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# Testing of stack-unit/aquifer sensitivity analysis using contaminant plume distribution in the subsurface of Savannah River Site, South Carolina, USA

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**Abstract** Published information on the correlation and field-testing of the technique of stack-unit/aquifer sensitivity mapping with documented subsurface contaminant plumes is rare. The inherent characteristic of stack-unit mapping, which makes it a superior technique to other analyses that amalgamate data, is the ability to deconstruct the sensitivity analysis on a unit-by-unit basis. An aquifer sensitivity map, delineating the relative sensitivity of the Crouch Branch aquifer of the Administrative/Manufacturing Area (A/M) at the Savannah River Site (SRS) in South Carolina, USA, incorporates six hydrostratigraphic units, surface soil units, and relevant hydrologic data. When this sensitivity map is compared with the distribution of the contaminant tetrachloroethylene (PCE), PCE is present within the Crouch Branch aquifer within an area classified as highly sensitive, even though the PCE was primarily released on the ground surface within areas classified with low aquifer sensitivity. This phenomenon is explained through analysis of the aquifer sensitivity map, the groundwater potentiometric surface maps, and the plume distributions within the area on a unit-by-unit basis. The results of this correlation show how the paths of the PCE plume are influenced by both the geology and the groundwater flow.

**Résumé** Rares sont les informations publiées sur des corrélations et validations concrètes de la technique de cartographie par unités composites (“stack-unit”) de la sensibilité des aquifères avec les panaches souterrains de contaminants renseignés. La caractéristique propre qui fait

de la cartographie par unités composites une technique supérieure aux autres, qui agrègent simplement les données, est la possibilité de décomposer unité par unité l’analyse de sensibilité. Une carte de sensibilité, délimitant la sensibilité relative de l’aquifère de Crouch Branch sur la Zone Administration/Production (A/M) du Savannah River Site (SRS) en Caroline du Sud (Etats-Unis), comprend six unités hydrostratigraphiques, des unités de sol, et des données hydrologiques pertinentes. La comparaison entre cette carte de sensibilité et la distribution du contaminant tétrachloroéthylène (PCE) fait apparaître la présence de PCE dans l’aquifère de Crouch Branch, dans un secteur classé comme hautement sensible. Pourtant, le PCE avait été originellement rejeté en surface dans des zones où l’aquifère est classé comme peu sensible. Ce phénomène peut s’expliquer en analysant unité par unité la carte de sensibilité de l’aquifère, les cartes piézométriques, et les distributions des panaches sur le secteur. Les résultats de la corrélation montrent comment les chemine-ments des panaches sont influencés à la fois par la géologie et par les écoulements souterrains.

**Resumen** Es rara la información publicada sobre la correlación y pruebas de campo de la técnica de unidad de apilamiento/cartografía de sensibilidad acuifera con plumas contaminantes subsuperficiales documentadas. La característica inherente de la cartografía de la unidad de apilamiento, que la hace una técnica superior a otros análisis que amalgaman los datos, es la habilidad para deconstruir el análisis de sensibilidad con base en la unidad-por-unidad. Un mapa de sensibilidad del acuífero, delineando la sensibilidad relativa del acuífero Crouch Branco, del área Administrativo/Industrial (A/I) en el Sitio del Río Savannah (SRS) en Carolina del Sur, EE.UU., incorpora seis unidades hidrostratigráficas, unidades de suelo superficial, y datos hidrológicos pertinentes. Cuando este mapa de sensibilidad se compara con la distribución del contaminante tetracloroetileno (PCE), el PCE está presente dentro del acuífero Crouch Branch, dentro de una área clasificada como muy sensible, aunque el PCE se liberó principalmente en la superficie del terreno, dentro de áreas clasificadas como de sensibilidad acuifera baja. Este fenómeno se explica a través del análisis del mapa de sensibilidad del acuífero, los mapas de la superficie potenciométrica del agua subterránea, y las distribuciones de la pluma dentro del área, con base en la unidad-por-

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Received: 23 March 2005 / Accepted: 24 June 2006

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unidad. Los resultados de esta correlación muestran cómo los caminos de la pluma de PCE, están influenciados tanto por la geología como por el flujo de agua subterránea.

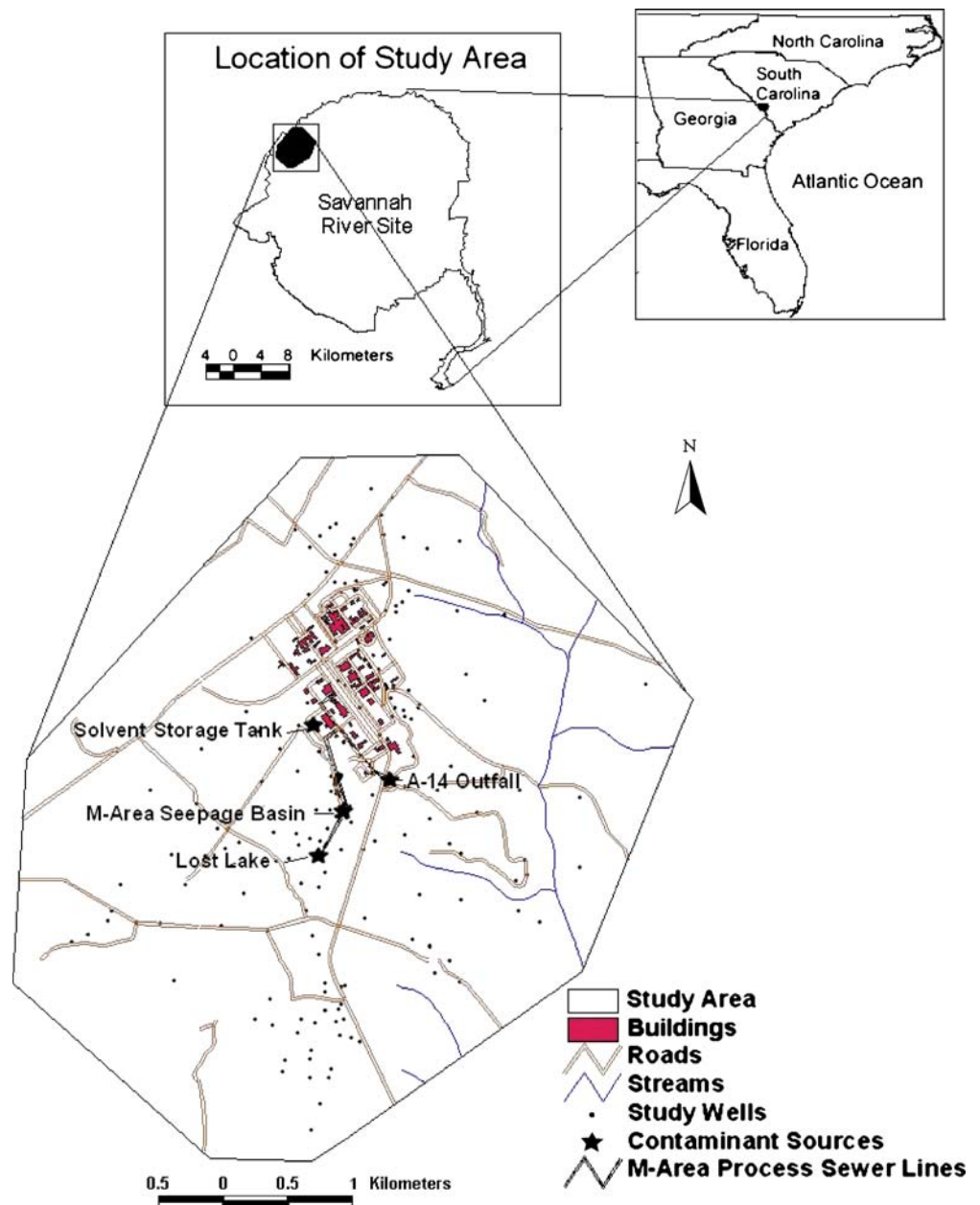
**Keywords** Aquifer sensitivity · Stack-unit mapping · Savannah River Site · Chlorinated hydrocarbons

## Introduction

In the mid-1990s, contaminants were detected in the Crouch Branch aquifer, over 100 m below the ground surface at the US Department of Energy's (US DOE) Savannah River Site (SRS) in South Carolina. The SRS is a former nuclear weapons manufacturing facility in southwestern South Carolina (Fig. 1). To help delineate

the probable pathways of the detected contaminants, the Westinghouse Savannah River Company funded the study described in this paper, to examine the hydrostratigraphic characteristics of the strata overlying the Crouch Branch aquifer, utilizing data from previous reports generated at the SRS. To analyze and integrate all of these data, a stack-unit mapping approach was employed. The stack-unit mapping methodology consists of overlaying multiple spatial data sets such as geology, soils, and certain hydrogeologic parameters and then defining the relative importance of the layers represented by these data sets for impeding the downward migration of contaminants. This approach, which has been successfully applied to other areas of the SRS (Rine et al. 1998), utilizes a geographic information system (GIS) to integrate subsurface data sets to create an aquifer sensitivity map or, as the 1998 study

**Fig. 1** The study area location is within the administration and manufacturing (A/M) area in the northwest portion of the Savannah River Site (SRS) in South Carolina. 174 wells and borings were utilized for this study. Shown are the reported and probable release sites of solvents within the M-Area (*starred*) such as the M-Area seepage basin or the solvent storage tank area. Linear sources of contaminants consist of the system of solvent bearing sewer lines that cross the site



termed it, a contamination potential map. This map helps predict areas where contaminants that were released at or near the ground surface, are most likely to reach the Crouch Branch aquifer (Fig. 2).

### Previous hydrogeologic stack-unit/aquifer sensitivity mapping analyses

The US EPA (USEPA 1993) defines aquifer sensitivity as:

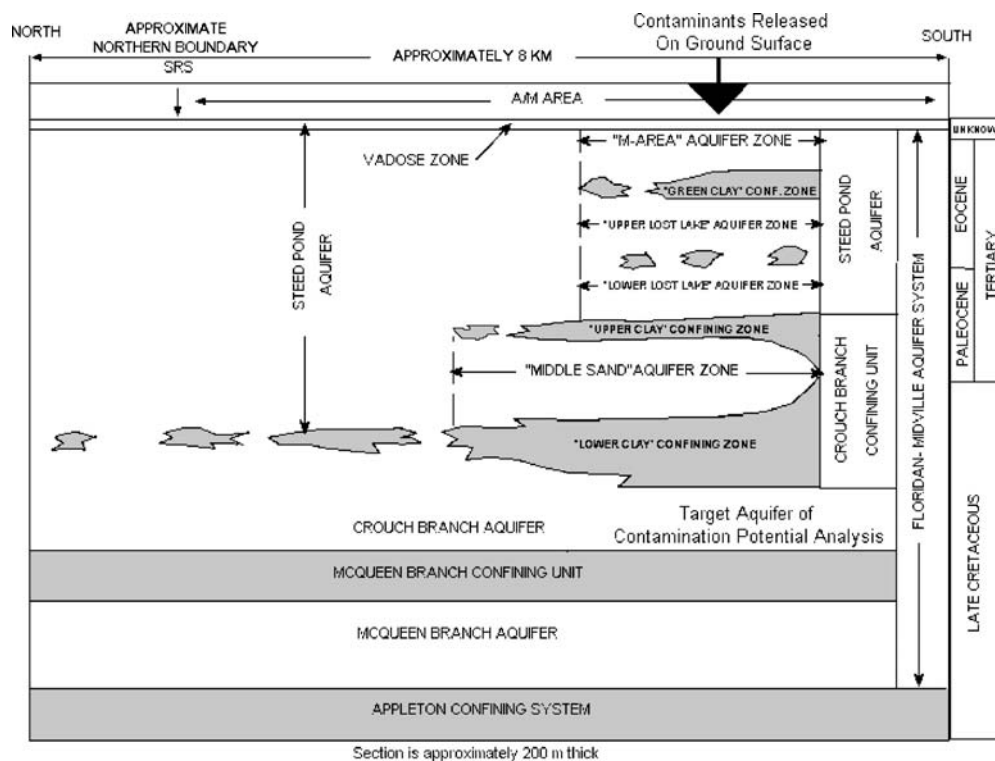
“A measure of the ease with which a contaminant applied on or near the land surface can migrate to an aquifer. It is a function of the intrinsic characteristics of both the geologic materials comprising the aquifer as well as overlying saturated and unsaturated materials. It is independent of land use and the types of contaminants.”

Determination of aquifer sensitivity across the US has been conducted in response to the need for more detailed geologic information to support regional land-use planning and resource-based decision-making. Establishment of the three-dimensional framework of geologic materials and the delineating of aquifer and non-aquifer materials have been essential to understanding the sensitivity of groundwater to potentially adverse land-use practices. For example, statewide and regional contamination potential maps have been used extensively in Illinois since the mid-1980s for landfill siting, prioritizing areas for groundwater monitoring, selecting candidate areas for development of a

low-level radioactive waste disposal facilities, and studying the potential effects of agricultural chemicals on shallow groundwater quality (Berg et al. 1984; Shafer 1985; Keefer and Berg 1990; Keefer 1995). In addition to sensitivity studies in Illinois, sensitivity of glacial drift aquifer systems also was determined for Michigan (Passero et al. 1989; Lusch et al. 1992), Iowa (Hoyer and Hallberg 1991), Wisconsin (Schmidt 1987), and Georgia (Trent 1992). County-scale groundwater vulnerability maps have been made in several states (e.g., in Indiana by Fleming 1994). The first aquifer sensitivity analysis of a coastal plain sequence was completed at the SRS within the general separations area that is adjacent to the administration/manufacturing (A/M) area (Rine et al. 1998). However, in the nearly 20 years of research on various techniques for three-dimensional geologic mapping and application of aquifer sensitivity analysis, no detailed field correlation of contaminant distributions with a contamination potential mapping analysis has been published.

A study by Harris et al. (2004) directly addresses the importance of building a hydrogeologic model when dealing with remediation within the A/M area. The study by Harris et al. (2004) maps percent mud (silt + clay) of the hydrogeologic units in the A/M area and states that the “understanding of local and regional groundwater flow patterns is vital in assessing the extent and distribution of contamination.” The Harris et al. (2004) study, however, does not directly correlate contaminant plume distribution with individual hydrogeologic unit maps, like the study described herein.

**Fig. 2** Schematic north-south, hydrostratigraphic section for northern SRS as modified from Aadland et al. (1995)



Modified From: Aadland, Gelici and Thayer (1995)

A study by Holman et al. (2005) tested a methodology termed “intrinsic groundwater vulnerability mapping” using “nitrate concentrations from 1,108 boreholes throughout England and Wales.” To determine a groundwater vulnerability ranking, Holman et al. (2005) combined “permeability of aquifer material within the unsaturated zone, the presence of low permeability drift deposits, and the presence and nature of overlying soil, as described by the Soil Leaching Potential.” A qualitative assessment concept utilized by Palmer et al. (1995) has also been adapted to soil and geologic conditions in Lithuania (Holman et al. 2000) and The Philippines (Holman and Palmer 1998, 1999). The aquifer sensitivity analysis described herein, differs from the “intrinsic groundwater vulnerability” methodology by incorporating both unsaturated and saturated strata, and analyzing these strata as discrete hydrogeologic units, utilizing a stack-unit mapping approach that considers the total package of geologic materials to a maximum depth of some 80 m.

### Historical background of study area

The SRS is a US DOE facility occupying 790 km<sup>2</sup> in southwestern South Carolina bordering the Savannah River and the Georgia state line. Beginning in the 1950s, the SRS mission was to produce nuclear materials primarily for national defense. Production of new atomic weapons materials has since ceased at the site. What continues, however, is the processing of previously generated radioactive waste materials and by-products for reuse or disposal. Another task for SRS is to clean up non-radioactive hazardous materials used and subsequently released during the 50-year history of operations at the SRS. The A/M area at the SRS contains many of the manufacturing facilities used to build and maintain the five reactors once operating at the SRS. Figure 1 shows re-

ported and probable release sites of solvents within the M-Area. These sites include individual, localized sites such as the M-Area seepage basin, the solvent storage tank area, and A-14 outfall. Linear sources of contaminants have been transported through a system of solvent bearing sewer lines that crisscross the site.

Between 1952 to 1982, M-Area used an estimated  $5.9 \times 10^6$  kg of chlorinated solvents with  $8.1 \times 10^5$  kg of PCE released to the M-Area settling basin and  $4.5 \times 10^5$  kg of PCE released to the A-14 outfall (Fig. 3; Marine and Bledsoe 1984). All this was done according to accepted practices of the day.

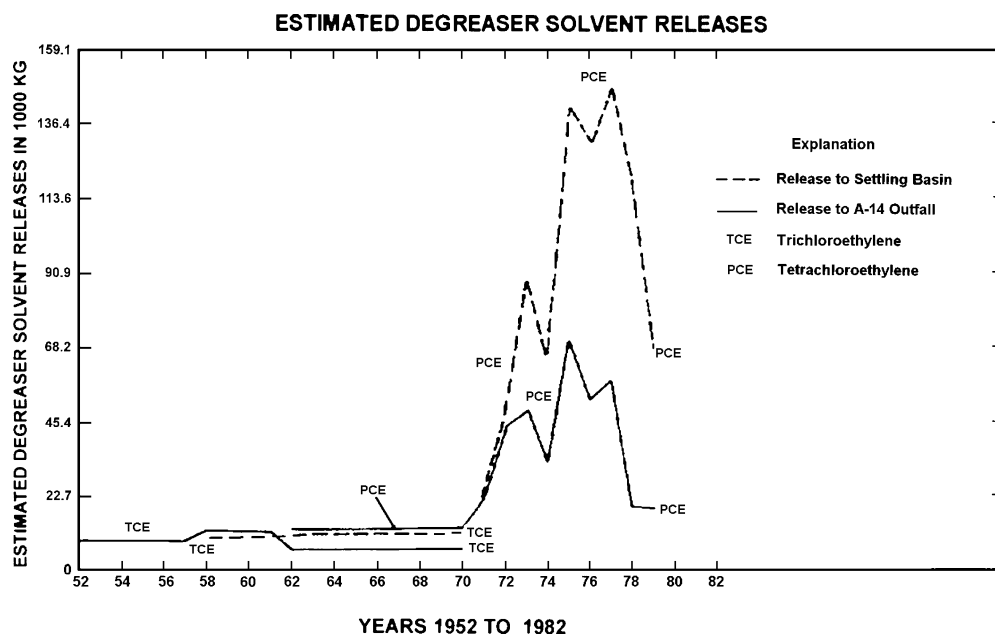
### Physiography of the study area

The SRS is approximately 160 km northwest of the Atlantic Coast and 40 km southeast and seaward of the “fall line” which separates the Piedmont from the Atlantic Coastal Plain physiologic provinces. The study area (i.e., A/M area), which is located in the northcentral portion of the SRS, is within the Upper Coastal Plain belt of Colquhoun et al. (1983). The Upper Coastal Plain generally slopes from a maximum elevation of 200 m along the fall line to approximately 75 m along the southeastern boundary. The area exhibits low to moderate relief with most depositional topography obscured by fluvial erosion.

### Geology of the study area

The SRS and the A/M area are underlain by Tertiary to Cretaceous-aged sediments of the Atlantic Coastal Plain. The predominant lithologies consist of poorly consolidated sand, muddy sand, and mud with patchy occurrences of calcareous sediments.

**Fig. 3** Estimated annual discharge of degreasing solvents tetrachloroethylene (PCE) and trichloroethylene (TCE) to the M-Area process sewer system as modified from Jackson et al. (1996)



Clay thicknesses and associated confining capacities generally increase from the upper to the lower part of the Tertiary and uppermost Cretaceous within the A/M area, while lateral variability appears more random (Fig. 2; Aadland et al. 1995). Clay beds are irregularly distributed within the M-Area aquifer. A Green Clay unit is extensive throughout the A/M area, but is locally irregular and probably eroded and infilled by the overlying M-Area (Composite Upland interval) sediments. Thicknesses of the Green Clay range from over 7 m in the south to less than 2 m in the northeastern portion of the study area. In the Lost Lake aquifer, there are intermittent clay beds as much as 3 m thick and are most common in the central to south-central portion of the study area (Aadland et al. 1995). These clay beds alter the hydrogeology enough to permit delineation of an upper and a lower Lost Lake aquifer zone. The Crouch Branch confining unit thickens to the west and southwest with a Middle Sand unit separating the upper and lower clay units in the eastern and southern parts of the study area (Fig. 2). The Lower Clay confining unit is thicker than the Upper Clay unit and is present, although not continuously, throughout the study area. Thicknesses of the entire Crouch Branch confining unit range from 9 to 24 m (Aadland et al. 1995). Detailed correlation of wells logs within the A/M area suggest that multiple structural events impacted the area during late Cretaceous and early Tertiary time, resulting in differing patterns of fault traces (Aadland 1996). Other researchers, however, also attribute the lithologic variations to variations in local depositional environments (e.g., channels) and erosional events (Harris et al. 2004).

## Methodology and results

### Construction of the geologic stack-unit map

A three-dimensional geologic map that helps define aquifer sensitivity was created by joining multiple spatial data sets such as geology, soils, and certain hydrogeologic components and by defining the relative importance of these units for impeding the downward migration of contaminants. The process of joining these layers into a single composite map is known as stack-unit mapping. Stack-unit mapping was applied to this study area to evaluate the combined influence of six hydrostratigraphic units and soil parameters on the migration of contaminants into the subsurface. However, before the hydrostratigraphic units could be stacked, each unit had to be digitally mapped in three dimensions. The initial step in this process involved the mapping of the stratigraphic surface elevation of each unit. Surface elevation maps of the Green Clay, Lost Lake aquifer and Upper Clay were largely derived from maps drawn by Aadland (1996) who interpreted faulting to be present within the shallowest three of the six subsurface units that were mapped. The surface of the Middle Sand, the Lower Clay, and the Crouch Branch aquifer were derived by mapping the tops of hydrostratigraphic units from wells and borings.

Available subsurface information decreases with depth from the ground surface: 174 borings were used to map the Green Clay, 142 borings were used to map the Congaree Formation, 74 borings were used to map the top of the Upper Clay; 64 borings were used to map the top of the Middle Sand unit, and 57 borings were used to map the top and base of the Lower Clay unit.

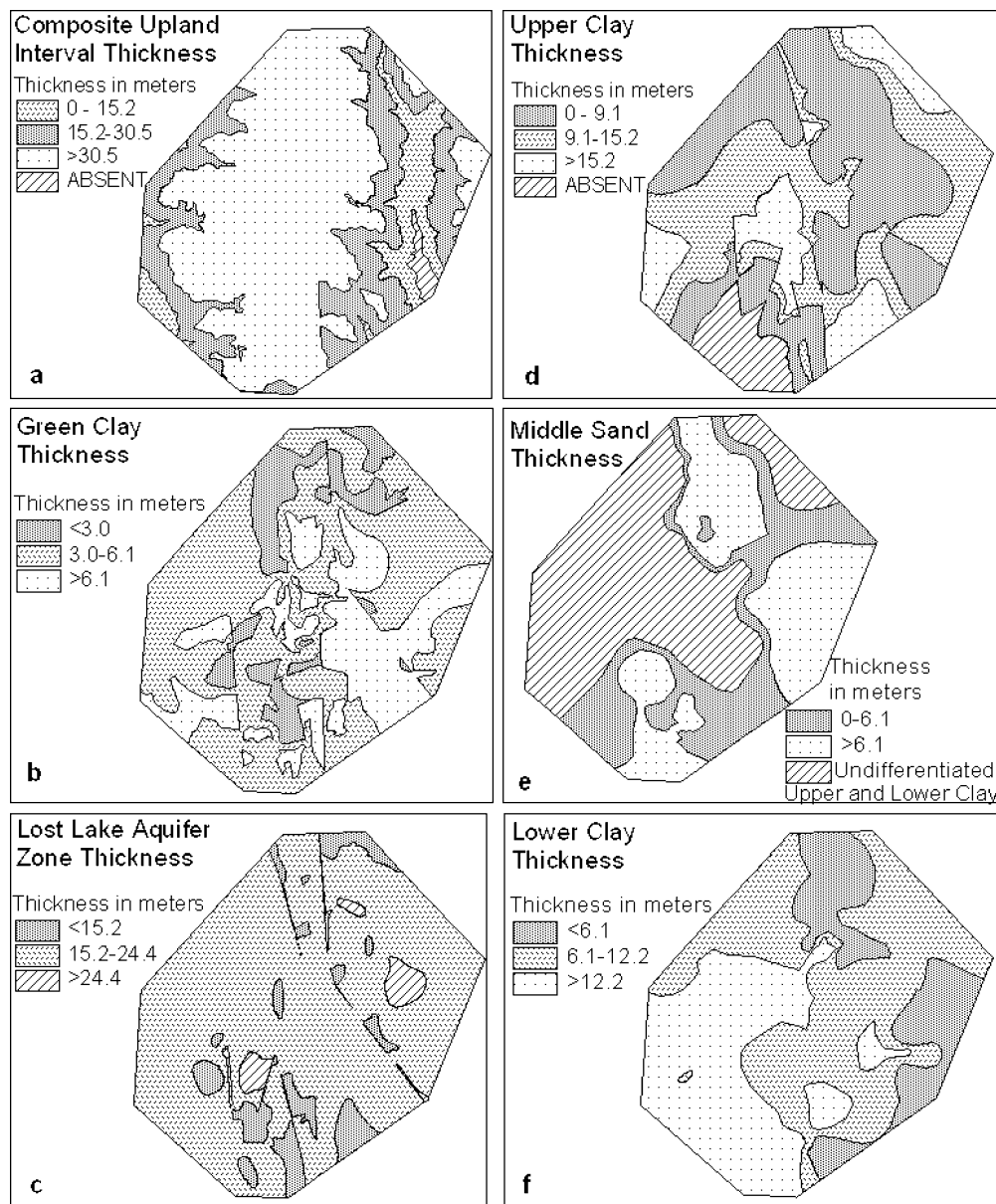
Isopach (i.e., thickness) maps of the six units were produced by machine subtraction of surface maps above and below each unit. Digital contour line coverages were converted by topogrid interpolation methods to digital elevation models (DEM). Topogrid is based on the ANUDEM program that is specifically designed to produce hydrogeologically sound DEMs (Hutchinson 1988). Separate grids for each of the six data layers were generated from digital contour line coverages. A 5-m resolution was chosen for each grid and was based on the smallest spacing between the contour lines to sufficiently capture the complexity of the terrain. The Arc/Info GRID module was used for further processing of grids with each of the isopach grids converted into Arc/Info polygon coverages. Elevations from vertically adjacent upper surfaces were “machine-subtracted” to create six isopach maps (Fig. 4). For example, the isopach map of the Composite Upland interval was produced by subtracting the elevation of the top of the Green Clay from the DEM of the land surface elevation. Linear contour features are quite noticeable for those isopach units where the top, bottom, or both contact surfaces include fault traces. Grids of these surfaces were created in segments corresponding to individual fault blocks (areas bounded by faults) with contours interpolated across the faults. Final isopach maps of each unit were made by interpretative-redrawing of machine-drawn maps because the machine-drawn maps commonly are not geologically plausible. A 3-m-thickness contour interval was used initially to help define any fine details in the individual unit maps. Thickness contours were simplified to retain the character of the unit but reduce the complexity of the combined stack-unit map (Fig. 4).

The stack-unit map of geologic materials was created by stacking these six isopach maps together and adding codes for each mapped polygon. Therefore, each polygon shows the absence/presence and thickness of each unit mapped from ground surface to the top of the Crouch Branch aquifer (Fig. 4).

### Compilation of hydrogeologic components for the aquifer sensitivity map

Aquifer sensitivity is not only a function of geologic properties, but also dependent upon various hydrogeologic properties, in particular, the hydraulic conductivity of the various geologic units under consideration and position of these units relative to the three-dimensional groundwater flow regime. Two parameters were considered to be mappable data sets: (1) spatial variability of relative leakances of the Green Clay confining unit as well as the Upper Clay and Lower Clay units of the

**Fig. 4** Interval thickness (isopach) maps for each of the six hydrostratigraphic units analyzed in this study. Elevations from vertically adjacent upper surfaces were “machine-subtracted” to create six isopach maps. See text for explanation



Crouch Branch confining unit, and; (2) the upward or downward groundwater flow potential between the aquifers separated by the Green Clay and the Crouch Branch confining unit.

There is a downward hydraulic gradient across both the Green Clay and the Crouch Branch confining unit for the whole study area (Aadland et al. 1995). Although some minor differences in this gradient are interpreted as being present, the variability was considered too small to be mapped for this study.

**Factoring the spatial variability in leakance coefficients of the Green Clay and Crouch Branch confining units**

Significant spatial variability exists in the “leakiness” of the Green Clay and the Crouch Branch confining units as

defined by variations in leakance coefficients calculated for wells and boreholes within the A/M area. Leakance is an averaging of the sums of the vertical conductivities of fine-grained lithologies divided by the thicknesses of the respective lithologies of that unit. The following equation, which utilizes primarily calculated conductivities, is from Aadland et al. (1995).

$$L_e = 1/[(b_c/K_{vc}) + (b_{cs}/K_{vcs})]$$

- $L_e$  effective leakance of confining unit (m/day/m or day<sup>-1</sup>)
- $K_{vc}$  vertical hydraulic conductivity of the clay to sandy clay beds and calcareous mud beds (m/day)

- $K_{vcs}$  vertical hydraulic conductivity of the clayey sand beds (m/day)
- $b_c$  thickness of sandy clay to clay beds and calcareous mud beds (m)
- $b_{cs}$  thickness of clayey sand beds (m)

Spatial variations in leakance values for a unit should correlate with the spatial variability of the potential for contaminants to be transported to underlying geologic units (or overlying depending on the vertical hydraulic gradient).

Three orders of magnitude variations in the leakance values are present for the Green Clay confining unit (Fig. 5). Aadland et al. (1995) reported variations ranging from  $1.04 \times 10^{-5} \text{ days}^{-1}$  for the fine-grained portions of the Green Clay and  $4.70 \times 10^{-2} \text{ days}^{-1}$  for the sandy parts of the sequence. Aadland et al. (1995) consider both lithologies with high and low leakance values to be part of the same Green Clay confining unit, even though the highly conductive, coarse-grained lithology is similar to the overlying Upland Composite unit of the M-Area aquifer unit. It is hypothesized, that the highly conductive lithology is actually the result of post-depositional incisement into the Green Clay deposit and infilling with M-Area aquifer lithology. Instead of remapping the Green Clay unit, however, it was decided to include the Green Clay leakance distribution as a map layer in the stack-unit mapping procedure (Fig. 5).

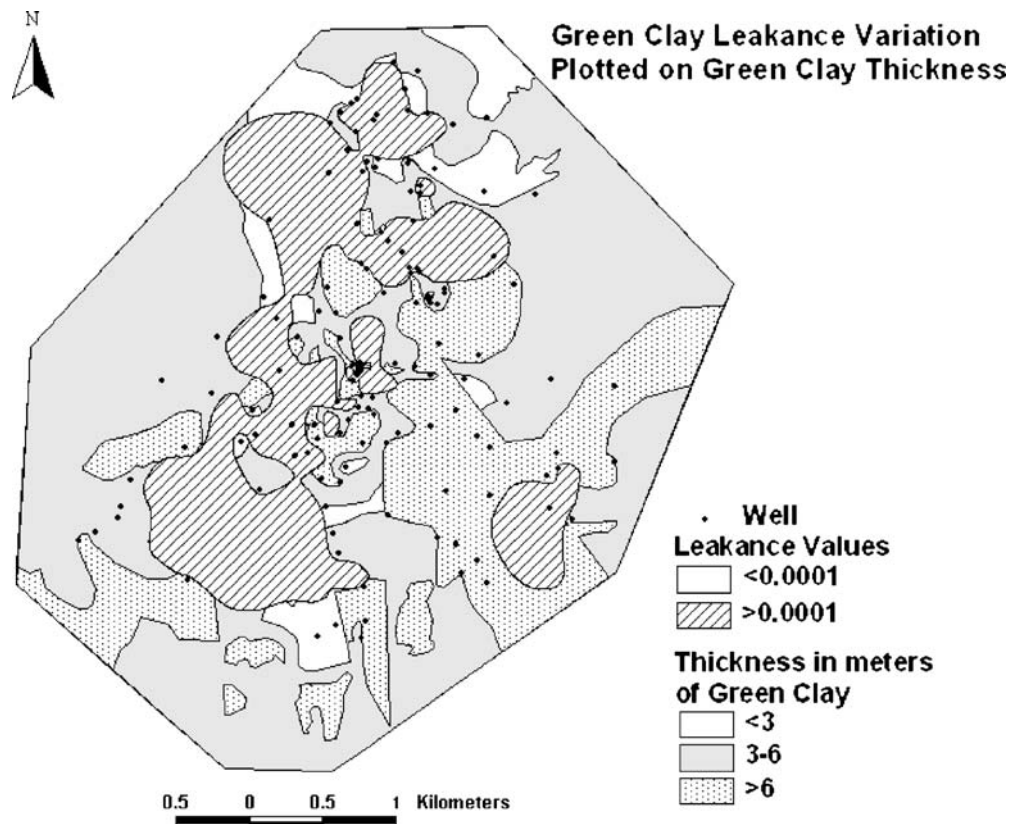
Leakance variations for the Crouch Branch confining unit mimic the spatial variability of the Middle Sand unit

that occurs within that confining unit. Consequently, a map of the Middle Sand unit can be used as a map of the Crouch Branch high leakance values.

### Ranking of hydrogeologic units and creation of a preliminary aquifer sensitivity map

A critical part of creating an aquifer sensitivity map is establishing the relative importance of the overlying hydrogeologic units in preventing potential contaminants from migrating downward to the target aquifer unit (in this case the Crouch Branch confining unit). The standard procedure in aquifer sensitivity mapping is to rate the geologic units according to their hydrogeologic properties and relative proximity to the ground surface (Berg and Greenpool 1993; Rine et al. 1998; Berg 2001). For instance, fine-grained units are more important than coarse-grained units because the former impede the flow of contaminants more so than the latter. Table 1 lists the hydrogeologic units and their comparative ranking with "1" being most important and "6" being least important in terms of retarding the downward migration of contaminants. Table 1 also shows the general hydrologic properties of the units. Relative proximity to the ground surface is important because an aquitard near the ground surface will impede the descent of contaminants at an earlier stage of migration than a similar confining unit deeper in the section (Rine et al. 1998). Consequently, the Green Clay confining unit is the highest ranked unit, being the shallowest aquitard, whereas deeper and highly conduc-

**Fig. 5** Leakance values for the Green Clay confining unit plotted over the Green Clay isopach. Leakance values, which are divided into less than or greater than 0.0001, may vary as much as three orders of magnitude. There is no apparent correlation between the distribution of leakance values and variations in Green Clay thickness



**Table 1** Ranking and hydraulic-property values for study units within the Tertiary interval of the A/M area at the SRS (modified from Aadland et al. 1995)

A/M area study units	Ranking	Study hydrologic units	Transmissivity (m <sup>2</sup> /s)	Leakance coefficient (1/day)	Effective vertical conductivity (cm/s)
Composite Upland	4	M-Area aquifer zone	$1.9 \times 10^{-4}$	–	$2.1 \times 10^{-6}$
Green Clay	1	Green Clay confining zone	–	$3.52 \times 10^{-4}$	–
Lost Lake	6	Upper Lost Lake aquifer zone	$2.4 \times 10^{-3}$	–	$7.1 \times 10^{-6}$
		lower			
		Lost Lake aquifer zone	$1.3 \times 10^{-3}$	$5.5 \times 10^{-6}$	–
Upper Clay	2	Upper clay of Crouch Branch confining zone	–	$2.66 \times 10^{-4}$	–
Middle Sand	5	Middle sand of Crouch Branch	$1.7 \times 10^{-3}$	–	$3.9 \times 10^{-6}$
Lower Clay	3	Lower clay of Crouch Branch confining zone	–	$6.43 \times 10^{-5}$	–

tive aquifer units such as the Lost Lake and Middle Sand aquifers are the lowest ranked units (Table 1). It should be noted, however, that this scheme assumes a uniform vertical conductivity for each unit, a condition that is not met in the Green Clay confining unit. Consequently, the leakance distribution of the Green Clay is included in the stack-unit map as a modifier of this highest ranked confining unit (Fig. 6).

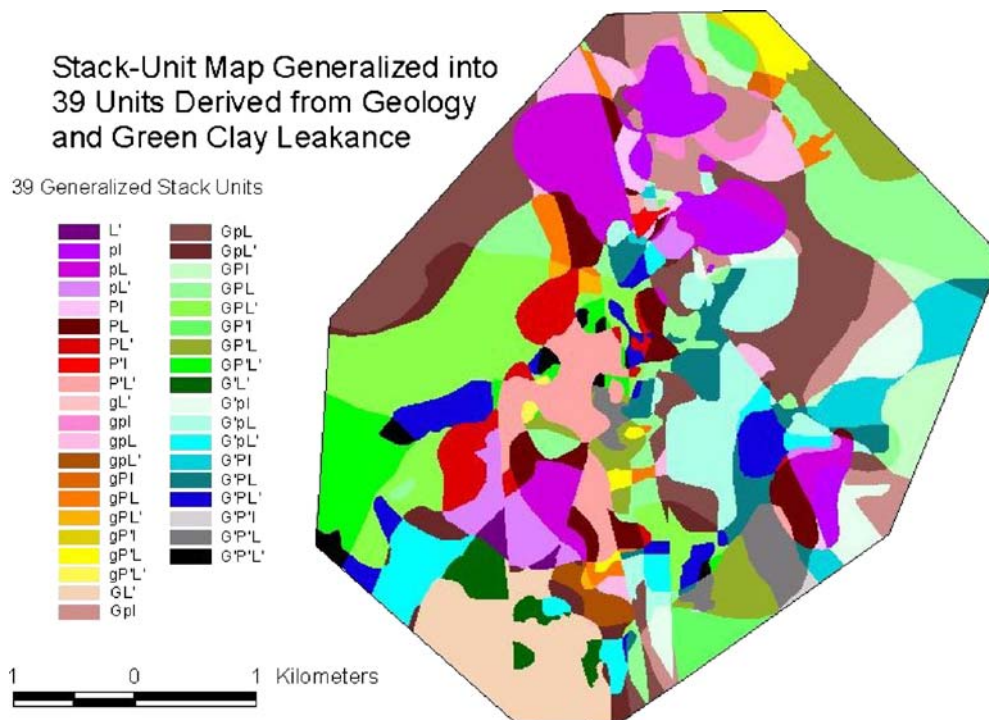
### Creating the hydrogeologic stack-unit map

The hydrogeologic stack-unit map was created by stacking polygon coverages of the six hydrogeologic units and the leakance distribution map of the Green Clay confining unit. This process in GIS, known as a “spatial overlay,” is fundamental to GIS spatial analysis and is accomplished in this study by using an overlay procedure called Union (ESRI 1993). The attributes for the polygons in the

resulting stack-unit map consist of a composite created from the separate unit maps (showing the various thicknesses and distributions of individual units) within the stack-unit polygons.

When overlying multiple polygon coverages that are unrelated to one another are spatially joined, the resulting stack-unit map is very complex and it requires editing and simplification to be made useable. This is because the individually mapped coverages of materials of variable thicknesses are from various depths that were deposited at different times, sometimes over different areas, and under varying sedimentological conditions. Therefore, they do not share common polygon boundaries. For instance, the unedited stack-unit map of the A/M area contains 1,267 polygons with over 600 unique combinations of stacked materials from land surface to the Crouch Branch aquifer. After editing to remove sliver polygons (those less than 1,000 m<sup>2</sup>) and dissolving other small polygons into larger

**Fig. 6** A generalized hydrogeologic stack-unit map was created with 39 categories defined from the 341 unique combinations of geologic sequences and thickness. The original 341 were rank ordered, according to their hypothesized potential to retard downward transport of contaminants, using a logarithmic approach called “utility theory.” Using the utility theory, each unit is assigned an order of magnitude corresponding to its ranked importance (see Table 2)



adjoining polygons with higher sensitivity rankings, the final stack-unit map is composed of 341 unique combinations of stacked successions contained in 455 polygons.

### Rank ordering of stack-units

The 341 unique combinations of geologic sequences and thicknesses were rank ordered, according to their hypothesized potential to retard downward movement of contaminants, using a logarithmic scale. Each unit was assigned an order of magnitude corresponding to its ranked importance (see Table 2). For example, the Green Clay confining unit, the highest ranked unit, was assigned  $10^5$  with three thickness intervals that “scored” 100,000 for a 0–3 m thickness, 200,000 for 3–6 m thickness, and 300,000 for thickness greater than 6 m. Similarly, the lowest ranked unit was assigned  $10^0$  (or 1) and scored 1 for a thickness less than 15 m, 2 for a thickness of 15 to 24.2 m, and 3 for a thickness of greater than 24.2 m. For the areas that fall within the zones of high Green Clay leakances, the mechanism used to arrive at a logical scoring is achieved by multiplying the Green Clay score by  $10^{-3}$ , which results in a numerical ranking equal to that of the Composite Upland unit, which is a sand unit. This was done because, as noted earlier, the areas of high leakance (high vertical conductivity) are actually infilling or incisions into the Green Clay deposit with Composite Upland unit (M-Area aquifer) lithology. Because a 341-unit map is very complex, a generalized hydro-

geologic stack-unit map was created with 39 categories (Fig. 6). To construct the generalized hydrogeologic stack-unit map, the 341 units were reduced to 39 based on the thickness and absence/presence of the three aquitards—the Upper Clay, the Lower Clay, and the Green Clay (modified by the Green Clay leakance values). These confining units have the most influence on slowing down contaminant transport.

### Integration of soil information into the stack-unit map

A comprehensive assessment of aquifer sensitivity must include the potential for infiltration through surface soils and potential attenuation of contaminants by soil organic matter (Keefer 1995). In the study area, 31 mappable soil series, interpreted into four soil hydrologic groups and five organic matter classes, were stacked to make one composite map for use in the analysis (Fig. 7). Soil information was obtained from the local USDA soil survey (Stuck 1980).

Figure 8a combines the generalized hydrostratigraphic stack-unit map (Fig. 6) and soils maps (Fig. 7). To create a color scheme for the combined soil and generalized hydrostratigraphic stack-unit map (Fig. 8a), an  $8 \times 39$  matrix was constructed that integrates the 39 hydrostratigraphic units (vertical axis) with the eight soil organic matter/hydrologic groups (horizontal axis; Fig. 8b). Colors show the transition from high (dark red or purple) to low (light green-dark green) aquifer sensitivity.

The areas of highest aquifer sensitivity ratings occur in areas of high Green Clay leakance values and soils with low organic matter content and high infiltration rates (hydrologic groups A or B) (Fig. 7). The areas of lowest aquifer sensitivity are locations of lower leakance values containing soils characterized by high organic matter content and low infiltration rates (i.e., hydrologic groups C or D, etc.)

### Correlation of aquifer sensitivity maps with distribution of PCE

The documented occurrence of contaminants in the subsurface of the A/M area offered the opportunity to test the accuracy of the aquifer sensitivity map produced for that area. The aquifer sensitivity map of the A/M area that is described in a report to the SRS by Rine et al. (1997), evaluated the potential for allowing (or impeding) a generic contaminant released at or near the ground surface to migrate through six hydrostratigraphic units to the Crouch Branch aquifer (Fig. 2). PCE was released at or near the ground surface in the late 1950s through the late 1970s and migrated through the six hydrostratigraphic units to the Crouch Branch aquifer by the mid 1990s (Jackson et al. 1996). A plot of the occurrence of PCE within the Crouch Branch aquifer shows that the plume is located within an area ranked with the highest aquifer sensitivity even though the PCE was originally released on the ground surface and into the M-Area aquifer zone in

**Table 2** Key to correlate attribute codes to units and unit thickness with the scheme for rank-ordering stacked geologic units within the subsurface of A/M area at the SRS

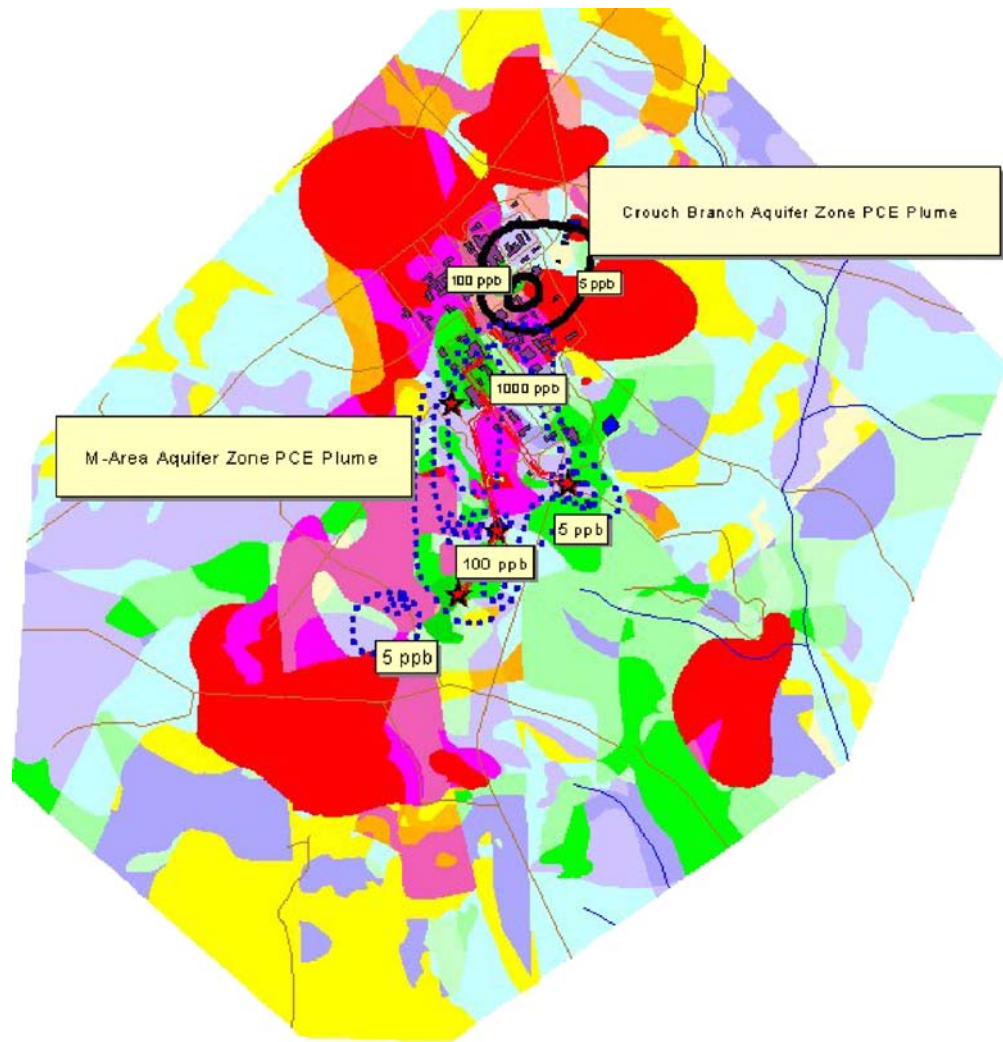
Key to unit codes				
Unit	Rank	Thickness (m)	Code	Score
Composite upland interval (M-Area)	4	Absent		0
		0–15.2	u	100
		15.2–30.5	U	200
Green Clay	1	>30.5	U'	300
		<3.0	g	100,000
		3.0–6.1	G	200,000
Lost Lake (Congaree)	6	>6.1	G'	300,000
		<15.2	c	1
		15.2–24.4	C	2
Upper Clay	2	>24.4	C'	3
		Absent		0
		0–9.1	p	10,000
Middle Sand	5	9.1–15.2	P	20,000
		>15.2	P'	30,000
		Absent		0
Lower Clay	3	0–6.1	s	10
		>6.1	S	20
		<6.1	l	1,000
Green Clay Leakance <sup>a</sup>		6.1–12.2	L	2,000
		>12.2	L'	3,000
		>0.0001 <sup>b</sup>	–	$\times 0.001$
		<0.0001 <sup>b</sup>	–	$\times 1$

<sup>a</sup> In wells with Green Clay leakances >0.0001, Green Clay score is multiplied by 0.001 and summed with other scores

<sup>b</sup> 1/day



**Fig. 9** Isoconcentration map of PCEs plotted on the aquifer sensitivity map shows the distribution of the contaminant plumes within the M-Area aquifer zone and the Crouch Branch aquifer zone. The plume within the M-Area aquifer directly underlies the major release sites and the M-Area process sewer line which were sited over areas of predominantly low aquifer sensitivity (to the Crouch Branch Aquifer zone). The plume within the Crouch Branch aquifer zone is offset to the major surface release sites of *PCE* and is within an area delineated as a zone of highest aquifer sensitivity. See Fig. 8b for key to colors of stacked-units on aquifer sensitivity map



strong influence of groundwater flow on the plume distribution (Fig. 10). However, the isolated plume to the south of the main plume is down gradient of the primary plume and, consequently, may be the combined result of groundwater transport of PCE followed by the perching of the PCE on a small clay bed.

### **PCE in the Lost Lake aquifer**

The PCE plumes within the Lost Lake aquifer reflect the influence of increased groundwater flow rates, continued downward migration of the PCE plume, and probable presence of free-phase PCE. The Lost Lake aquifer is divided into Upper and Lower zones separated by lenticular aquitard beds. However, the distribution of these beds was beyond the resolution of this study (Fig. 2). Within the Upper Lost Lake zone, vertical migration down from the M-Area aquifer and through the Green Clay appears to be the dominant transport mechanism. The highest plume concentrations of PCE within the Upper Lost Lake aquifer zone directly underlie the solvent storage tank/railroad off-

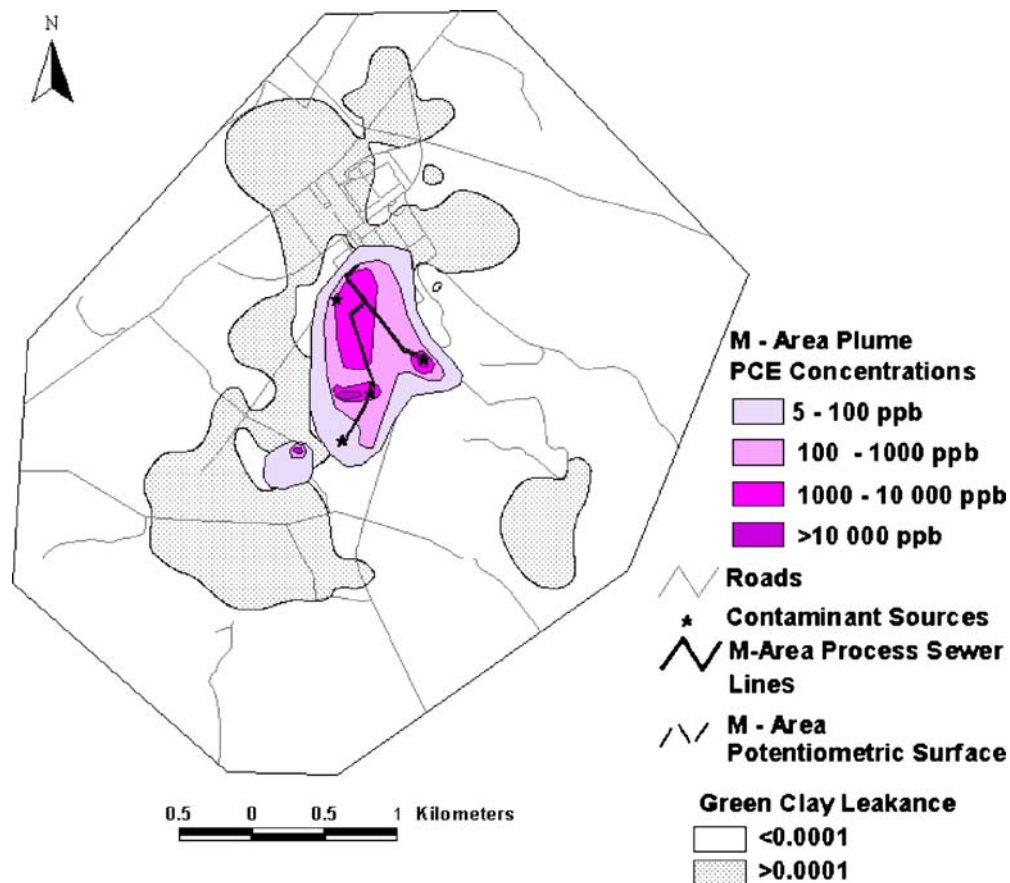
loading area (49,000 ppb) and the M-Area seepage basin—34,000 ppb; both within the >10,000 ppb areas in Fig. 11a; Jackson et al. (1996). These high concentrations are probably associated with pockets of free-phase PCE that are perched on lenticular clayey beds at or near the base of the Upper Lost Lake aquifer.

Within the Lower Lost Lake aquifer, groundwater flow influences the geometry of the PCE plume. Although the higher concentrated areas of PCE remain under their ground surface points of origin, the lower concentration plumes are being transported down the potentiometric gradient to the southeast for 100s to 1,000s of meters (Fig. 11b).

### **PCE in the Middle Sand unit of the Crouch Branch confining unit**

PCE within the Middle Sand unit of the Crouch Branch confining unit is concentrated into two horizontally discrete plumes with the northern plume, which coincides with a relatively thick occurrence of Middle Sand, having

**Fig. 10** Isoconcentration map of PCEs within the M-Area aquifer zone is plotted on the Green Clay leakance value distribution map and the M-Area aquifer potentiometric surface. Generally, the PCE plume coincides with areas of relatively low leakances, indicating that the contaminants are “perched” on top of less vertically conductive portions of the Green Clay unit



the higher concentration (>100 ppb; Fig. 12). The southern plume is within an area delineated as an area of undifferentiated Upper and Lower Clay with discontinuous sands where sand is obviously present, but probably only as thin beds within a predominantly clay strata. Distribution of the PCE plumes within the Middle Sand aquifer unit are largely controlled by the groundwater influenced distribution of the PCE plumes within the overlying Lost Lake aquifer (Fig. 11b). The plume within the Middle Sand unit that has the highest concentrations (>100 ppb) underlies an area of the Lower Lost Lake aquifer with similar PCE concentrations and convergent downward flow (Fig. 11b).

### **PCE in the Crouch Branch aquifer**

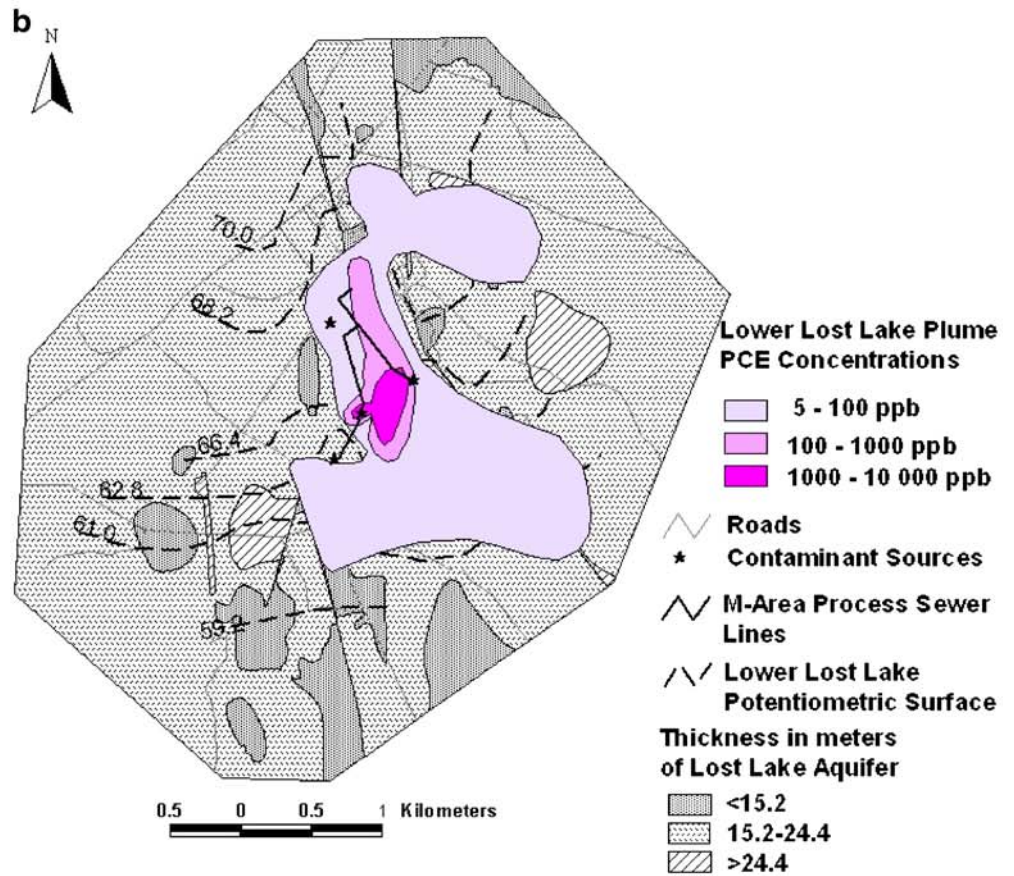
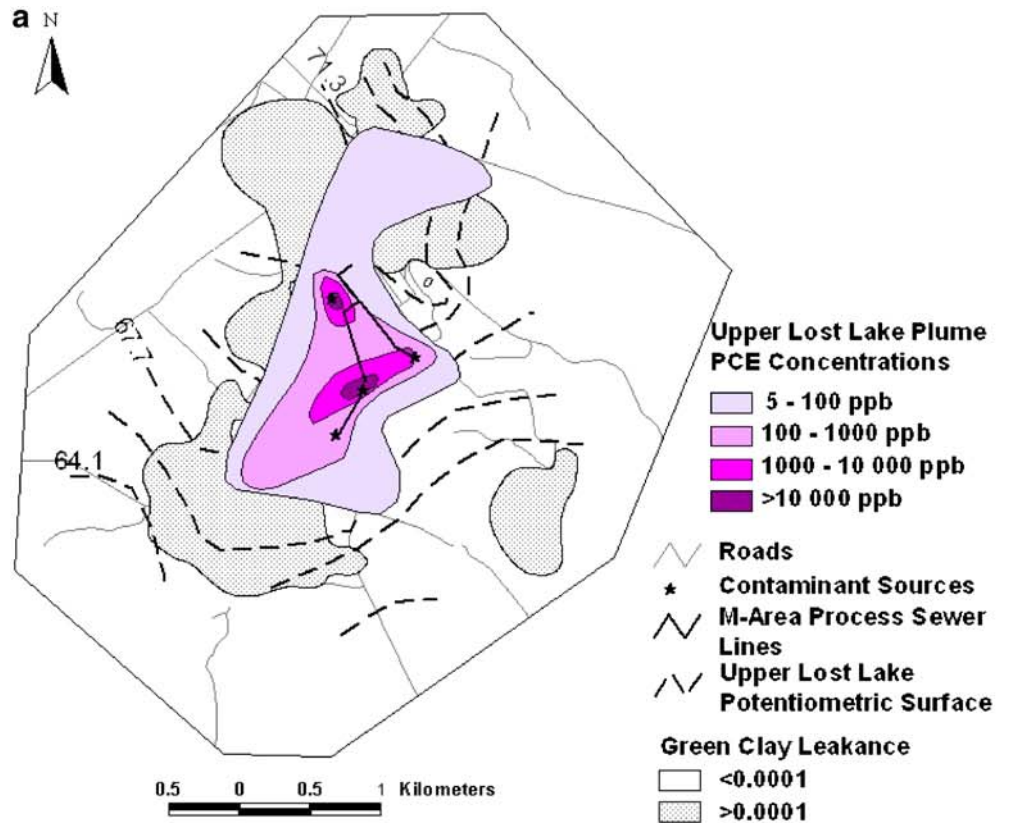
The migration path of PCE from the Middle Sand unit downward to the Crouch Branch aquifer is probably controlled by three major factors. First, the distribution of the PCE plume within the Middle Sand interval (i.e., the area of higher concentration within the Middle Sand unit) overlies the occurrence of PCE within the Crouch Branch aquifer unit (Fig. 13). Second, there is a negative hydraulic head difference between the Middle Sand unit and the Crouch Branch aquifer. Third, a relatively thin Lower Clay confining unit separates the Middle Sand PCE plume from the Crouch Branch aquifer plume (Fig. 13).

### **Conclusions**

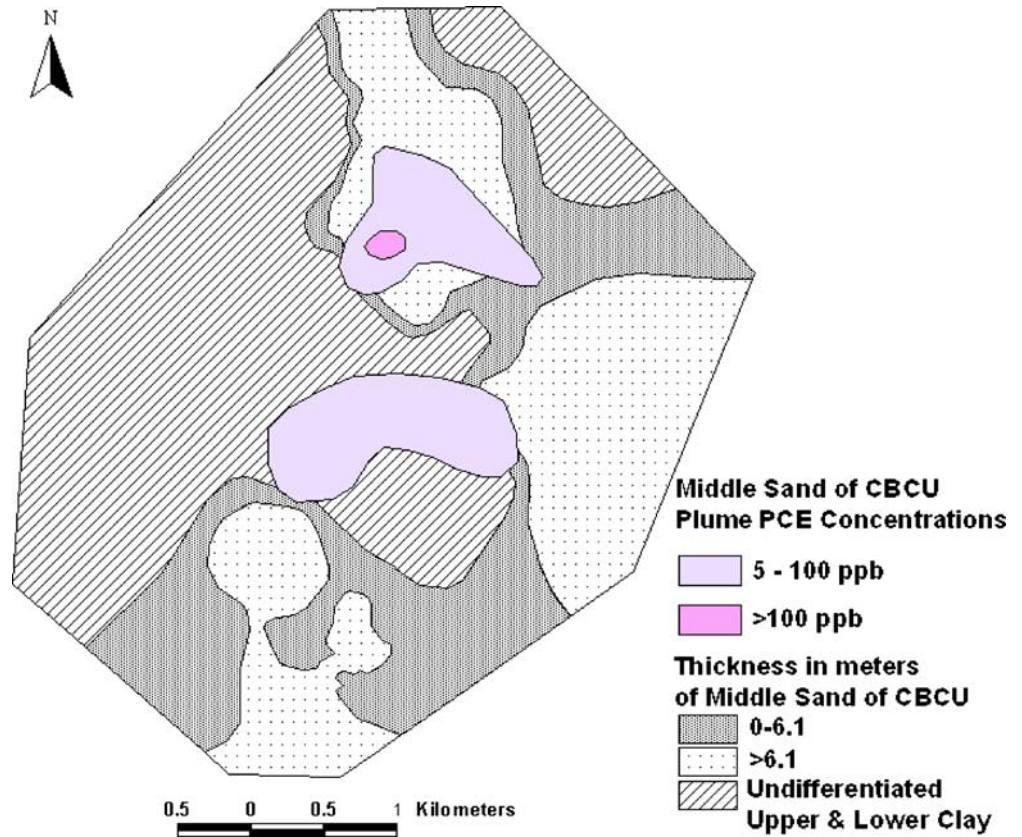
This paper is the first published correlation and field-testing of the technique of stack-unit/aquifer sensitivity mapping with documented subsurface contaminant plumes. The inherent characteristic of stack-unit mapping, which makes it a superior technique to other analyses that amalgamate data, is the ability to deconstruct the sensitivity analysis on a unit-by-unit basis. The application of stack-unit mapping to contamination potential assessment is useful because it summarizes in a two-dimensional format, a generally complex three-dimensional phenomenon. It is also very valuable because individual hydrostratigraphic units can be examined as well as the relationship between adjacent units. The stack-unit mapping exercise shows that the contaminant plume distribution in the uppermost unconfined aquifer (M-Area aquifer), is controlled by placement of the initial contaminant releases and the irregular distribution of the underlying effective aquitard (Green Clay). In the next lower aquifer (Lost Lake), contaminant distribution is controlled by where it was introduced from above and groundwater flow. The placement of contaminants in the “target” aquifer (Crouch Branch) is the result of the combination of a thin aquitard (Lower Clay unit), location of the contaminant plume in an overlying aquifer, and the downward flow gradient.

**Fig. 11 a** Isoconcentration map of PCEs within the Upper Lost Lake aquifer zone is plotted on the Green Clay leakance value distribution map and the potentiometric surface map of the Upper Lost Lake aquifer zone. The PCE plume has spread into areas of high leakances for the overlying Green Clay and generally dispersing down gradient from the release sites. The indentation in the northeast corner of the plume coincides with a high in the potentiometric surface.

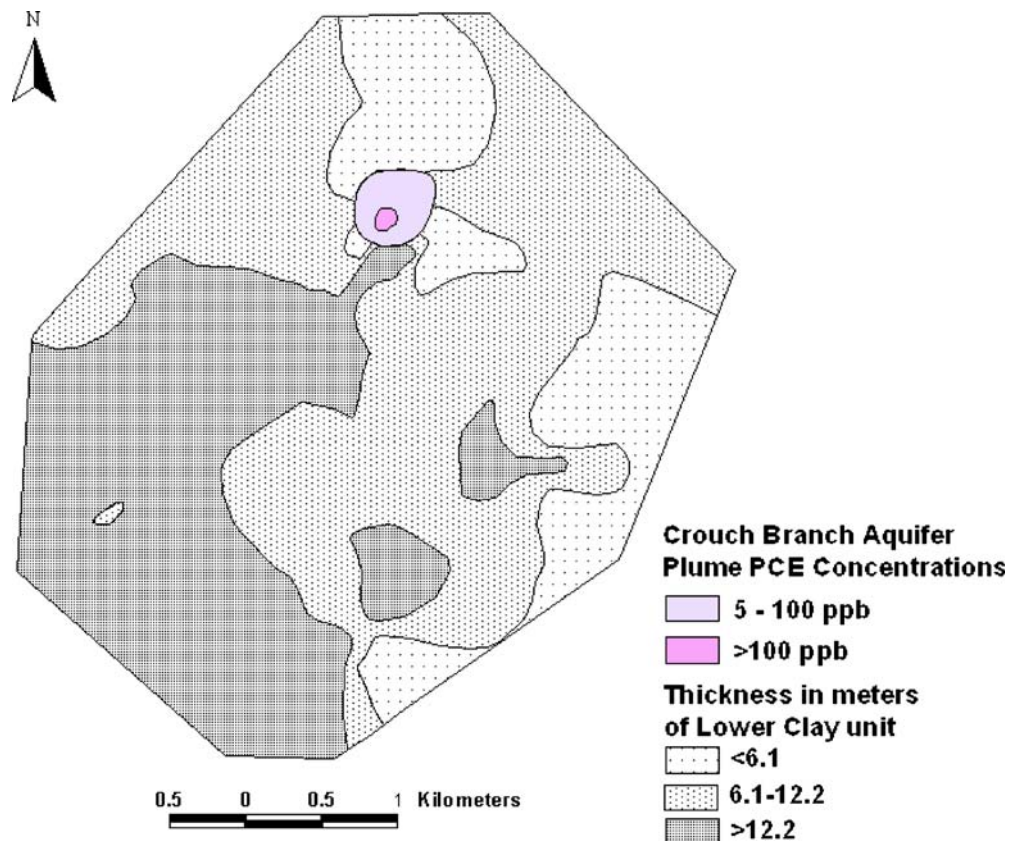
**b** Isoconcentration map of PCEs within the Lower Lost Lake aquifer zones is plotted on the Lost Lake aquifer zone thickness map and with the Lower Lost Lake aquifer zone potentiometric surface. The Lower Lost Lake plume is dispersed down gradient from the Upper Lost Lake plume



**Fig. 12** Isoconcentrations of PCEs within the Middle Sand unit of the Crouch Branch confining unit (CBCU) are plotted on the Middle Sand unit thickness map. Higher PCE concentration coincides with higher occurrence of sand



**Fig. 13** Isoconcentrations of PCE's within the Crouch Branch aquifer zone are plotted on the Lower Clay of the Crouch Branch confining unit thickness map. The Crouch Branch aquifer zone PCE plume underlies where PCE concentrations in the Middle Sand unit coincide with thinner portions of the Lower Clay confining unit



Aquifer sensitivity maps are useful planning tools to begin the process of assessing how vulnerable aquifers are to becoming contaminated. At the SRS study area, the actual release points of PCE occurred in low sensitivity areas. The actual occurrence of PCE within the targeted Crouch Branch aquifer agrees well with areas mapped as having high aquifer sensitivity, but this is best explained after evaluating additional hydrological parameters.

By combining hydrogeologic stack-unit mapping with additional hydrogeologic data such as potentiometric surface plots and groundwater pathline analyses, the fate of contaminants in the subsurface can be more completely explained and accurately predicted. Consequently, any aquifer sensitivity analyses should include both rigorous geologic investigations that delineate the complexities of the three-dimensional geology and subsequent hydrologic studies that further refine conclusions.

**Acknowledgements** This project was funded through the South Carolina Universities Research and Education Foundation (SCUREF) Task Order #161 by the Westinghouse Savannah River Company (WSRC). Completion of this phase of Task 161 is the direct result of cooperation between personnel at the Earth Sciences and Resources Institute, University of South Carolina (ESRI-USC) and the researchers at WSRC. SRS technical oversight staff responsible for monitoring task progress and furnishing approved data sets are John Reed and Robert Van Pelt. Particular thanks go to the late Rolf Aadland who furnished updated geologic unit structure maps and who shared many hours discussing the peculiarities of SRS geology.

## References

- Aadland RK (1996) Geology of the A/M Area, Savannah River Site (U). Westinghouse Savannah River Co., Report WSRC-RP-96-505
- Aadland RK, Gelici JA, Thayer PA (1995) Hydrogeologic framework of west-central South Carolina. Water Resources Division Report 5, State of South Carolina Department of Natural Resources, Columbia, SC
- Berg RC (2001) Aquifer sensitivity classification for Illinois using depth to uppermost aquifer material and aquifer thickness. *Illinois State Geol Surv Circ* 560
- Berg RC, Greenpool MR (1993) Stack-unit geologic mapping: color-coded and computer-based methodology. *Illinois State Geol Surv Circ* 552
- Berg RC, Kempton JP, Stecyk AN (1984) Geology for planning in Boone and Winnebago Counties. *Illinois State Geol Surv Circ* 531
- Colquhoun DJ, Woolen ID, Van Niewenhuise DS, Padgett GG, Oldham RW, Boylan DC, Bishop JW, Howell PD (1983) Surface and subsurface stratigraphy, structure and aquifers of the South Carolina Coastal Plain. Dept. of Geology, University of South Carolina, Columbia, SC
- Environmental Systems Research Institute (ESRI) (1993) *Understanding GIS: the ARC/INFO method*. Wiley, New York, NY
- Fleming AH (1994) The hydrogeology of Allen county, Indiana: A geologic and ground-water atlas. Indiana Geological Survey Special Report 57, Indiana Geological Survey, Bloomington, IN
- Harris, MK, Looney BB, Jackson DG (2004) Geology and environmental remediation: Savannah River Site, South Carolina. *Environ Geosci* 11(4):191–204
- Holman IP, Palmer RC (1998) Introducing multidisciplinary groundwater vulnerability mapping to the Philippines: a case study from Cebu City. *J Geol Soc Philippines* 53(3–4):158–179
- Holman IP, Palmer RC (1999) Groundwater protection incorporated into land use planning: a study from Cebu City, the Philippines. In Ellis B (ed) *Impacts of urban growth on surface water and groundwater quality*. Proc IUGG 99, Symposium HS5. IAHS Publ. No. 259, IAHS, Wallingford, UK, pp 125–132
- Holman IP, Palmer RC, Leonaviciute N (2000) Using soil and Quaternary geological information to assess the intrinsic groundwater vulnerability of shallow aquifers: an example from Lithuania. *Hydrogeol J* 8:636–645
- Holman IP, Palmer RC, Bellamy PH, Hollis JM (2005) Validation of an intrinsic groundwater pollution vulnerability methodology using a national nitrate database. *Hydrogeol J* 13:665–674
- Hoyer BE, Hallberg GR (1991) Groundwater vulnerability regions of Iowa. Iowa Geological Survey Bureau Special Map Series II, scale 1:500,000, Iowa Geological Survey, Des Moines, IA
- Hutchinson MF (1988) Calculation of hydrologically sound digital elevation models. Proceedings of the Third International Symposium on Spatial Data Handling, 17–19 August 1988, Sydney. International Geographical Union, Columbus, OH, pp 117–133
- Jackson DG, Payne TH, Looney BB, Rossabi J (1996) Estimating the extent and thickness of DNAPL within the A/M Area of the Savannah River Site (U). Westinghouse Savannah River Co. Report WSRC-RP-96-0574, Westinghouse Savannah River Co., Aiken, SC
- Keefer DA (1995) Potential for agricultural chemical contamination of aquifers in Illinois. Illinois State Geological Survey Environmental Geology 148, Illinois State Geological Survey, Champaign, Ill
- Keefer DA, Berg RC (1990) Potential for aquifer recharge in Illinois. Illinois State Geological Survey Map. Scale 1:1,000,000, Illinois State Geological Survey, Champaign, Ill
- Lusch DP, Rader CP, Barrett LR, Radner N (1992) Aquifer vulnerability to surface contamination in Michigan. Center for remote sensing and department of geography. Michigan State University, E. Lansing, MI
- Marine IW, Bledsoe HW (1984) Supplemental technical summary M Area groundwater investigation, DPSTD-84-0112, E.I. Du Pont de Nemours, Savannah River Laboratory, Aiken, SC
- Palmer RC, Holman IP, Lewis MA (1995) Guide to groundwater vulnerability mapping in England and Wales. HMSO, London
- Passero RN, Cohen FJ, Dulaney SJ, McNamara, J, Benton SE (1989) Determining the vulnerability of glacial drift aquifer systems in Michigan. 34th Annual Midwest Groundwater Conference, program with abstracts, 18–20 October 1989, Kalamazoo, MI
- Rine JM, Shafer JM, Covington ER, Trudnak JE, Berg RC (1997) Development of a GIS contamination potential map for the tertiary interval within a portion of the Administration/Manufacturing (A/M) Areas, Savannah River Site, South Carolina. Report 97-F124-1, Earth Sciences and Resources Institute, University of South Carolina, Columbia, SC
- Rine JM, Berg RC, Shafer JM, Covington ER, Reed JK, Bennett CB, Trudnak JE (1998) Development and testing of contamination potential mapping system for a portion of the General Separations Area, Savannah River Site, South Carolina. *Environ Geol* 35(4):263–277
- Schmidt RR (1987) Groundwater contamination susceptibility in Wisconsin: Wisconsin Department of Natural Resources. Wisconsin's Groundwater Management Plan Report No. 5. PUBL-WR-177-87, Wisconsin Department of Natural Resources, Madison, WI
- Shafer JM (1985) An assessment of groundwater quality and hazardous substance for a statewide monitoring strategy (P.A. 83-1268). Contract Report 367, Illinois State Water Survey, Bloomington, IN
- Stuck WM (1980) Soil survey of Beaufort and Jasper Counties, South Carolina. US Department of Agriculture Soil Conservation Service Report, US Department of Agriculture Soil Conservation, Washington, DC
- Trent VP (1992) Ground-water pollution susceptibility map of Georgia: GIS-1. Department of Natural resources Environmental Protection Division Georgia Geologic Survey, GIS Data Bases, Atlanta, GA, 6.9 MB
- US Environmental Protection Agency (1993) Groundwater resource assessment. EPA 813-R-93-003, US EPA Office of Groundwater and Drinking Water, Washington, DC