Creation of a Geologic GIS database for the St. Louis Metropolitan Area, Missouri and Illinois

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Final Technical Report

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ABSTRACT

The purpose of this study was to construct seven geodata layers in a Virtual Geotechnical Database (VGDB) in a Geographic Information Systems (GIS) for the St. Louis Metropolitan area of Missouri and Illinois. This process involved combining vast quantities of dissimilar geologic, hydrologic, geophysical, and topographic data from a number of public agencies and private sector sources that were stored in dissimilar analog and electronic formats. All of these data were then georeferenced and entered into the ArcGIS architecture for quick reconnaissance and dissemination. These information layers include: 1) surficial geology; 2) loess thickness; 3) bedrock geology; 4) well locations; 5) measured shear wave velocities and their respective locations, 6) depth to bedrock basement; and, 7) groundwater level. Depths to bedrock and groundwater levels between sampled sites were interpolated using geostatistical techniques.

1. INTRODUCTION

In 2004 the St Louis Metropolitan area (*STL*) was identified by the U.S. Geological Survey (USGS) Earthquake Hazard Program's (EHP) plan as one of three urban areas slated for detailed study in the Central and Eastern United States (CEUS) for the next decade. It's intended purposes were to: 1) develop an internet-accessible database for use by scientists, engineers, insurance industry, government agencies, as well as the public; 2) produce natural hazards maps for seismically-induced ground movement hazards, such as lateral spread and liquefaction; and, 3) reduce the risks of hazards posed by earthquakes likely to emanate from the New Madrid Seismic Zone (NMSZ) in the Upper Mississippi Embayment, which is the most active seismic zone in Midwestern United States (Figure 1).

The STL is located between Missouri and Illinois, which are split by Mississippi River. Both state surveys have employed different mapping criteria (depositional environment versus map units), disparate mapping scales, and dissimilar storage systems. As a result, there has rarely been any over-arching geodatabase or protocol established to conjoin existing geologic, hydrologic, or geotechnical records in the STL area, even though the USGS attempted to compile consistent geologic maps across the state boundary during the 1990s (Harrison, 1997; Schultz, 1993) of the St Louis 30’ × 60’ quadrangle at 1:100,000 scale, based on the existing data sources. The St Louis 30’ × 60’ quadrangle covers the 22 USGS 7.5-minute quadrangles of STL study area, which consists of 29 USGS 7.5-minute quadrangles (described later).

The collection of geodata into a single Virtual Geotechnical Database (VGDB) for the STL is intended to encourage scientists and engineers to standardize geologic interpretations and use the database to construct earthquake hazard maps, using the protocol being established in the pilot study by Karadeniz (2007), under the review of the St. Louis Area Earthquake Hazard Mapping Project-Technical Working Group (SLAEHMP-TWG). The accurate locations of water wells and geotechnical borings are crucial metadata for assessing hazards because the physical spacing between these data points influences the uncertainty of predicted positions, between the borings or wells. For example, there is the paucity of reliable subsurface data in the undeveloped portion of eastern St. Charles County, in the lowland flood plain bordering the confluence of the Missouri and Mississippi Rivers. The baseline geodata layers in the VGDB have enabled researchers to assign increased levels of uncertainty in the ‘data gaps’ and allow the SLAEHMP-TWG to establish priorities for subsurface exploration and geophysical evaluations during the balance of the multi-year EHP.

The objectives of this research were to 1) collect and digitally input existing geodata (surficial geology, loess thickness, bedrock geology, well collar locations, and the measured values and locations of shear wave velocity (V_S) tests and 2) interpolate depths to bedrock basement formations and groundwater elevations between measured data points using geostatistical techniques. These tasks were performed with an ArcGIS v.9.1 from Environmental System Research Institute (ESRI). Whenever possible, this study used the Universal Transverse Mercator (UTM) grid coordinates, which are expressed as distance in meters to the east and north. UTM Zone 15 covers Missouri and western Illinois within the STL, whereas eastern Illinois lies within UTM Zone 16.

2. STUDY AREA

The study area encompasses 29 USGS 7.5-minute quadrangles in the greater STL of Missouri and Illinois, encompassing a land area of 4,432 km^2 (Figure 1). The STL consists of St. Charles, St. Louis, and Jefferson counties in Missouri and portions of Jersey, Madison, St. Clair, and Monroe counties in Illinois. This area is located near known seismic sources, the New Madrid Seismic Zone (NMSZ) in the upper Mississippi embayment and the Wabash Valley Seismic Zone (WVSZ) in southeastern Illinois and southwestern Indiana, which have produced prehistoric and historic earthquakes. The topographic elevations in the study area range between 116 m to 288 m above mean sea level (1989 NGVD). The STL includes the confluences of the Missouri, Illinois, and Meramec Rivers with the Mississippi River, and it includes low-lying alluvial floodplains developed along these four major rivers, which are bounded by loessal uplands. Bergstrom and Walker (1956) reported that the alluvial fill in the Mississippi River was consistently deeper than 33m, with the deepest part up to 51m, on the Illinois side.

3. COMPILATION OF GEODATA

3.1. SURFICIAL GEOLOGIC MAP

The surficial geology map is intended to characterize the unconsoililidated sediments capping the Paleozoic age bedrock basement. These materials are collectively referred to as the “soil cap” by many engineering seismologists and they can exert a profound influence on seismic site response because of impedance contrasts at the interface between the bedrock and the unconsolidated cover. Surficial geologic maps were collected from the publications of the MoDGLS, the ISGS, and the USGS. These data sources (17) were used in compiling the surficial geologic map of the STL, presented in Figure 2 (the surficial geology of Jefferson County, Missouri, has not been mapped at a useful scale (<1:100,000) and, thus remains unmapped in this project). A stratigraphic unit and correlation, recognized in Missouri and Illinois by Schultz (1997) and the ISGS, are presented in Table 1, and the compiled map is shown in Figure 2.

3.2. LOESS THICKNESS MAP

It has been recognized that loess thickness affects soil development and productivity, as well as soil management for engineering and other uses (Fehrenbacher et al., 1986; Su, 2001). The physical properties of loess can cause numerous engineering challenges, due to its unconsolidated nature and uniform silt-size grains. The Peoria silt and the underlying Roxana silt form the two major loess deposits in the STL, both of which are interpreted as windblown deposits of Wisconsinan age. A much older sequence of loess was deposited during the Illinoian Episode, called the Loveland Loess (Fehrenbacher et al., 1986; Goodfield, 1965). The loess is thickest along the bluffs bordering the modern Missouri and Mississippi valleys and thins rapidly away from these bluffs (Allen and Ward, 1977; Fehrenbacher et al., 1986; Goodfield, 1965; Grimley et al., 2001). The further removed the loess is from the major river valleys, the more fine-grained its grains become. The five data sources and the compiled map illustrating the total reported thickness of loess (combination of Peoria loess and Roxana units in feet) are presented in Figure 3.

3.3. BEDROCK GEOLOGY

Bedrock geologic maps provide information on 1) the host rock and geologic structure, including economic mineral deposits such as coal and petroleum, and 2) the stability of structure foundations and road cuts (Devera, 2004; Devera and Denny, 2003; Satterfield, 1977). Paleozoic age bedrock basement rocks, dominated Mississippian carbonates and Pennsylvanian shales, influence the fundamental shape of the land surface in the STL. The oldest exposed rock in the STL area is an Ordovician formation found in

Jefferson County. The Paleozoic bedrock units underlying the Mississippi River flood plain are not defined on the Missouri side, but are on Illinois side.

The major geologic structures in the study area are described in detail by Harrison (1997), Denny (2003), and Devera (2000, 2004). The geologic structures were plotted on the basis of existing maps in hardcopy form (Devera, 2000; Harrison, 1997) and GIS digital format in the Missouri Environmental Geology Atlas (MEGA; MoDGLS, 2006). The map symbol and unit correlation are shown in Table 2. The five data sources and complied seamless bedrock geologic map of STL is shown in Figure 4.

3.4. BOREHOLE INFORMATION

Borehole records of geotechnical logs, stratigraphic borings, and water wells are extremely useful reference data for geologic, hydrologic, and geotechnical applications. The existing borehole information databases were provided from the MoDGLS (Palmer et al., 2006) and the ISGS (Bauer 2007, personal commun.). The borehole records covered 2,394 sites in Missouri and 4,817 sites in Illinois over STL. Table 3 shows a tabulation of boring type (originally classified by MoDGLS and ISGS) and the respective number of borehole records used in the subject study. The GIS map (Figure 5) presents boring locations and types of the STL.

3.5. SHEAR WAVE VELOCITY AND SITE AMPLIFICATION

The simplest way of accounting for site conditions is to consider the impedance contrast likely to be generated at the bedrock/soil cap interface beneath a site of interest. This estimate is commonly made by comparing the shear wave velocity (V_S) of the shallow subsurface with that of the weathered and less weathered or unweathered rock lying beneath the site. Seismic shaking tends to increase where sites are underlain by low density (unconsolidated) sediments with low shear wave velocity (V_S). A total of 117 shear wave velocity (V_S) profiles were measured and provided to this study by the University of Missouri-Rolla (UMR; Hoffman 2007, personal commun.), the USGS (Williams 2007, personal commun.; Williams et al., 2007), and the ISGS (Bauer 2007, personal commun.). For the MASW profiles not extending to 30m, the velocity from 20m to 30m was assumed to be constant (Hoffman 2007, personal commun.). Figure 6 shows the distribution of measuring agencies, and average values of V_S in the upper 30m (V_S^{30}) at test sites.

4. INTERPOLATION OF GEODATA

4.1. ESTIMATION OF DEPTHS TO BEDRCOK SURFACE

The position of the bedrock-soil cap interface is of great import to assessments of seismic site response (Kramer, 1996; Borcherdt et al., 1991). Knowledge of the likely elevation of the bedrock-soil cap interface is also crucial to the interpretation of shear wave velocity data recorded at the ground surface, upon unconsolidated materials overlying the bedrock basement. Sites underlain by thick accumulations (>14m) of unconsolidated sediments appear to be more prone to magnification of ground motion than those on shallow bedrock in the STL (Rogers et al, 2007).

Data Set

In this study, the subsurface data for defining depth to bedrock consist of geotechnical borings and seismic reflection interpretations. Geotechnical boring records were supplied by the MoDGLS, the ISGS, the MEGA (MoDGLS, 2007), the URS Corporation, and Missouri departments of transportation (MoDOT). Seismic reflection profiles were measured and interpreted by Williams et al (2007). These datasets were classified into data type, state, and landform, as summarized in Table 4.

Method

Ordinary kriging with the spherical model was employed to interpolate depth to bedrock surface between measured sites in uplands and flood plains. Kriging is a geostatistical technique commonly used to estimate values at unsampled locations between known data points, using a linear estimation procedure. Detailed discussions of kriging can be found in Journel and Huijbregts (1978), Isaaks and Srivastava (1989), and Kelkar and Perez (2002). Using ordinary kriging, the estimated value at an unsampled location is obtained by

$$X^*(u_0) = \sum_{i=1}^{n} \lambda_i X(u_i)$$

where $X^*(u_0)$ = estimated value at a location, u_0, $X(u_i)$ = sample value at a location u_i, and λ_i= weighting factor.

Using the kriging technique provided by ArcGIS v. 9.1 software, two interpolation maps of the depth-to-bedrock surface were initially generated: 1) one using 5,104 borings logs and 17 seismic reflection profiles that pierced the bedrock basement, and, 2) a minimum depth-to-bedrock map interpolated from 8,260 boring logs and 17 seismic reflection profiles, which included borings that did not pierce bedrock interface. The resulting depth-to-bedrock map was refined by discarding minimum depth interpolation values that were shallower than the depths predicted by the depth-to-bedrock map and by including minimum depth interpolations that were deeper than those elevations predicted by the depth-to-bedrock map. The bedrock outcrops exposed along the river bluffs were then added to final map in order to portray the data more realistically for the bedrock topography map. The maps of kriging and corresponding standard error are shown in Figure 7.

4.2. ESTIMATION OF THE DEPTH TO GROUNDWATER TABLE

The elevation of the permanent groundwater table and its relative position with respect to sloping ground surfaces are important factors in geoengineering assessments of geoenvironmental, geotechnical, and hydrogeologic conditions. Natural hazards such as landslides, shaking-induced liquefaction, and lateral spreading are all driven by pore pressure imbalances, driven by relatively short-term changes in groundwater conditions.

Water table contouring has long been used to estimate the preferred paths of the groundwater flow, recharge, and loss assessments.

Data Set

The input data of groundwater elevation in the STL consisted of the following components: 1) 1,069 well logs obtained from the MoDGLS and the ISGS, recorded between January 1959 to December 2005, 2) 469 elevations (about 1 km apart) along the major river channels interpolated from digital raster graphics (DRGs; scale 1: 24,000), and 3) 2,100 data points along perennial water courses taken from hydrography digital line graphics (DLG). The ground surface elevation of data points of 2) and 3) were extracted from 10m digital elevation models (DEM). The water table elevations in perennial streams and rivers were assumed equal to the ground surface elevation. These were used to prevent geostatistical technique from over- or underestimating the groundwater table where the data points are lack. The locations of the well logs and interpolated water table elevations are shown in Figure 8.

Method

In this study, cokriging was employed to realistically estimate the elevation of the groundwater table across the STL. Cokriging can improve the estimate by considering a bounding ground surface elevation as a second variable (Hoeksema et al., 1989). Cokriging, a multivariate extension of kriging, presumes that the principal variable of interest (groundwater table in this study) and the covariable (ground surface elevation) are spatially related to each other. The equation employed by cokriging to estimate a datum in unsampled locations can be written as

$$X^*(u_0) = \sum_{i=1}^{n} \lambda_{X\,i} X(u_{X\,i}) + \sum_{k=1}^{m} \lambda_{Yk} Y(u_{Yk})$$

$$\sum_{i=1}^{n} \lambda_{X\,i} = 1 \textit{ and } \sum_{k=1}^{m} \lambda_{Y\,i} = 0$$

where $X^*(u_0)$ = estimated value at location, u_0, $X(u_{Xi})$ = sample value located at u_{Xi}, $Y(u_{Yk})$ = covariable value located at u_{Yk}, λ_{Xi} = weighting factor at $X(u_{Xi})$, and λ_{Yi} = weighting factor at $\mathrm{Y}(u_{Yk})$.

The ground surface elevation points (500m × 500m spaced elevation points extracted from 30m × 30m DEMs using MICRODEM software) were employed as second cokriging variables. Figure 9 presents the map of predicted groundwater elevations based on cokriging and the corresponding estimation error map.

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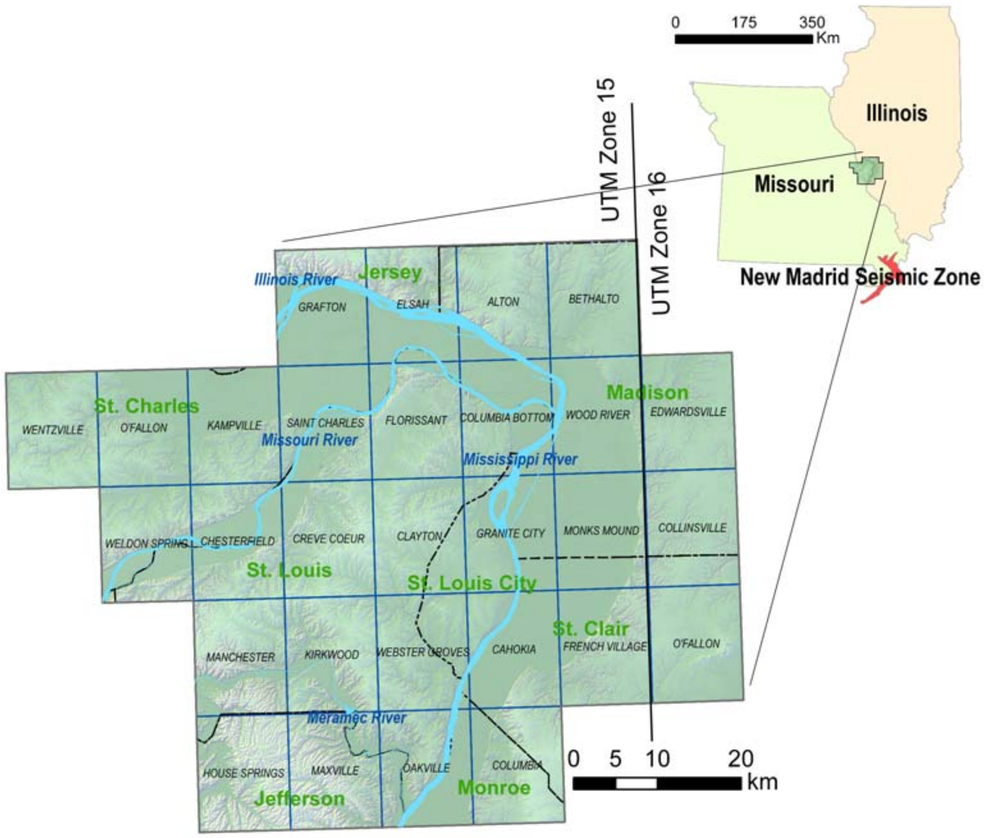


Figure 1. The St. Louis Metropolitan area, Missouri and Illinois, as defined for this study, consists of 29 USGS quadrangles, which are georeferenced to Universal Transverse Mercator (UTM) Zones 15 and 16. The southern St. Louis Metro area is approximately 200 to 300 km north of the New Madrid Seismic Zone (NMSZ).

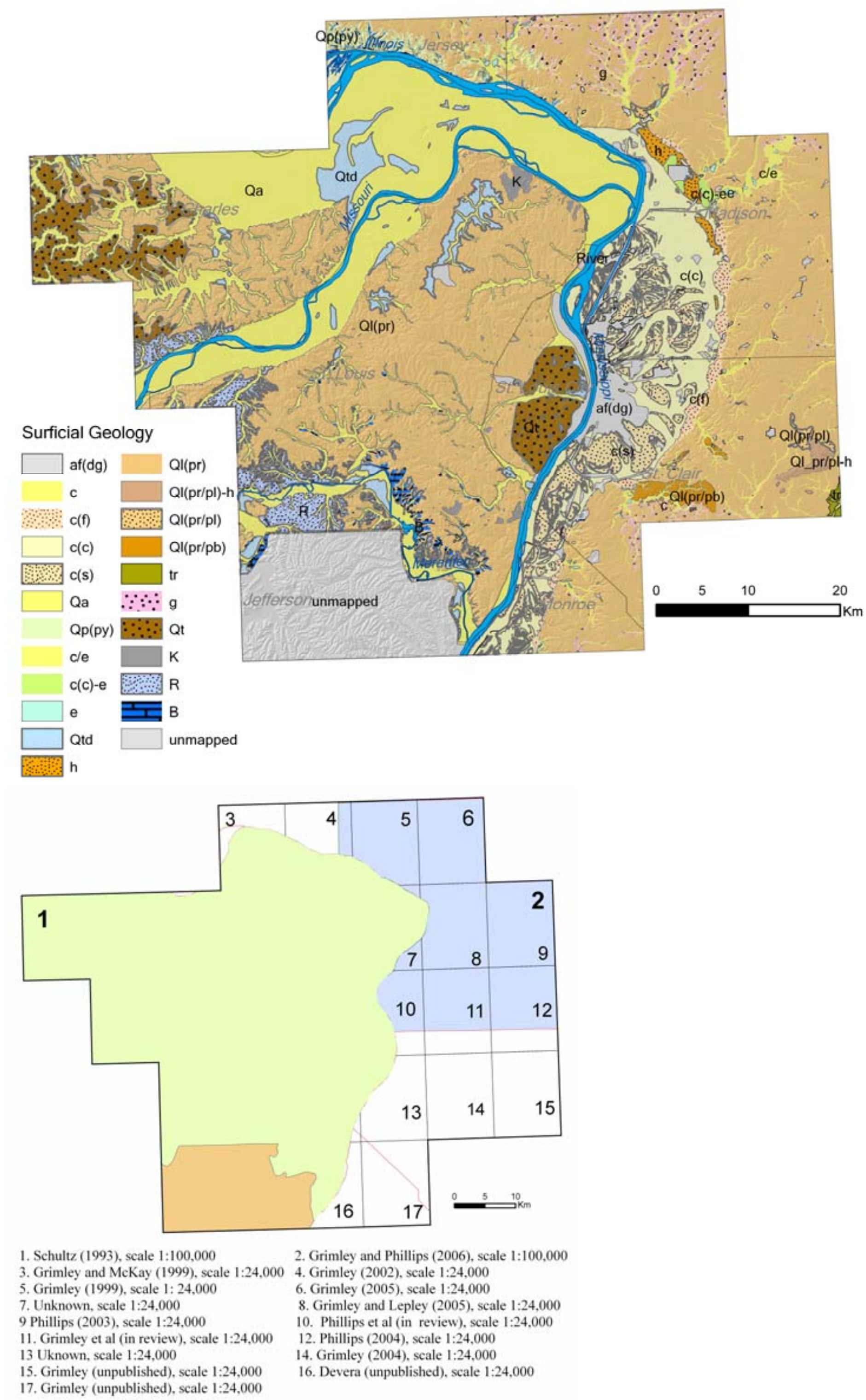
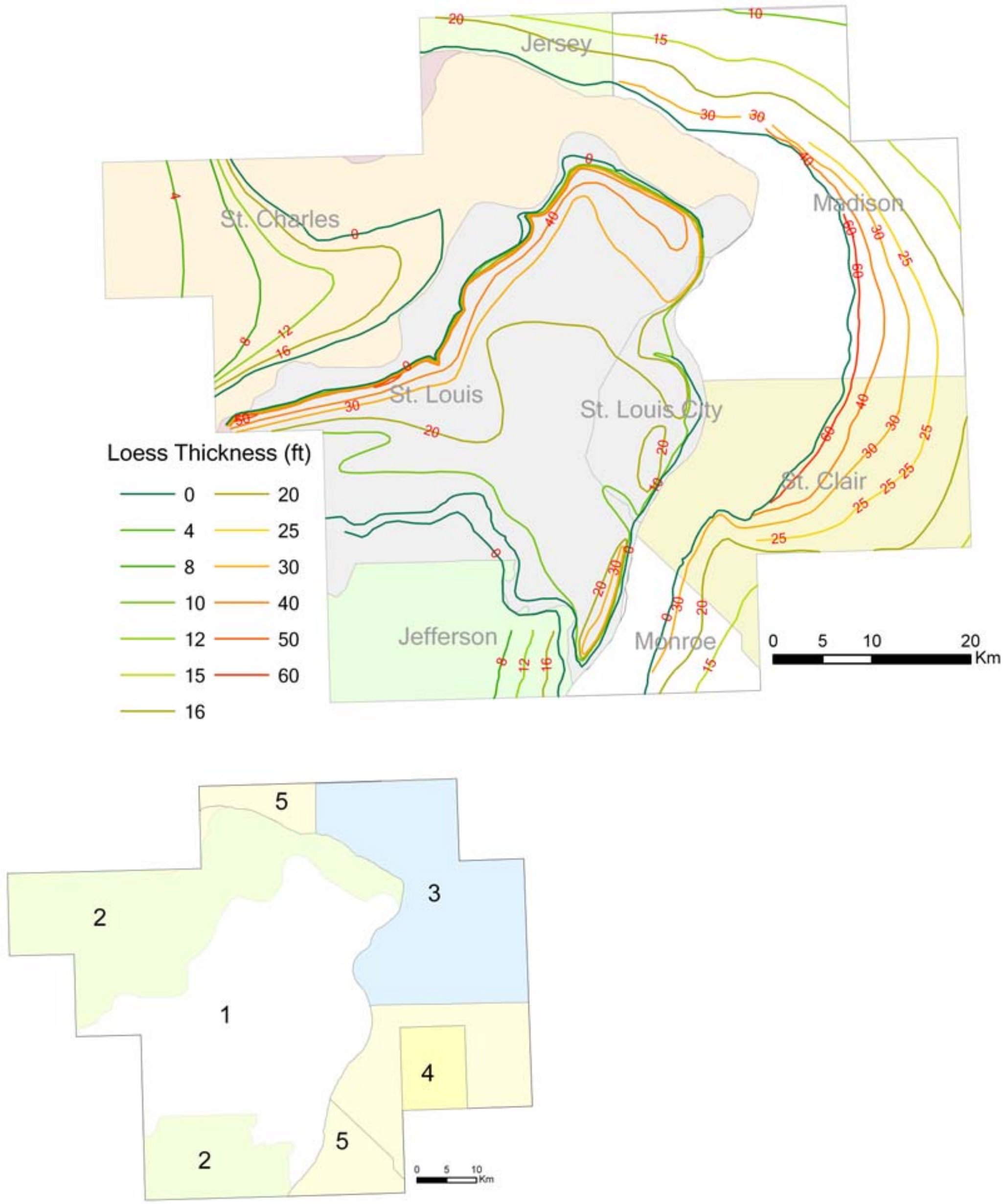


Figure 2. Compiled surficial geologic map and data sources of the St. Louis Metropolitan area in a GIS vector format. Note unmapped area in Jefferson County, Missouri.

Table 1. Correlation of recognized surficial geologic units and map symbols used in the St. Louis Metropolitan area, Missouri and Illinois.

Time Scale	Interpretation	**This study**	**Missouri (Schultz, 1993)**		**Illinois (ISGS publications)**	
		Symbol	Symbol	Unit	Symbol	Unit
Holocene (post-glacial)	Man-made fill or cut	**af(dg)**	af	Artificial fill	dg	Disturbed Ground
	Residuum	**R**	R	Residuum		
	Alluvium	**Qa or c**	Qa	Alluvium	c	Cahokia Fm
	Alluvial or colluvial fans	**c(f)**	Qa	Alluvium	c(f)	Cahokia-Fan
	Alluvium (backswamp, channel-fill or overbank)	**c(c)**	Qa	Alluvium	c(c)	Cahokia-Clayey
	Alluvium (point bar or channel)	**c(s)**	Qa	Alluvium	c(s)	Cahokia-Sandy
	Colluvium	**Qp(py)**	Qp	Peyton	py	Peyton Fm
Holocene over Pleistocene	Alluvium over lake deposits	**c/e**			c/e	Cahokia Fm over Equality Fm
	Alluvium (clayey) or lake deposits	**c(c)-e**			c(c)-e	Cahokia-Clayey or Equality Fm
Pleistocene (Wisconsinan)	Lake sediment (slackwater)	**Qtd or e**	Qtd	Terrace deposits	e	Equality Fm
	Outwash	**h**			h	Henry Fm
	Loess	**Ql(pr)**	Ql	Loess	pr	Peoria and Roxana Silts (pr)
Pleistocene (Wisconsinan over Illinoian)	Loess over ice-contact drift	**Ql(pr/pl-h)**			pr/pl-h	(pr) over Pearl Fm-Hagarstown M
	Loess over outwash	**Ql(pr/pl)**			pr/pl	(pr) over Pearl Fm
	Loess over till over lake sediment	**Ql(pr/pb)**			pr/pb	(pr) over Glasford Fm-Petersburg Silt
Pleistocene (Illinoian)	Lake sediment	**Qtd or tr**	Qtd	Terrace deposits	tr	Teneriffe Silt
	Till and ice marginal sediment	**Qt or g**	Qt	Till	g	Glasford Fm
Pre-Illinoian (Kansan)	Till	**Qt**				
		K	K	Karst		
Paleozoic	Bedrock	**B**	B	Bedrock	R	

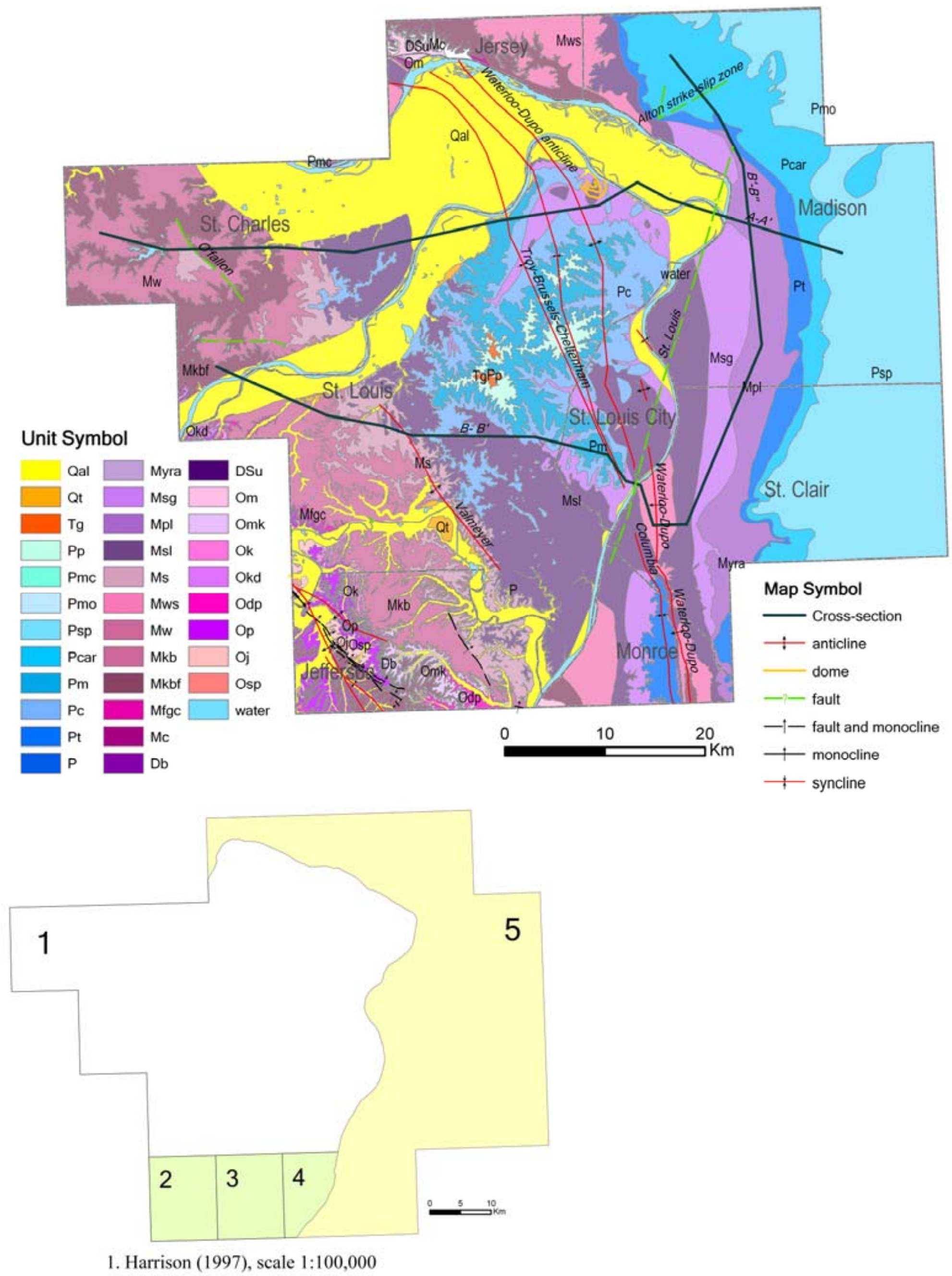


1. Goodfield (1965), scale 1:62,500
2. Thorp and Smith (1952), scale 1:2,500,000
3. Grimley and Phillips (2006), scale 1:100,000
4. Grimley and McKay (2004), scale 1:24,000
5. Grimley (2007, personal communication)

Figure 3. Isopach map showing the combined thickness and data sources of loess deposits of varying age in the St. Louis Metropolitan Area. Loess deposits are locally absent in the floodplains, thickest along the river bluffs bordering the Missouri and Mississippi rivers, and thin rapidly with increasing distance from the main river valleys.

Table 2. Stratigraphic correlations between recognized bedrock geologic units and corresponding map symbols used in the St. Louis Metropolitan area, Missouri and Illinois.

ERA	SYSTEM	SERIES	FORMATION	SYMBOL		
CENOZOIC	Quaternary	Holocene	Alluvium	Qal		
		Pleistocene	Terrace Deposit	Qt		
			Unconformity			
MESOZOIC	Tertiary	Pliocene	Grover Gravel	Tg		
		Miocene				
			Unconformity			
PALEOZOIC	Pennsylvanian	Missourian	Pleasanton Group	Pp		P
		Desmoneisian	Modesto Formation/McLeansboro Group	Pmo	Pmc	
			Shelburn-Patoka	Psp		
			Carbondale	Pcar		
			Marmaton Group	Pm		
			Cherokee Group	Pc		
		Atokan	Tradewater	Pt		
			Unconformity			
	Mississippian	Chesterian	Yankeetown Sandstone	Myra		
			Renault Limestone			
			Aux Vases Sandstone			
			Ste. Genevieve Limestone	Msg		
			Lower Pope Group	Mpl		
			Unconformity			
		Meramerician	St. Louis Limestone	Msl		
			Salem	Ms	Mws	
			Warsaw	Mw		
		Osagean	Keokuk-Burling Limestone	Mkb	Mkbf	
		Kinderhookain	Fern Glen and Bachelor	Mfgc		
			Chouteau Limestone		Mc	
			Unconformity			
	Devonian	Upper Devonian	Bushberg Sandstone and Glen Park Limestone	Db		
	Silurian			Su		
			Unconformity			
	Ordovician	Cincinatian/ Champlainian/Mohawkian	MaQuoketa Shale	Om	Omk	
			Cape Limestone/Kimmswick Limestone	Ok	Okd	
		Champlainian/Mohawkian	Decorah		Odp	
		Mohawkian	Plattin Limestone	Op		
			Joachim Dolomite	Oj		
			St. Peter Sandstone	Osp		



1. Harrison (1997), scale 1:100,000
2. Whitfiled (2002), scale 1:24,000
3. Stincomb and Fellows (2002), scale :1:24,000
4. Middendorf and Brill (2002), scale 1:24,000
5. Kolata (2005), scale 1:500,000

Figure 4. Data sources and compiled bedrock geologic map of the St. Louis Metropolitan Area in a seamless GIS vector format.

Table 3. Borehole purpose and information contained on logs used for the St. Louis Metropolitan area study, Missouri and Illinois.

State	Borehole purpose	# of records	Information noted on logs
Missouri	Bedrock	2338	Depth to bedrock, Bedrock type
	Core log	729	Core recovery (%), Rock Quality Designation (RQD)
	Grain Size	93	Grain size analysis of soil
	Material	2330	Description of soil material
	Physical Property	1906	Standard Penetration Test (SPT) N-value, Cone Penetration Test (CPT), ASTM class, Unit weight (water content,%), Liquid limits, and Plastic index
	Water Observation	961	Depth to groundwater
	Site	2394	
Illinois	Highway Log	857	Description of soil material
	Highway Engineering	496	Standard Penetration Test (SPT) N-value
	Highway Head	2226	Description of geotechnical boring
	Log	3636	Description of soil material
	Water Well	4728	Description of water well
	Site	4817	

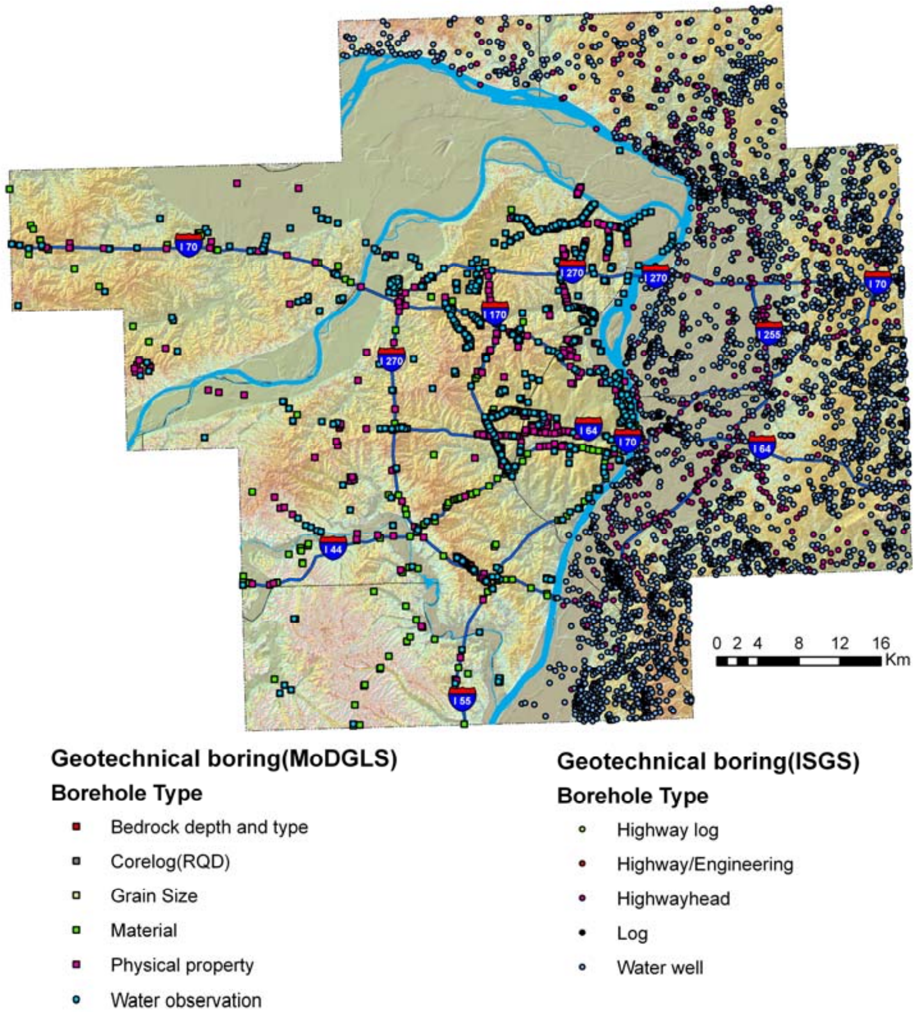


Figure 5. Borehole locations and types in the St. Louis Metropolitan area, Missouri and Illinois in a seamless GIS vector format.

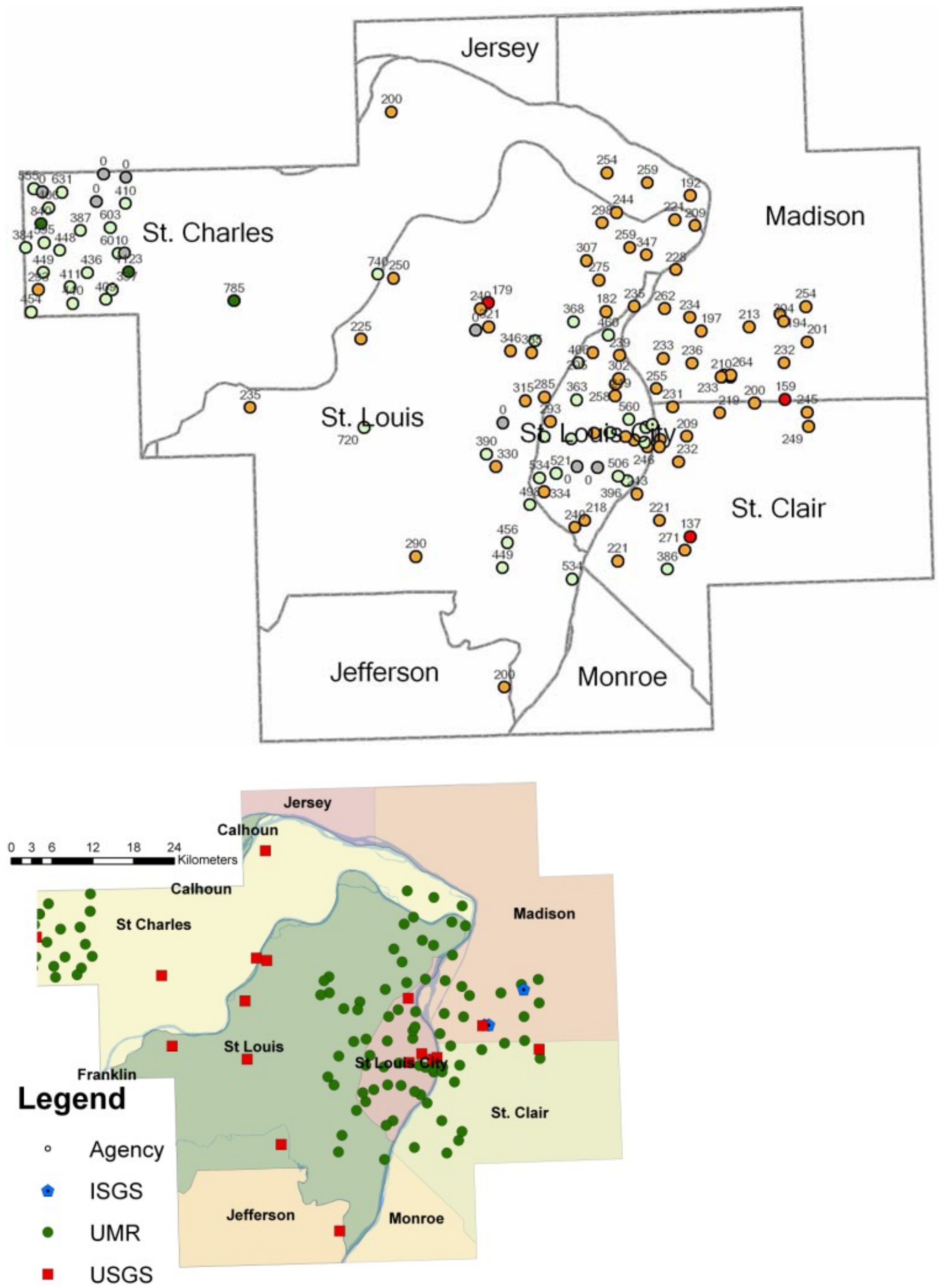


Figure 6. Estimated average shear wave velocity (Vs^{30}) in the upper 30m and data sources at the respective test locations.

Table 4. Input data for depth to bedrock interpolations (surficial material thickness).

Location		Geotechnical borings to bedrock surface		Seismic reflection
Landform	State	Piercing	Not piercing	
Floodplain	Missouri	450	115	9
	Illinois	348	1060	1
Upland	Missouri	2888	788	6
	Illinois	1401	1193	1
	sub-total	5087	3156	17
			Total	8260

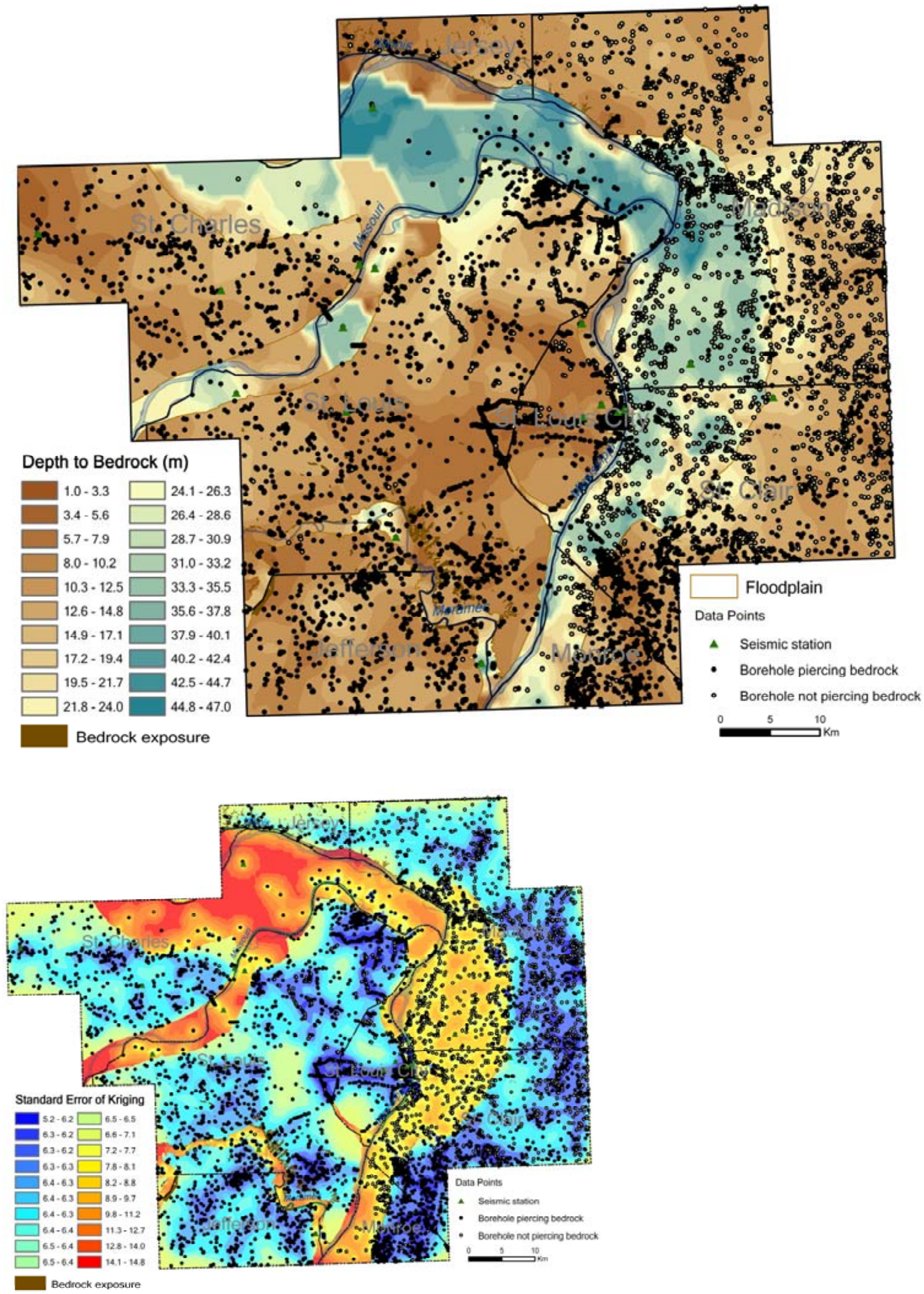


Figure 7. Depth-to-bedrock maps predicted by kriging and corresponding standard error maps, showing sample distributions.

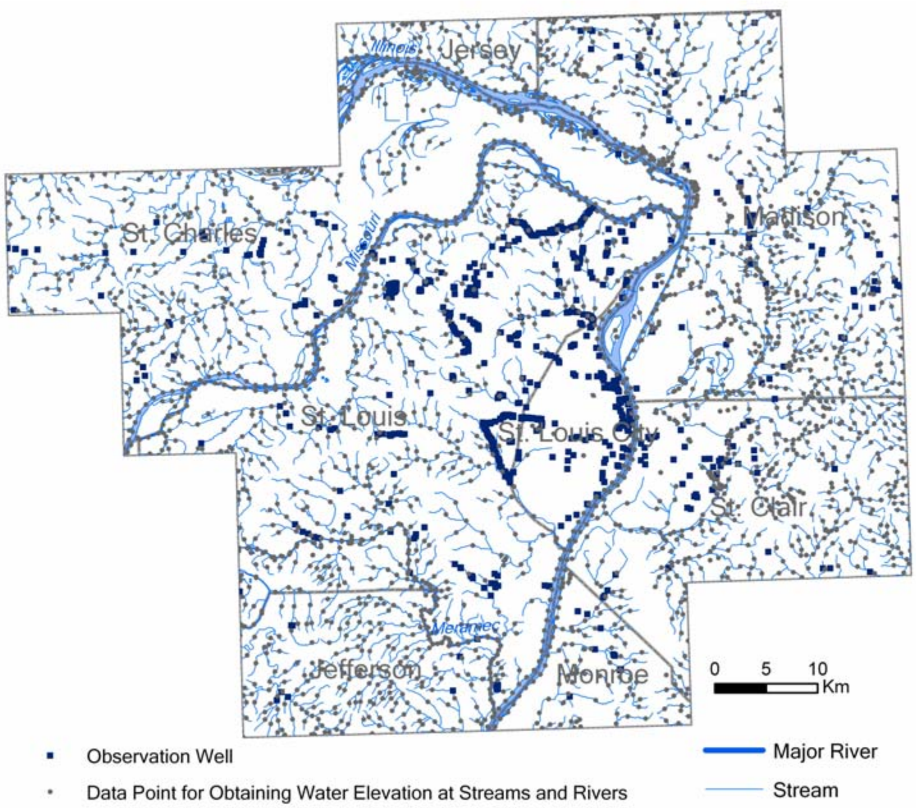


Figure 8. Locations of data points used in the predictions of water table elevation.

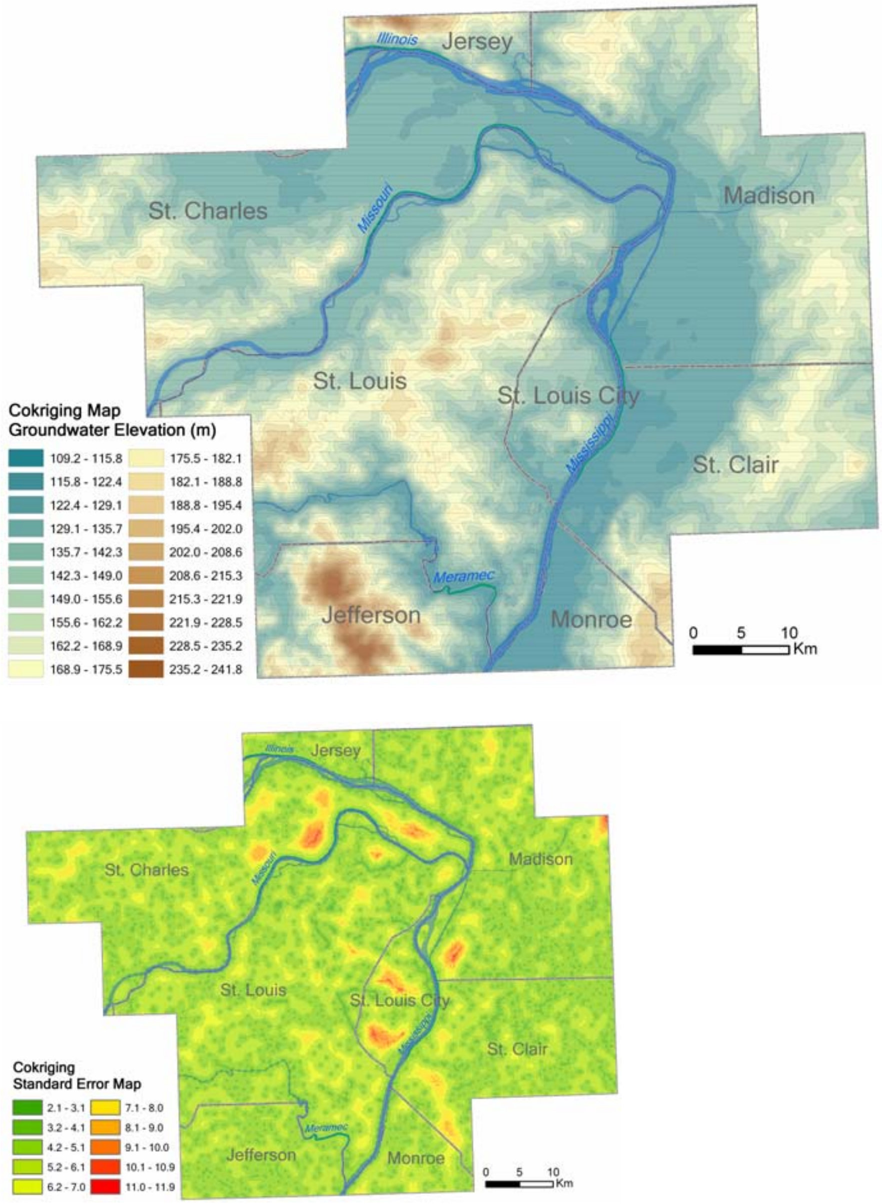


Figure 9. Map showing predicted groundwater elevations based on cokriging and the corresponding standard error map.