PREDICTING DEPTH TO SULFIDIC SEDIMENTS IN THE COASTAL PLAIN OF VIRGINIA[1]

Zenah W. Orndorff, and W. Lee Daniels[2]

Abstract. Construction through sulfidic materials in the Coastal Plain province of Virginia has resulted in localized acid sulfate drainage that threatens water quality, fill stability, integrity of building materials, and vegetation management. Information regarding the likelihood of encountering sulfide-bearing sediments in construction zones can help minimize the negative impacts that result from the exposure of these materials. The objectives of this study were to evaluate field relationships between depth to sulfide-bearing sediments and landscape parameters, and to test models for predicting depth to sulfides. A study area in Hanover County, Virginia was evaluated using landscape parameters including elevation, slope, distance to streams, and surficial geology to predict depth to reduced sediments (depth-rs). Actual depth-rs values were interpreted from stratigraphic data for 408 well logs obtained from the Hanover County Health Department. A regression model could not be developed to accurately predict depth to sulfidic sediments based on the landscape parameters. Similarly, interpolation using a random subset of the well log data was unsuccessful at predicting depth-rs for the remaining points. However, since excavation depths in the study area are typically less than 9 m a procedure was developed to evaluate the likelihood of encountering sulfidic sediments within this depth based on two risk factors - elevation and soil type. This procedure accurately described the likelihood of encountering depth-rs within 9 m for 90% of 58 test points. Samples collected from twenty-three deep borings all had relatively high sulfur values and did not contain calcium carbonate, indicating that exposure of Tertiary sediments would always present a high risk of acid production.

Additional Key Words: acid rock drainage, acid sulfate soils, construction, pyrite, soil-landscape relationships

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Introduction

Over the past few decades, exposure of sulfidic materials from development in coastal areas throughout the world has resulted in environmental degradation and has produced negative engineering impacts (Dent and Pons, 1995; Orndorff, 2001; Prokopovich, 1986; Stone et al., 1998; Valladares, 1998; van Holst and Westerveld, 1973). Recognition of acid sulfate soils and depth to unoxidized sulfidic materials, prior to land development is essential for minimizing environmental impacts. In upland settings, traditional soil survey techniques do not always provide sufficient information as sulfidic materials usually occur deeper than standard sampling depths (1.5 m), but within routine construction excavation depths. A few studies (Lin and Melville, 1994; Lin et al., 1995; Madsen et al., 1985; Madsen and Jensen, 1988; Valladares, 1998) focus on developing models that can be used locally to predict the occurrence of acid sulfate soils using soil-landscape relationships.

The study by Valladares (1998) in Anne Arundel County, Maryland, is of particular interest because this upland setting is similar to that of Virginia's inner Coastal Plain. By examining depth to sulfidic materials along multiple transects in three different geologic settings Valladares determined that 75% to more than 90% of the variability in depth to sulfides was attributed to point relief (the difference in elevation between a given point and the lowest point in the landscape unit). The study concluded that the surface of sulfide-bearing strata generally followed trends in the landscape surface, but occurred relatively deeper at summit locations than at toeslopes. This difference is presumably a function of water table depth, since shallower water tables that would inhibit oxidation occur at lower landscape positions. In most cases, sulfides were encountered within 15 m at higher elevations (up to 52 m), and within 2 to 3 m at lower elevations (< 35 m).

Problems associated with acid sulfate weathering increasingly are being recognized in the Coastal Plain province of Virginia, and numerous construction projects producing acid rock drainage have been documented (Orndorff, 2001). The depth at which sulfide-bearing sediments occur in this region is highly variable, ranging from approximately 3 m to over 30 m. Information regarding the likelihood of encountering sulfide-bearing sediments within a construction zone can help minimize the negative impacts that result from exposure of these materials. When deposits cannot be avoided, advance knowledge of their locations and characteristics will allow for appropriate construction design and remediation procedures. Therefore, the objectives of this study were (1) to evaluate field relationships between depth to sulfide-bearing sediments and landscape parameters, and (2) to test models for predicting depth to sulfides.

Materials and Methods

Description of Study Area

The study area (Fig. 1) encompasses the intersection of Hanover County, VA, with the Studley and Seven Pines United States Geological Survey (USGS) 7.5 minute topographic quadrangles, along with small areas of surrounding quadrangles to the east (Manquin and Quinton) and west (Yellow Tavern and Richmond). This area was selected based on proximity to extensive acid roadcuts at the interchange of US-360 and I-295 at Mechanicsville and our assumption of associated regional geologic and geomorphic conditions. Elevation ranges from approximately 6 m to over 62 m above sea level, and regionally the area slopes eastward at approximately 1.7 m per km. The area is drained by two northwest to southeast running rivers - the Pamunkey River to the north and the Chickahominy River to the south. Three main landforms exist in this region: broad, gently rolling uplands, incised valleys along drainages, and broad level floodplains along the two major rivers.

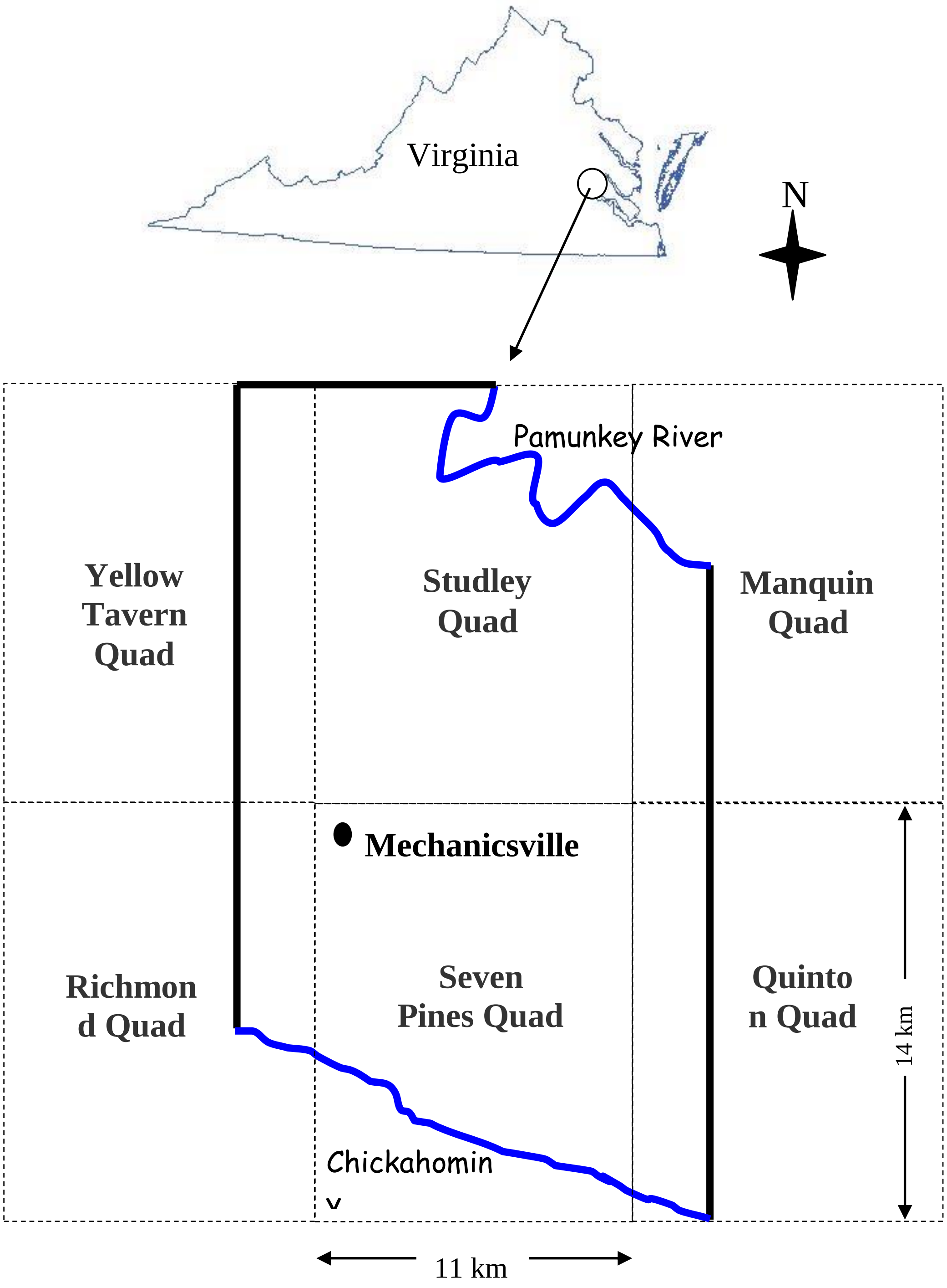

Figure 1. Location of study area outlined in bold with USGS 7.5 minute topographic quadrangles identified and outlined with dashed line.

Detailed descriptions of geology in the study area are provided by Daniels and Onuschak (1974) and Ward (1984). Basement rocks, including the Petersburg granite and Triassic red-beds, underlie a wedge of Coastal Plain sediments at depths ranging from approximately 62 to 215 m. Cretaceous age fluvial sediments of the Potomac Formation overlie the basement rock and are generally brightly colored and heterogeneous in character and extent. Lower Tertiary deposits overlie the Cretaceous sediments, and are typically described as drab grayish-green, glauconitic clayey silt and quartz sand, with some fossiliferous layers. Tertiary marine and estuarine sediments unconformably overlie the Lower Tertiary deposits, and similarly consist of drab, gray, green, and blue marine sediments. Within the study area, the Tertiary record typically includes the following formations, from youngest to oldest: Yorktown, Eastover, Choptank, Calvert, Nanjemoy, Marlboro Clay, and Aquia (Rick Berquist, personal communication). Daniels and Onuschak (1974) group the Calvert formation and younger transgressive sediments (now mapped as the Eastover and Yorktown formations) into a clayey silt (cs) map unit, which is exposed in small areas along streams throughout the study area, and in larger areas along the floodplains of the Pamunkey and Chickahominy Rivers. Where overlain by Quaternary sediments, the surface of the cs unit is believed to somewhat parallel surface topography. Maximum elevation of the cs unit is estimated to be about 55 m, near the western margin of the study area, and dips gently eastward to an elevation of about 43 m; however, ancient and present-day streams have incised the unit to much lower elevations. Although little information exists on sulfide occurrence in these sediments, pyrite has been documented in several formations of the Lower Tertiary and Tertiary marine deposits in Virginia (Orndorff, 2001) and Maryland (Valladares, 1998). Overlying the marine deposits, Tertiary and Quaternary age fluvial sands and gravels blanket most of the study area to a maximum thickness of 30 m, except where removed by stream incision. These oxidized sediments range in color from buff to red, and in particle size from clays to boulders.

Detailed information on soils in the study area is provided by the Soil Survey of Hanover County, Virginia (Hodges et al., 1980). Flood plains and terraces along the two major rivers are mapped as the Pamunkey-Dogue-Forestdale association, which consists of deep, well-drained, moderately well drained, and poorly drained soils with loamy or clayey subsoil. Pamunkey soils are found mainly along the Pamunkey River and are typically strongly acid to neutral. The Dogue and Forestdale soils are found on terraces and low-lying upland areas along the Chickahominy. The Dogue soil is typically extremely to strongly acid, while the Forestdale is very strongly to medium acid. Other soils found in this association include: Altavista, Tarboro, Chewacla, Fork, Myatt Variant, Wahee, and Wehadkee series, and Fluvaquents, Hydraquents, and Udifluvents. The uplands between the Chickahominy and Pamunkey Rivers are mapped as the Norfok-Orangeburg-Faceville association and the Udults-Ochrepts-Suffolk association. These associations consist of deep, moderately-well drained to excessively drained soils with sandy, loamy, and clayey subsoils, which are typically very strongly to strongly acid. Other series found in these associations include: Atlee, Bourne, Caroline, Dunbar, Duplin, Goldsboro, Kempsville, Kenansville, Masada, Suffolk, and Varina soils.

Well Log Analysis

Regional depth to reduced sulfide-bearing marine sediments (hereafter referred to as depth-rs) was determined from water well logs provided by the Hanover County Health Department. Depth-rs was indicated by distinct color changes between the overlying oxidized sands and gravels and the reduced sediments. Oxidized materials are typically described as red, yellow, or brown while the reduced materials are described as gray, blue, or green. In some cases the boundary was identified at a specific depth, but often it was identified as occurring within a depth interval. For example, the data may be recorded as "14 – 34 ft: red sand to blue clay". In such cases, the mean depth (i.e. 24 ft) was used as depth-rs. Well locations were determined from parcel plats accompanying the well logs. Only well logs that clearly marked both the location of the well, and depth-rs, was used, resulting in a data set of 408 points. The utility of basing a predictive model on existing well logs is that such data are readily available, and can be used in other areas to construct similar hazard rating maps at relatively low cost.

Twenty-three borings were drilled throughout the study area for use as validation points to test our interpretations from the well logs, as well as to assess the frequency of S occurrence. Samples from within the first 30 cm of reduced sediments were collected from these borings, analyzed for %S using an Elementar Vario Max CNS analyzer, and rated for presence of calcium carbonate by the HCl fizz test (Sobek et al., 1978).

A digital map of Hanover County streams and spatial data transfer standard digital elevation maps (SDTS DEM's) with 30 m horizontal resolution for the 7.5-minute quadrangles were obtained from the USGS. A digital tax parcel map was provided by the Hanover County Planning Office and a digital soils map was obtained from the United States Department of Agriculture. The USGS 7.5 minute geologic maps for this area were digitized in-house. Digital maps were analyzed using ARCView geographic information systems (GIS) software to determine elevation, slope, distance to streams, surficial geology and soils for all data points.

Three approaches were used to predict depth-rs. First, regression analysis was used to develop a predictive model by evaluating relationships between depth-rs and landscape variables, including elevation, slope, distance to streams, and surficial geology. Second, interpolation was used to calculate a depth-rs surface based on depth-rs from the well logs. Approximately three-fourths of the total data set was randomly selected to generate an interpolated surface in ARCView using the default options of inverse distance weighting on the twelve nearest neighbor points. The remaining well points were used to evaluate the accuracy of the predicted values. This approach was repeated three times. Third, a procedure was developed to create probability maps indicating the likelihood of encountering reduced sediments within a given depth for defined elevation groups. The procedure used two risk factors based on elevation and soil type. The data were divided into seven elevation classes. For each class the depth-rs data were summarized with descriptive statistics, including the relative proportion of data points with depth-rs less than 5, 9, and 13 m. An elevation risk factor was designated and quantified (as indicated below in parenthesis) for each elevation class based on the proportion of wells with depth-rs below the specified depth. Risk factors were assigned in the following manner: i) > 50% is a very high risk (4), ii) 26 – 50% is a high risk (3), iii) 11 – 25% is a moderate risk (2), and iv) ≤ 10% is a low risk (1). The data also were divided based on soil map unit, and again the depth-rs data were summarized with descriptive statistics. For soil map units containing at least 5 well data points, the relative proportion of wells with depth-rs less than 9 m was calculated and used to assign soil risk factors as follows: i) > 25% is a high risk (3), ii) 11 – 25% is a moderate risk (2), and iii) ≤ 10% is a low risk (1). For soil map units with fewer than 5 data points, soil risk factors were designated based on mean depth-rs as follows: i) ≤ 9 m is a high risk (3), ii) 10 to 19 m is a moderate risk (2), and iii) ≥ 20 m is a low risk (1). A final compiled map was generated to indicate the two risk factors using DEM's and the digital soil map.

Results and Discussion

Regression analysis of depth to reduced sediments and landscape parameters

Geographic distribution of the well logs is shown in Fig. 2. Cross-sections (Fig. 3) illustrate that the surface of reduced Tertiary sediments tends to parallel surface topography. In these cross-sections the dashed lines represent generalized surface topography and the surface of reduced Tertiary sediments as interpolated from the well log data. The bold line illustrates more detailed surface topography as interpolated from numerous points along the transects, illustrating that surface topography is much more variable than indicated by the well logs alone. Despite the apparent relationship between surface topography and the surface of reduced Tertiary sediments, regression analysis of depth-rs versus elevation was not significant ($R^2 = 0.22$). A plot of depth-rs versus elevation for all data points (Fig. 4) indicated that variability increased significantly with increasing elevation, and that shallow depth-rs values (< 4 m) occurred at all elevations. Regression using various combinations of elevation, slope, distance to streams, and geology did not improve results (Table 1). Despite repeated efforts, a model could not be developed by regression analysis to adequately predict depth-rs using landscape variables.

Several factors may help explain these poor results. Depth-rs is mainly controlled by two variables: depth of sediments overlying the sulfidic strata and depth of weathering within that strata. Where Tertiary marine sediments are surficially exposed, depth-rs is a function of weathering, and is largely affected by hydrology. Surface features such as elevation, slope, and distance to streams should be related to depth-rs. However, as indicated in Table 1, these factors alone could not be used to predict depth-rs. Underlying factors, such as textural changes between layers, may affect hydrology in locations that otherwise seem similar. Furthermore, local topographic features, such as intermittent streams or depressions, which are not apparent at the available map scale, may help explain discrepancies between seemingly similar locations.

Where Tertiary marine sediments occur in the subsurface, depth-rs is determined more by depth of sediments overlying the sulfidic strata than by hydrology. This depth is a function of the depositional, structural, and erosional features that control the thickness of overlying Quaternary sediments, and may be further complicated by geologic factors such as lateral variation in sedimentary facies during deposition, the shallow dip of Coastal Plain sediments to the southeast, and the occurrence of normal faults. Consequently, the variables that control depth-rs over the entire study area may be too complex for regression analysis to allow approximations, let alone precise predictions, of depth-rs.

As indicated in Fig. 4 sites with shallow depth-rs are dispersed throughout the study area and occur over the full range of elevations. Shallow depth-rs is expected at lower elevations because overlying Quaternary sediments have been removed and the water table occurs at shallower depths. Shallow depth-rs at higher elevations are more difficult to explain. Twelve high-elevation wells had depth-rs values of less than 7 m. These wells were not geographically clustered, and they occurred at various elevations (45 m – 61 m), stream proximities (175 – 720 m) and slopes (1 – 15%). These data do not explain the shallow depth-rs values; however, site visits could reveal local conditions that account for these occurrences. Furthermore, features which are controlled by the same factors that influence depth-rs, such as soil types (discussed below), may serve as useful indicators for estimating depth-rs.

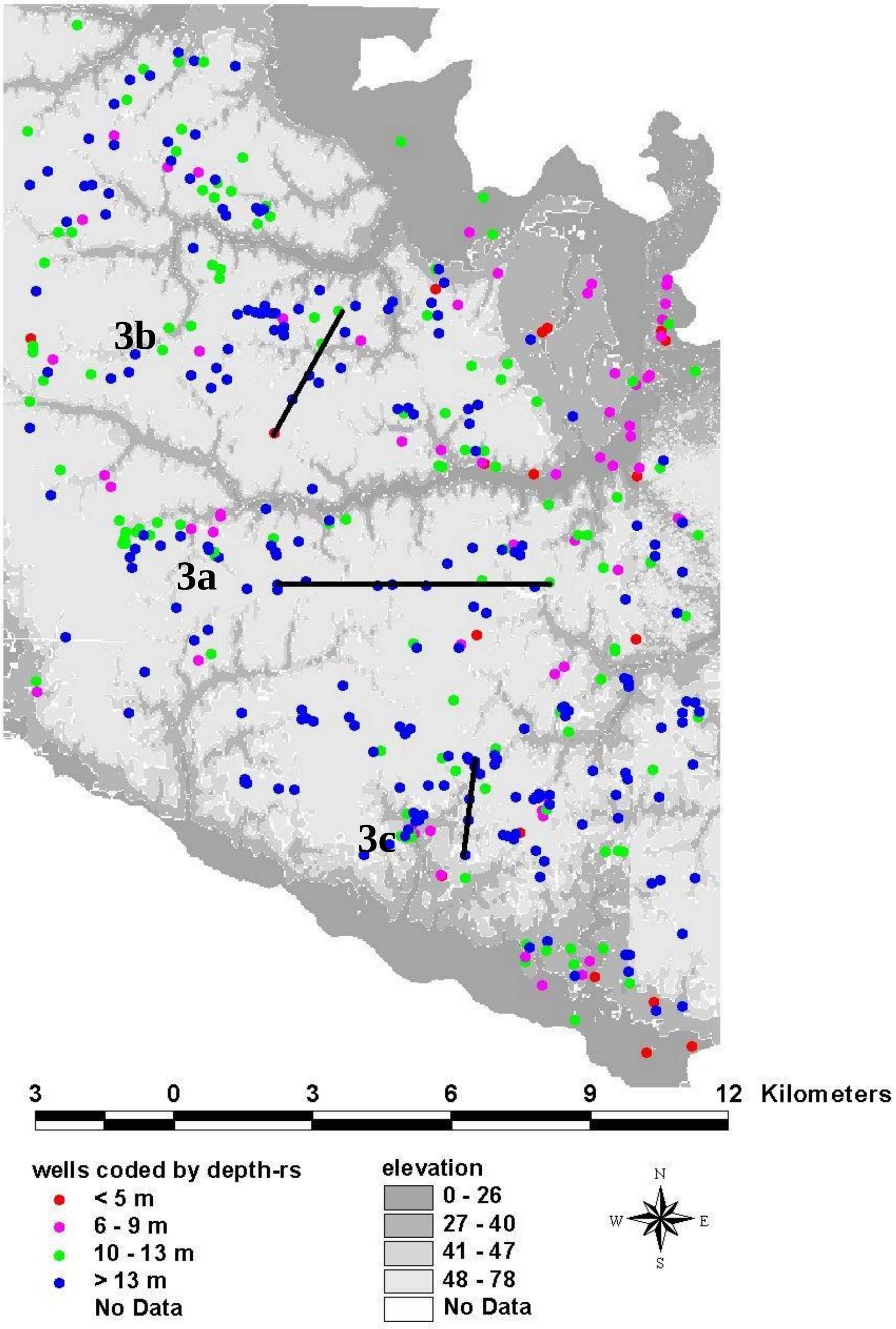

Figure 2. Elevation, geographic distribution, and depth-rs of 408 well logs in the study area near Mechanicsville, Virginia (see Fig. 1). Black lines indicate locations of transects for Fig. 3a, 3b, and 3c.

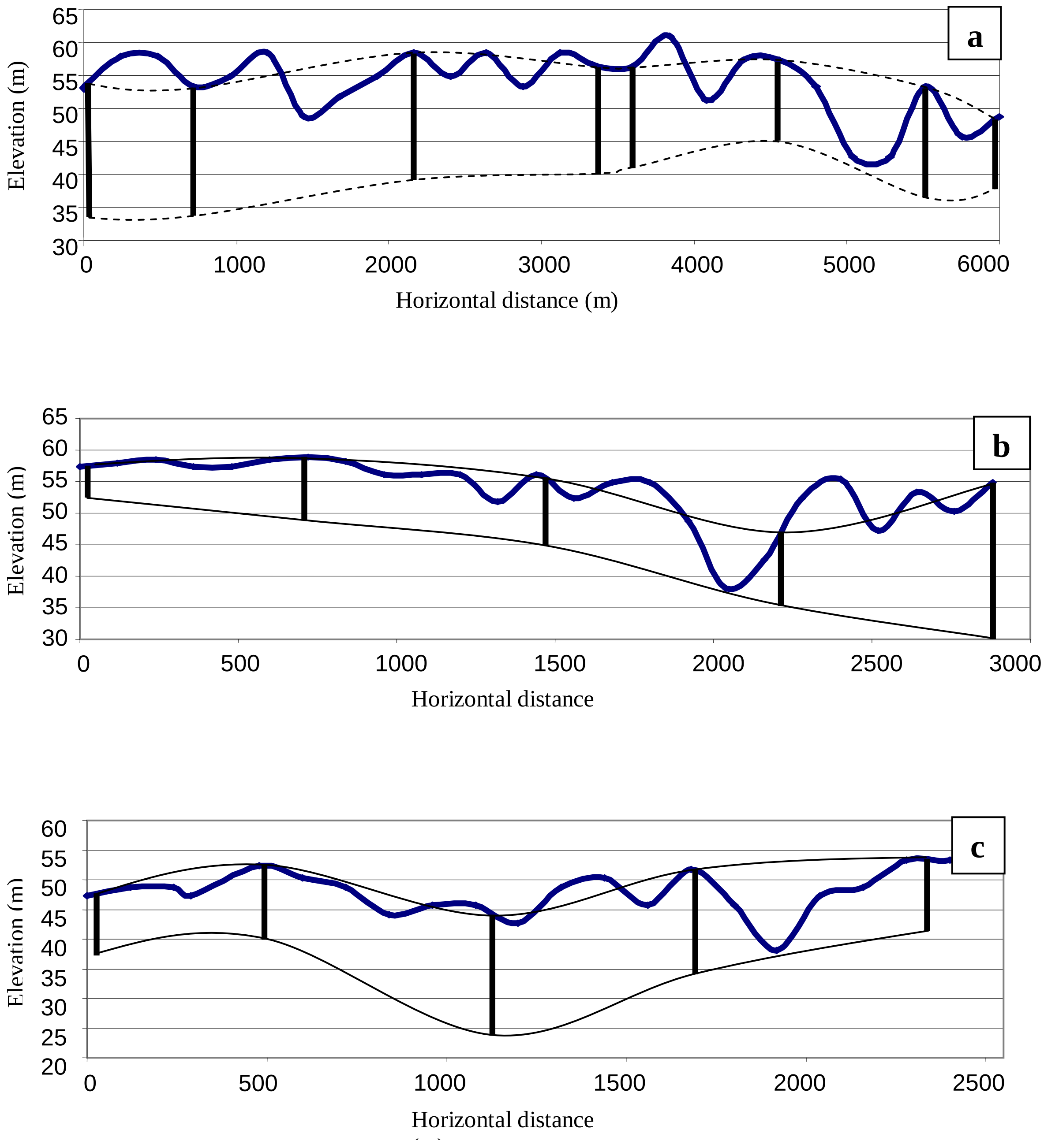

Figure 3. Cross-sections from transects shown in Fig. 2. The dark horizontal line represents surface topography and the dark vertical lines show depth to reduced sediments as indicated by wells along each transect. The dashed lines represent interpolated surface topography, and the boundary between oxidized and reduced sediments, as indicated by the wells. (Vertical exaggeration is approximately 40X for 3a, 18X for 3b, and 16X for 3c.).

Finally, while it is impossible to assess the true extent of data error, a number of possible sources may contribute to the poor regression results. For example, given the relatively low elevations throughout the study area even small errors in vertical accuracy could significantly impact elevation determinations. Similarly even a slight error in positional accuracy could result in a relatively large difference in elevation determination. At the time this study was completed, DEM's for the study area were available only at 30 m resolution. Use of finer resolution DEM's may improve results by providing more accurate elevation data.

Other sources of data error may arise from the precision and accuracy of the well logs. While some logs identified the boundary between reduced sediments and overlying materials at a specific depth, others identified the boundary within a depth interval. Estimating the boundary depth within this interval could result in an error of a few meters from the true value. Also, the accuracy with which these logs are recorded is unknown and may vary among well drillers. Most of the well logs clearly indicated the well location on a parcel plat, and positional errors within the plat would have little impact on the elevation determination. However, for some wells slight positional changes would result in significant elevation differences. Therefore, mislocation of some wells may have resulted in inaccurate elevation determinations.

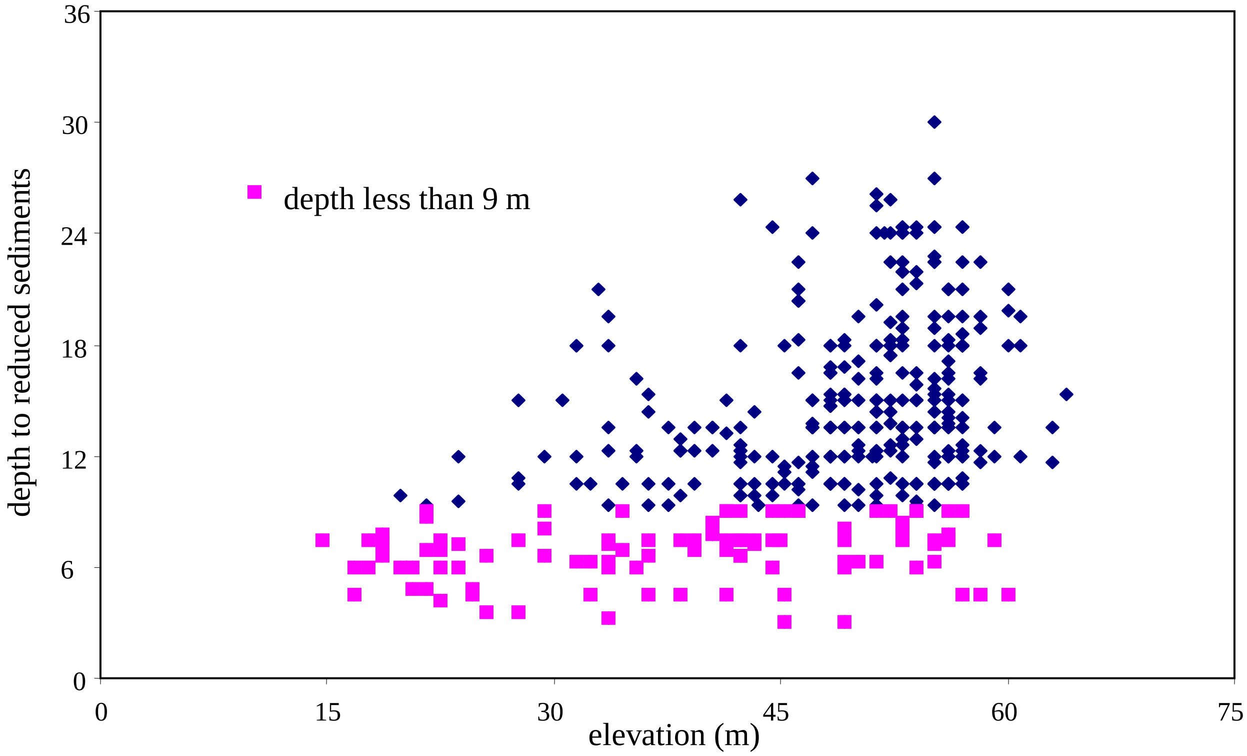

Figure 4. Scatterplot of depth to reduced sediments (depth-rs) versus elevation for all well logs in the study area. Points with depth-rs < 9 m are highlighted in pink.

Table 1. Coefficients of determination (R^2) from simple and multiple regression analyses of depth to reduced sediments against selected landscape variables.

Variable	Data set	R^2
Elevation	all wells	0.22
Slope	all wells	0.02
distance to nearest stream	all wells	0.02
Elevation/slope/distance to nearest stream	all wells	0.23
Elevation	Wells from areas surficially mapped as Tertiary sediments	0.03
Elevation/slope/distance to nearest stream	Wells from areas surficially mapped as Tertiary sediments	0.23
Elevation	Wells from areas surficially mapped as Cretaceous sand and gravel	0.13
Elevation	Wells from areas surficially mapped as alluvium	0.15

Unlike the study by Valladares (1998), depth to sulfidic sediments in this study area could not be predicted precisely by regression analysis using landscape parameters. This may be explained by three main differences between these two studies. First, the Quaternary sediments that occur as a blanket of variable thickness over most of the Virginia study area are almost non-existent in the Maryland study area. Where these sediments do occur in the Maryland landscape studied they tend to exist as a relatively thin layer (less than 4 m deep). Therefore, depth-rs in Valladares' study area is dominantly controlled by weathering and hydrology, which may be explained by landscape parameters that are easy to quantify, such as point relief. In contrast, depth-rs in the Virginia study area was more difficult to predict due to various controls over depth to sulfidic strata as previously described. Second, Valladares observed depth-rs from his own deep borings, and determined elevation by surveying transects in the field. These data should be more accurate than that obtained from the well logs and DEM has used in this study. Finally, the Valladares study was based on detailed observations from a few locations, and validation data were obtained from the same location as the data used to derive the predictive models. This study was based on observations dispersed over a larger study area. Factors that control weathering and hydrology are likely to be more uniform for a specific location than over a larger area. Consequently, relationships should be more predictable for a small area than for a large area. To evaluate the application of predictive models based on data from a few specific locations, validation data should be collected from outside the study sites.

Interpolation of depth to reduced sediments

For a second approach to predicting depth to reduced sediments, depth-rs values were interpolated to generate a depth-rs surface. The interpolation procedure was repeated three times using randomly selected subsets of the well data. Regression analysis of the interpolated depth-rs values and the known depth-rs values for the remaining well points indicated poor results for all three trials (r^2 = 0.19, 0.19, and 0.24). In each case, the root-mean-square error was approximately 5 m with a standard deviation of 4 m. Interpolation cannot adequately predict depth-rs because the surface of the sulfide-bearing strata is too variable and some areas are not adequately represented with well data. While some regions of the study area have dense clusters of data points, such as around new housing developments, other regions yield few data points. Similarly, drinking water wells tend to be located at a distance from creeks and rivers leaving those areas poorly represented. Also, since well log data have been kept on file at the Health Department only for the past few decades the existence of numerous old farms throughout the study area results in relatively large regions without data. Considering the significant landscape changes that may exist between data points, depth-rs is too variable to be accurately interpolated with the density and distribution of available sample points for this study area.

Probability mapping of depth to reduced sediments based on general elevation classes

Although regression analyses and interpolation could not provide accurate means for predicting depth-rs, evaluation of the data did reveal a few generalizations. Most importantly, depth-rs values increase with increasing elevation and shallow depth-rs values are found over the entire elevation range, although they are less frequent at higher elevations. To provide general estimates of depth-rs, the data were grouped into seven elevation classes and depth-rs values were summarized by descriptive statistics. The results are provided in Table 2 and illustrated in Fig. 5. Overall, the data may be divided into three groups based on mean values. Mean depth-rs was 7 m at elevations below 26 m, 10 - 12 m at elevations between 27 - 47 m, and 15 m at elevations greater than 48 m. Standard deviation increased noticeably above 26 m, indicating that depth-rs is much more variable at moderate to high elevations.

The three groups coincide with the three main landforms present in the study area. Elevations below 27 m are found primarily in floodplains, and to a lesser extent in drainages. Depth-rs is consistently shallow at lower elevations for two reasons. First, the floodplain landforms which dominantly occur at low elevations in the study area have naturally exposed Tertiary marine sediments at the surface, although a thin layer of alluvium covers some areas. Second, floodplains have high water tables that prevent oxidation of these sediments. Therefore, sulfidic sediments are maintained in a reducing environment at relatively shallow depth. Elevations between 27 – 46 m typically occur within the incised valleys surrounding drainages. Within this setting, Tertiary marine sediments may be naturally exposed at the surface, or they may be covered by a thin layer of alluvium or a variably thick layer of Quaternary sands and gravels. These geological differences, in combination with variable water table depths, result in a higher range of depth-rs values than for the floodplain landscapes. For a large extent of the study area the 150 ft (46 m) contour line marks a distinct break between upland topography and incised drainage slopes. Elevations greater than 47 m typically occur in the broad, gently rolling uplands. In this landscape, a variably thick layer of Quaternary sands and gravel overlies the Tertiary marine sediments. This blanket of material, in combination with various possible structural and micro-relief features previously discussed, results in the highest mean and range of depth-rs values.

Summarizing the data in the manner described above provides predictive ranges for depth-rs using elevation to represent related landforms. To evaluate the accuracy of these ranges, 23 deep borings were made at ten sites dispersed throughout the study area. Data from these borings are shown in Table 3 and Fig. 5. For one high-elevation point, reduced sediments were not encountered before reaching the maximum drill depth of 20 m. Depth-rs for this hole was assigned a value of 21 m to represent the minimum value at which reduced materials would be likely to occur. For each of the validation points, depth-rs fell within the depth-rs ranges defined for each elevation class, as indicated in Fig. 5. At lower elevations the validation points lay within the shallow end of the depth-rs ranges, while at higher elevations some validation points

Table 2. Descriptive statistics summarizing depth to reduced sediments (depth-rs) from well log data for seven elevation classes in the study area.

elevation (m)	n*	mean depth-rs(m)	median depth-rs (m)	standard deviation (m)	min depth-rs(m)	max depth-rs (m)
< 20	8	7	7	1	5	8
20 - 26	22	7	7	2	4	12
27 - 33	17	10	11	4	4	18
34 – 40	39	11	11	4	3	21
41 - 47	65	12	11	5	3	26
48 - 54	133	15	14	5	3	27
> 55	124	15	15	5	5	30

***** number of wells

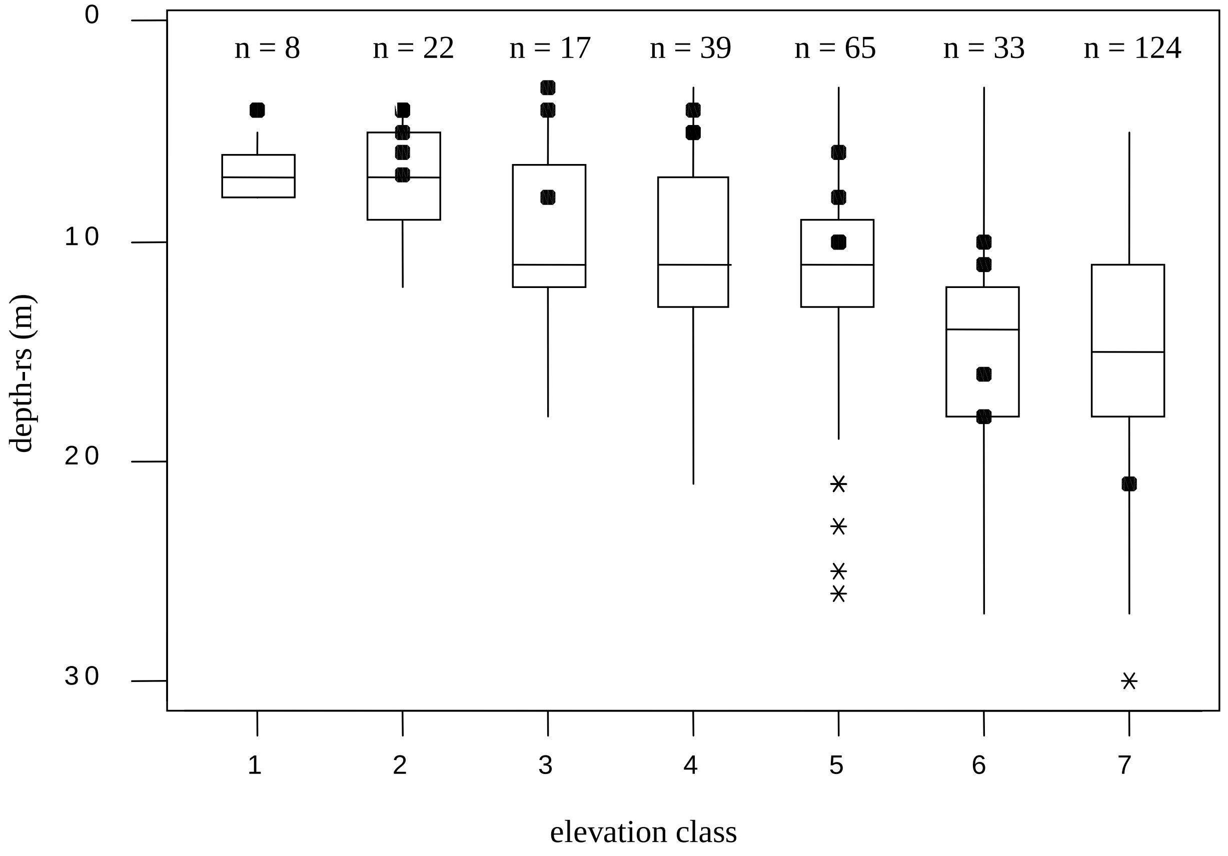

Figure 5. Boxplot of depth to reduced sediments for elevation classes. Asterisks indicate outliers from the well log data. Bullet markers indicate validation drill holes.

Table 3. Elevation, elevation class, depth to reduced sediments (depth-rs), percent S at depth-rs, for 23 deep borings used as validation points.

sample	elevation (m)	elevation class	Depth-rs (m)	%S
vdawk1	29	3	3	0.8
vdawr2	19	1	4	0.7
vdawr1	27	3	4	1.4
vdawk2	27	3	4	0.8
vdatot2	32	3	4	1.2
vdamcv10	35	4	4	1.4
vdaecw2	12	1	4	2.7
gas	25	2	4	1.3
vdatot3	41	5	5	0.7
vdabcw3	20	2	5	1.1
vdaph1	41	5	5	0.6
vdamcv7	43	5	6	1.4
vdaecw1	22	2	6	2.1
vdabcw1	23	2	7	0.9
vdapeas1	47	5	8	0.7
vdabcw2	30	3	8	2.6
wm2	47	5	10	1.1
vdatot1	47	5	10	0.6
vdatot4	52	6	10	0.6
vdacp1	50	6	11	0.5
vdalfr	55	6	16	0.6
vdapc	55	6	18	0.9
vdavl1	57	7	21	n.d.

occurred more deeply within the ranges. The apparent over prediction of depth-rs by the well log data for lower elevations may be due in part to inadequate distribution of the validation points. The twelve lowest elevation validation points, which represent the three lowest elevation classes and part of class 4, were located in areas where Tertiary marine sediments were exposed at the surface, or overlain by only a thin layer of alluvium or terrace deposits. Most of the well log data for elevation classes 1 and 2 were from similar geological settings. Class 1 had only 1 validation point, which lay at the extreme shallow end of the depth-rs values. For class 2, the validation points span over half of the depth-rs range defined by the well log data. As elevation increases, the well logs are increasingly located in areas overlain by Quaternary deposits. Therefore, for elevation classes 3 and 4, overlying Quaternary sediments will result in greater depth-rs values for the well logs than for the validation points. More uniform distribution of validation data over the different geologies may have resulted in closer agreement between the well log data and the validation data. For the remaining elevation classes, well log data and validation data were from areas where reduced sediments are generally overlain by Quaternary deposits. Validation points for elevation classes 5 and 6 were mostly within the average range of depth-rs values. Class 7 had only 1 validation point, which lay within the deep end of depth-rs values. Overall, agreement of the validation points with the defined depth-rs ranges supports the use of the summarized well log data for providing general estimates of depth-rs based on elevation.

In the study area, and surrounding regions, most highway construction tends to involve excavation to depths of less than 9 m. For each elevation class, the relative proportion of data with depth-rs less than 9 m indicates the likelihood of encountering sulfidic materials within common excavation depths. This process may be repeated with the data set for any depth of interest. For example, for each elevation class the data were evaluated to determine the proportion of wells with depth-rs less than 5, 9, and 13 m. The results are presented in Table 4. Elevation risk factors were designated based on the proportion of wells with depth-rs below the specified depth for each elevation class as follows: i) greater than 50% is a very high risk (4), ii) 26-50% is a high risk (3), iii) 11-25% is a moderate risk (2), and iv) less than 11% is a low risk (1). As shown in Table 4, elevations below 26 m have a very high probability of encountering reduced sediments within 9 m. The probability is high between elevations of 27 – 40 m, moderate for elevations between 41 – 47 m, and low for elevations above 47 m.

Table 4. Proportion of well logs for each elevation class with depth to reduced sediments (depth-rs) less than 5, 9, and 13 m, and associated risk factor designations.

			depth-rs < 5 m			depth-rs < 9 m			depth-rs < 13 m		
elevation class	elevation (m)	n	n5*	n5/n	risk**	n9*	n9/n	Risk	n13*	n13/n	risk
1	< 20	8	0	0.00	l (1)	8	1.00	vh (4)	8	1.00	vh (4)
2	20 - 26	22	2	0.09	l (1)	15	0.68	vh (4)	22	1.00	vh (4)
3	27 - 33	17	1	0.06	l (1)	7	0.41	h (3)	14	0.82	vh (4)
4	34 – 40	39	1	0.03	l (1)	14	0.36	h (3)	29	0.74	vh (4)
5	41 - 47	65	1	0.02	l (1)	15	0.23	m (2)	48	0.74	vh (4)
6	48 - 54	133	1	0.01	l (1)	9	0.07	l (1)	45	0.34	h (3)
7	> 55	124	0	0	l (1)	10	0.08	l (1)	45	0.36	h (3)

* n5, n9, and n13 = number of wells with depth-rs less than 5 m, 9 m, and 13 m, respectively.

** risk assessment: l = low probability of encountering sulfidic sediments, m= moderate probability, h = high probability, vh = very high probability. Value in parenthesis indicates quantification of risk.

Probability mapping of depth to reduced sediments – soils

Soils data may provide additional information for predicting general depth-rs values. Soil development results from the interaction of five factors – parent material, time, climate, organisms, and relief. Locally, areas that are mapped with similar soil series likely have experienced the same relative influence of these factors. Furthermore, to some extent, the factors that control soil formation may affect depth-rs. For example, depth-rs values should be shallowest where Tertiary marine sediments are naturally exposed at the ground surface, and depth-rs is primarily a function of the weathering profile. Specific soil types that form over Tertiary marine sediments may be associated with shallow depth-rs, and therefore can be used as an indicator. Similarly, certain soils that form over Quaternary sands and gravels may indicate deeper depth-rs values by reflecting the presence of this material overlying sulfidic sediments.

Table 5. Soil map units represented by the well log data. For each map unit the dominant soil series, total number or wells, minimum, mean, and maximum depth to reduced sediments (depth-rs) values, and associated soil risk designations are identified.

	dominant soil series	n*	minimum depth-rs (m)	mean depth-rs (m)	maximum depth-rs (m)	n9/n**	soil risk
46	Myatt Variant	1	4	4	4	n.d	h (3)
8	Augusta	1	5	5	5	n.d	h (3)
30	Forestdale	1	6	6	6	n.d	h (3)
43	Kenansville Variant	1	6	6	6	n.d	h (3)
70B	Udults-Ochrepts	1	7	7	7	n.d	h (3)
70F	Udults-Ochrepts	1	9	9	9	n.d	h (3)
65B	Turbeville	1	17	17	17	n.d	m (2)
2	Altavista	1	18	18	18	n.d	m (2)
10B	Bourne	1	20	20	20	n.d	l (1)
40A	Kempsville-Bourne	1	24	24	24	n.d	l (1)
12D2	Caroline	2	7	10	14	n.d	m (2)
63C	Suffolk	2	22	23	24	n.d	l (1)
55B	Pamunkey	3	7	9	12	n.d	h (3)
63A	Suffolk	3	9	13	19	n.d	m (2)
28	Fluvaquents	4	5	7	14	n.d	h (3)
23	Dogue	4	6	8	11	n.d	h (3)
13B2	Caroline-Dogue	5	5	14	25	0.20	m (2)
69D	Udults	5	11	13	16	0.00	l (1)
25A	Duplin	6	5	17	25	0.17	m (2)
25B	Duplin	6	9	16	21	0.00	l (1)
39C	Kempsville	6	9	13	21	0.00	l (1)
34B	Goldsboro	6	9	14	17	0.00	l (1)
69C	Udults	7	6	10	16	0.29	h (3)
50A	Orangeburg-Faceville	8	5	15	25	0.12	m (2)
41	Kenansville	10	8	17	30	0.10	l (1)
13C2	Caroline-Dogue	16	6	14	24	0.25	m (2)
49B	Orangeburg	16	10	15	25	0.00	l (1)
70E	Udults-Ochrepts	17	5	11	26	0.53	h (3)
39B	Kempsville	17	8	12	18	0.18	l (1)
70C	Udults-Ochrepts	19	3	10	18	0.37	h (3)
54B	Pamunkey	19	5	10	20	0.50	h (3)
47A	Norfolk	27	7	14	23	0.11	m (2)
50B	Orangeburg-Faceville	30	8	16	27	0.07	l (1)
70D	Udults-Ochrepts	34	5	10	18	0.38	h (3)
40B	Kempsville-Bourne	37	5	14	25	0.08	m (2)
63B	Suffolk	42	5	14	26	0.12	m (2)
47B	Norfolk	46	3	15	27	0.11	m (2)

n = number of wells

** n9/n = proportion of wells with depth-rs < 9 m.

To evaluate the relationship between soil map units and depth-rs in the study area, the well log data were summarized to indicate the number of wells in each represented soil map unit, along with the minimum, maximum, and average depth-rs for those wells. The proportion of wells with depth-rs less than 9 m was calculated for map units represented by at least 5 data points. The results are presented in Table 5. Thirty-seven map units were represented by the well log data. For map units with 5 or more data points, soil risk was designated in a manner similar to elevation risk based on the proportion of wells with depth-rs less than or equal to 9 m. A number of map units contained few data points and additional data would be necessary to accurately assess these units. Nonetheless, soil risk factors based on mean depth-rs were assigned to help illustrate the interpretive process. Map units with a high risk factor included 46, 8, 30, 43, 70B, 70F, 54B, 69C, 70C, 70D, and 70E. Map units with a moderate risk included 65B, 2, 12D2, 63A, and 13B2, 13C2, 25A, 39B, 40B, 47A, 47B, 50A, and 63B. Map units with a low risk included 10B, 40A, 63C, 25B, 34B, 39C, 41, 49B, 50B, and 69C.

Finally, two sets of data points were used to evaluate risk assessments based on elevation and soil type. The first set consisted of the previously described validation points. The second set consisted of 35 well logs provided in Daniels and Onuschak (1974). These well logs included engineering test borings, public water wells, and Virginia Department of Mineral Resources test borings. In the following discussion these two sets of data are referred to collectively as the test points. As described above, and indicated in Table 5, each test point was assigned an elevation risk factor and a soils risk factor for encountering depth-rs at less than or equal to 9 m. Three test points occurred in soil map units which were not previously represented by the well log data. These points, indicated in Table 6, were assigned soil risk factors based on comparison of the map unit descriptions with the map units listed in Table 5. An overall risk was assigned by multiplying the elevation and soil risk factors. Overall risk values of 1 or 2 indicate that the most severe risk is moderate for only one factor, and therefore suggest a relatively low probability of encountering depth-rs within 9 m. Overall risk factors of 3 or higher indicate that at minimum either one factor has a high risk, or both factors have moderate risks, and therefore suggest a relatively high probability of encountering depth-rs within 9 m.

Of the 58 test points, 20 had depth-rs less than 9 m. Of these 20 points, 18 (90%) were accurately assigned high overall risk factors of at least 3. The 2 remaining points, which were assigned low overall risk values, had borderline depth-rs values of 7 and 8 m. Of the 38 points with depth-rs greater than or equal to 9 m, 34 (89%) were accurately assigned low overall risk factors of 1 or 2. Of the 4 remaining points which were assigned high overall risk values, 3 had borderline values of 9 or 10 m. These results demonstrate that use of the elevation risk factor, in conjunction with the soil risk factor, can successfully predict if depth-rs is less than 9 m. The interpretations presented in Table 4 and 5 were applied to DEM's and soils maps using ARCView to generate a risk map (Fig. 6) that may be used to evaluate the likelihood of encountering reduced sediments within 9 m for specific locations. By evaluating the well log data with respect to a specified depth-rs, and appropriately re-assigning risk factors, this process could be repeated for other depth-rs values. These elevation and soil risk factors are specific to the study area, and should not be extrapolated beyond its boundaries. However, this method of risk assessment could be applied to other areas in the Coastal Plain, where the data are available.

Table 6. Test points used to evaluate the application of elevation risk and soil risk for predicting depth to reduced sediments (depth-rs).

well ID	soil map unit	depth-rs (m)	elevation (m)	elevation risk*	soil risk*	Overall risk (elevation risk X soil risk)
vdawk1	23	3	29	h (3)	h (3)**	9
1799	70D	3	50	l (1)	h (3)	3
vdawr2	28	4	19	vh (4)	h (3)**	12
vdawr1	63B	4	27	h (3)	m (2)	6
vdawk2	23	4	27	h (3)	h (3)**	9
vdatot2	28	4	32	h (3)	h (3)**	9
vdamcv10	70E	4	35	h (3)	h (3)	9
vdaecw2	22	4	12	vh (4)	h (3)***	12
gas	8	4	25	vh (4)	h (3)**	12
2237	69C	5	43	m (2)	h (3)	6
vdatot3	70E	5	41	m (2)	h (3)	6
vdabcw3	64B	5	20	vh (4)	m (2)***	8
vdaph1	63B	5	41	m (2)	m (2)	4
vdamcv7	70E	6	43	m (2)	h (3)	6
vdaecw1	70D	6	22	vh (4)	h (3)	12
vdabcw1	2	7	23	vh (4)	h (3)**	12
3901	40B	7	54	l (1)	m (2)	2
3087	70E	8	48	l (1)	h (3)	3
vdapeas1	41	8	47	m (2)	l (1)	2
vdabcw2	39B	8	30	h (3)	m (2)	6
3900	40A	9	17	vh (4)	l (1)**	4
3638	41	9	49	l (1)	l (1)	1
1842	50B	9	46	m (2)	l (1)	2
2573	50B	9	50	l (1)	l (1)	1
1800	70B	9	50	l (1)	h (3)**	3
2197	47B	9	56	l (1)	m (2)	2
wm2	63A	10	47	m (2)	m (2)**	4
vdatot1	70C	10	47	m (2)	h (3)	6
vdatot4	63B	10	52	l (1)	m (2)	2
2841	47A	10	55	l (1)	m (2)	2
vdacp1	63B	11	50	l (1)	m (2)	2
2349	39B	12	49	l (1)	m (2)	2
1662	63B	12	50	l (1)	m (2)	2
199	40B	12	52	l (1)	m (2)	2
493	50B	13	46	m (2)	l (1)	2
3068	40B	14	50	l (1)	m (2)	2
1770	41	14	57	l (1)	l (1)	1
969	63C	15	58	l (1)	l (1)**	1
2224	63A	15	52	l (1)	m (2)**	2
2417	64B	15	52	l (1)	m (2)***	2
1948	41	15	53	l (1)	l (1)	1
1301	47B	15	53	l (1)	m (2)	2
590	63B	15	57	l (1)	m (2)	2
3638	40B	15	57	l (1)	m (2)	2
1791	70E	15	61	l (1)	h (3)	3
vdalfr	50B	16	55	l (1)	l (1)	1
338	50A	16	50	l (1)	m (2)	2
vdapc	50B	18	55	l (1)	l (1)	1
749	63A	18	53	l (1)	m (2)**	2
2800	50B	18	53	l (1)	l (1)	1
3546	47A	18	59	l (1)	m (2)	2
2501	63A	20	49	l (1)	m (2)**	2
2617	63B	21	56	l (1)	m (2)	2
vdavl1	50A	21	57	l (1)	m (2)	2
3904	63B	21	52	l (1)	m (2)	2
3782	50B	26	51	l (1)	l (1)	1
750	50B	27	53	l (1)	l (1)	1
3401	50B	34	52	l (1)	l (1)	1

* h = high, m = moderate, h = high, vh = very high

** soil risk factor based on fewer than 5 data points

*** soil risk factor based on assessment of soil map unit description

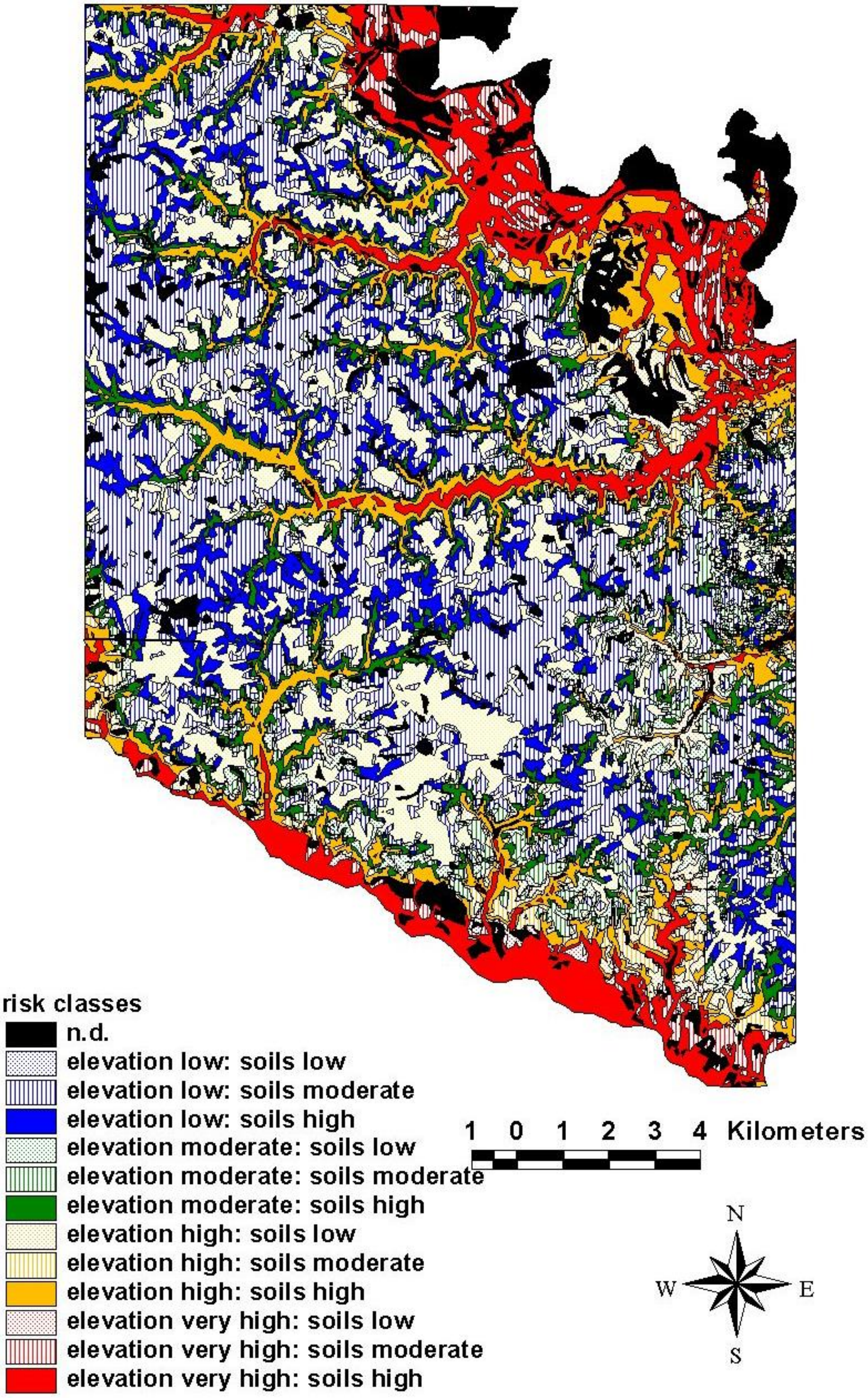

Figure 6. Risk map, based on elevation and mapped soil type, for encountering reduced sediments within a depth of 9 m for study area near Mechanicsville, VA (see Fig. 1).

Exposure of reduced Tertiary sediments is problematic only if the material contains high levels of S (> 0.2%). Therefore, the deep borings were used to evaluate the large-scale lateral distribution of S in reduced Tertiary sediments. From each boring, a sample was collected from the upper 30 cm of reduced sediments and evaluated for %S and presence of calcium carbonate. Previous work indicated that %S is highly correlated with potential peroxide acidity for samples that do not contain calcium carbonate (Orndorff, 2001). All samples had relatively high S values (Table 3), and none of the samples contained $CaCO_3$, indicating that exposure of reduced Tertiary sediments would always present a high risk of acid production.

Conclusions

Within the study area, depth-rs values generally increased with elevation, although values were as shallow as 3 - 4 m for all elevations, and were much more variable at higher elevations. A model could not be developed by regression analysis to accurately and precisely predict depth-rs using landscape variables, which included elevation, slope, distance to streams, and surficial geology. Similarly, interpolation based on depth-rs from a subset of the well logs data was unsuccessful at predicting depth-rs for the remaining points. However, by grouping the data into seven elevation classes, depth-rs values could be summarized to provide predictive value ranges. Depth-rs from twenty-three validation points supported the use of these predictive ranges. Significant breaks in mean depth-rs among the elevation classes reflected local geomorphic differences. Classes 1 and 2, which represent floodplains, had a mean depth-rs of 7 m. Classes 3, 4, and 5, which represent incised drainages, had a mean depth-rs of about 11 m. Classes 6 and 7, which represent uplands, had a mean depth-rs of 15 m. The data may be further analyzed to predict the likelihood of encountering sulfidic sediments within specific excavation depths by evaluating the relative proportion of wells that have depth-rs below the specified value for each elevation class. Within the study area, road corridor excavation depths are typically less than 9 m. For this depth, there is a low risk of encountering sulfidic materials at elevations greater than 47 m, a moderate risk at elevation between 41 – 47 m, and a high to very high risk at elevations below 41 m. Similarly, by evaluating the minimum, maximum, and mean depth-rs values for well logs within each represented soil map unit, soil risk factors may be assigned to those units. High-risk map units contained the following series: Augusta, Dogue, Caroline, Forestdale, Kenansville, Myatt Variant, and Pamunkey. Soil map units consisting of unspecified Udults, Ochrepts, and Fluvaquents also had a high risk. The elevation risk factor in conjunction with the soil risk factor accurately described the likelihood of encountering depth-rs at less than 9 m for 90% of 58 test points. All reduced sediment samples from locations throughout the study area contained high S levels, indicating that exposure of reduced Tertiary sediments should always be considered hazardous in terms of acid production.

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