-alluvium profile, and MO-Qsnd is MoDGLS sandy-alluvium profile.

Unfortunately, the use of the Missouri Qa profile (MO-F2) in the lowlands underestimates the long period hazard by a factor of 1.5-2 (test runs 4-5, 8). So a better substitute is needed for the MO-F2 profile in the Mississippi flood plain (lowlands). One alternative would be to have Mo DGLS geologist divide the Qa between the uplands and lowlands and then substitute an appropriate Illinois Q profile in the lowlands. Another approach would be to simply discriminate Mo DGLS Qa designations by depth to bedrock (maybe at 20 m) and then substitute an appropriate Illinois Q profile for the thicker soil sites. Further examination and discussion by the SLAEHMP TWG may suggest other alternatives and should lead to a recommendation as to the best way to resolve this issue. However, the tests in Table 2 suggest that the PGAs used to generate the liquefaction hazard maps in this report will not change very much with the above suggested alternatives and hence neither will the liquefaction hazard maps, but the long period (1.0 s) seismic hazard maps should be affected.

Table 2. Estimates of PGA and 1.0s Sa at a test site at 38.875N, 90.25W in the Missouri lowlands.

Test #	Surface Geology	Ref. Vs Prof.	PGA(g)	1.0s Sa(g)
38.7 m depth to bedrock:				
1	Qac	MO – Qcly	0.086	0.110
2	Qac	IL – 3	0.129	0.112
3	Qac	IL – 4	0.127	0.120
4	Qa	MO – F2	0.109	0.072
5	Qa	IL – 12	0.095	0.157
6	Qas	MO – Qslt	0.083	0.124
7	Qas	MO – Qsnd	0.109	0.076
8	Qas	IL – 2	0.114	0.108
10.0 m depth to bedrock:				
9	Qa	MO – F2	0.120	0.048
10	Qa	IL – 12	0.126	0.059
11	Qa	IL – 2	0.144	0.053

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Publications from this Research

No publications have resulted from this research as of this date. Future papers based on this work will be provided, as required, when publication occurs.

Appendix

Table A1. Regression Statistics for Weibull Equation.

Geologic Unit		Groundwater Level	LPI	Regression Coefficient				R^2
				a	b	c	X_0	
Low-lying floodplains	Qa	High	LPI>5	0.7851	0.0224	0.6093	0.1199	0.9967
			LPI>12	0.7539	0.0522	0.9356	0.1472	0.9970
		Normal	LPI>5	0.6366	0.1036	1.3630	0.1940	0.9954
			LPI>12	0.5702	0.1289	1.2010	0.2494	0.9968
	Qa(C)	High	LPI>5	0.7886	0.0108	0.6288	0.1091	0.9984
			LPI>12	0.7906	0.0231	0.5745	0.1230	0.9972
		Normal	LPI>5	0.7744	0.0703	1.2870	0.1632	0.9936
			LPI>12	0.7693	0.1048	1.1740	0.2255	0.9947
	Qa(S)	High	LPI>5	0.7968	0.0120	0.7968	0.1108	0.9978
			LPI>12	0.7955	0.0267	0.7067	0.1251	0.9924
		Normal	LPI>5	0.7829	0.0580	0.8447	0.1759	0.9920
			LPI>12	0.7729	0.1139	1.2040	0.2474	0.9928
	Qf	High	LPI>5	0.7843	0.0306	1.3580	0.1196	0.9958
			LPI>12	0.7426	0.0424	1.1970	0.1316	0.9974
		Normal	LPI>5	0.7389	0.0258	0.9114	0.1553	0.9956
			LPI>12	0.7158	0.0422	0.6161	0.1967	0.9884
	Qld	High	LPI>5	0.8038	0.0179	0.5673	0.1193	0.9923
			LPI>12	0.7762	0.0497	1.0670	0.1446	0.9978
		Normal	LPI>5	0.7022	0.0721	1.2410	0.1971	0.9909
			LPI>12	0.6652	0.1079	1.1010	0.2670	0.9969
	Qo	High	LPI>5	0.7667	0.0325	0.9235	0.1218	0.9984
			LPI>12	0.7148	0.0624	0.8399	0.1583	0.9932
		Normal	LPI>5	0.5463	0.1654	1.0880	0.2544	0.9772
			LPI>12	0.4778	0.2013	1.8490	0.3507	0.9903
	af	High	LPI>5	0.7752	0.0146	0.7608	0.1120	0.9994
			LPI>12	0.7802	0.0330	0.7607	0.1313	0.9971
		Normal	LPI>5	0.6299	0.0989	1.7050	0.1872	0.9939
			LPI>12	0.6298	0.1335	1.0940	0.2630	0.9979
Uplands	Ql	High	LPI>5	0.7159	0.0718	1.0530	0.1534	0.9976
			LPI>12	0.6494	0.1076	1.3890	0.1898	0.9964
		Normal	LPI>5	0.2634	0.1608	0.9990	0.3032	0.9964
			LPI>12	0.1558	0.2389	2.4300	0.3793	0.9981
	Qt	High	LPI>5	0.6870	0.0668	0.8854	0.1542	0.9975
			LPI>12	0.6045	0.0911	1.3590	0.1966	0.9930
		Normal	LPI>5	0.2635	0.2030	0.7729	0.3251	0.9944
			LPI>12	0.2206	1.2960	0.4311	0.8354	0.9890
	af	High	LPI>5	0.6796	0.0298	0.9545	0.1218	0.9996
			LPI>12	0.6170	0.0382	1.5250	0.1341	0.9989
		Normal	LPI>5	0.6446	0.0671	0.4885	0.2294	0.9926
			LPI>12	0.5720	0.0513	0.7059	0.3108	0.9989
	R	High	LPI>5	0.4425	0.1297	0.7950	0.1943	0.9935

	LPI>12	0.3636	0.1106	0.8186	0.2119	0.9948
Normal	LPI>5			n.a		
	LPI>12			n.a		

a, *b*, *c*, and x_0 = fitted coefficients; R^2 = coefficient of determination