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Factors of subaqueous soil formation: a system of quantitative pedology for submersed environments

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Abstract

The development and use of estuarine sediment maps for estuarine restoration efforts have been hindered by the lack of a formal classification system or comprehensive model that explains the distribution of sediments. To enhance the evaluation, understanding, and management of sediments in shallow water habitats, a new approach must be developed in order to provide a more holistic assessment and cartographic representation of the sediment column. Having demonstrated that shallow water sediments undergo pedogenic processes and are systematically distributed across the subaqueous landscape, we applied this new technique to the development of subaqueous soil resource inventories of Sinepuxent Bay, MD and Indian River Bay, DE. These efforts indicate that the present concept of sediment as unconsolidated geologic materials must give way to a new concept—the concept of subaqueous soils. In addition, our studies indicate the need to alter present methodologies for the acquisition and cartographic representation of sediment data through the utilization of the soil–landscape paradigm and a classification scheme (such as *Soil Taxonomy*) for the development of subaqueous soil resource inventories. Here we present the supporting rationale for the development of subaqueous soil resource inventories; and through a synthesis of geologic and pedologic principles and concepts, propose a new state factor equation to explain subaqueous soil genesis and distribution.

Keywords: Pedogenesis; Sediment; Estuarine; State factors

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1. Introduction

Geological concepts and methods have dominated estuarine sediment mapping efforts for over 100 years. Due to their apparent relationship to sedimentary rocks found in upland positions, early sediment research primarily focused on documenting sediment attributes and distribution in an effort to understand the mechanisms and processes related to fossil and oil-bearing strata (Trask, 1932). The near exclusive focus on geologic aspects of estuarine sediments remained intact until ecologists began to relate benthic communities to substrate characteristics (Sanders, 1958; Rhoads, 1974). Yet even with the inclusion of new ecological concepts, the historical emphasis on geology in the study of estuarine substrates has had major impacts on the sediment mapping methodologies and on ecological interpretations. With the initiation of efforts to restore submersed aquatic vegetation (SAV) and other benthic organisms, it is imperative that a more detailed and ecologically oriented estuarine sediment mapping model be developed to better target restoration sites.

2. Historical approach to sediment mapping

When the study of estuarine sediments was initiated, as is common with developing disciplines, the first step undertaken was characterization. Grid-pattern sampling schemes were frequently employed, particularly because this was a useful approach when spatial relationships among the data were not otherwise established and/or poorly understood. Thus, the utility of grid-pattern sampling in characterization studies is partially based upon the underlying assumption that the variability is more random than systematic (Wilding and Drees, 1983). Although technologies and related concepts have evolved dramatically over the past 75 years, the sampling design and methods employed in estuarine sediment mapping efforts have remained relatively static. The continued use of grid-pattern schemes for data acquisition (and subsequent analyses) has severely limited detailed development and understanding of systematic relationships. Use of this approach has also led to the analysis and presentation of sediment data by individual parameter (%Pb or %OC), rather than through a more holistic approach where the attributes of the sediment column are synthesized and delineated.

The continued application of differing methodologies and class systems for the acquisition, presentation, and interpretation of sediment data limits the utility of the information, especially for ecological studies. Sediment maps today look much the same as they did in the early 1900s—individual parameters presented on separate maps. In some cases, these may be delineations of particle size (Louderback, 1939; Wells, 1989), while in others the maps may be concentration isobars for organic carbon or other parameters (Hough, 1942; Kerhin, 1980). Another limitation involves the lack of uniformity in attribute classes, resulting in confusion in what is actually represented by the classes. Wentworth's scale (Wentworth, 1922), Inman's classes (Inman, 1952), Shepard's classes (Shepard, 1954) as well as subjective terminology are all used to describe sediment texture. One of the problems confronted when comparing or interpreting sediment maps is that some attempt (if possible) at normalization of the data is required. Thus, it is very difficult to determine what combination of sediment characteristics exist at any one location and what impact their *combined* presence may have on benthic plants and animals. This single parameter, non-integrated approach lacks inherent power to synthesize data into integrated units for management or interpretation.

Most often, sediments are sampled neither by pedogenic horizon (due to the absence of this concept among most researchers) nor by uniform depth (owing to the wide variety of samplers commonly used in the field for surficial sampling) and nearly always neglects any material deeper than about 30 cm. However, the surface oxic layer of some sediments may be relatively thick (8–10 cm), thin ($<$ 10 mm), or may be essentially absent. Due to the design of the samplers, the depth of sampling can vary by as much as 15 cm. Thus, analyses may at times reflect a "mixed" sample of surface and subsurface layers that could have significant differences in physical and chemical attributes. Analyses of "surficial" samples that cross a redox discontinuity and include both oxic and reduced materials will be different from those that do not. This could be critical to the accuracy of an ecological or environmental interpretation such as the sediment's effect on aquatic plant roots or the potential for acid-sulfate weathering.

In addition to these problems, estuarine sediment maps are being produced at scales and with attribute classes that are inappropriate for detailed ecological work. Most of the available sediment maps are produced at scales of 1:1,000,000 or smaller (Wells et al., 1994). In contrast, United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) soil survey maps are produced at a scale of 1:12,000 (Brown, 1995). Another major difference between soil survey maps and sediment maps is that sediment maps typically present surficial characteristics (upper 5–10 cm), while soil maps present the characteristics of the soil profile (upper 200 cm). Sediment maps can therefore be viewed as two-dimensional maps, a surface attribute over area, while soil maps are three-dimensional, delineating profile attributes over an area.

The last, and possibly most important, limitation of sediment data is the relative paucity of information in shallow ($<$ 2 m) water habitats. Nearly all estuarine sediment mapping efforts have focused on sediments in water greater than 4 m deep. This is extremely critical as shallow water habitats have been shown to be vital to the growth and survival of estuarine benthic organisms such as clams, scallops, crabs, and SAV. The lack of standard sampling techniques, variable surficial sampling depths, no defined “vertical” taxonomic control section, lack of an adequate mapping protocol, no formal sediment taxonomic system, and the small scale of sediment maps makes it almost impossible to determine ecological relationships at the level now required to enhance and restore estuarine benthic communities. These problems can only be resolved by developing a new sediment mapping model with standardized protocols more applicable to modern needs.

3. Fundamentals of the soil–landscape paradigm

Early pedological concepts (circa late 1800s) of soil were very similar to those underlying present day sediment research. At that time, pedology relied heavily on geologic principles in evaluating soil distribution. The Russian soil scientist, V.V. Dokuchaiev, proposed the first break from the geologic perspective in 1883 by presenting the concept of soil as an independent natural body which “cannot be mistaken as surface rocks” (Dokuchaiev, 1948). He also believed that soils were a result of the interactions of plants and animals, local climate, parent rocks, topography, and the age of landscapes. This approach to the study of soils was later popularized by Jenny (1941) who described the primary factors affecting soil formation as climate (C), organisms (O), relief (R), parent material (P), and time (T). This approach describes the systematic variation in soil properties as related to the five soil forming factors and further implies that soils have unique genetic histories. The publication of these concepts and their later inclusion in soil classification systems completed the break from the early geologic perspective of soil genesis. The concept of soil as an organized natural body resulting from the interaction of the five state factors provided the foundation for the discipline of pedology.

Soil mapping efforts benefited greatly from this new concept of soil genesis. Sampling design could begin to incorporate and rely on the recognized systematic variation of soil properties (Wilding and Drees, 1983) as they relate to the five state factors of soil formation. Of the five factors, relief (topography) has perhaps received the most attention. Milne (1936) first suggested the concept of a *catena*, which is considered to be an interlocking arrangement of soils across a changing landscape. Watson (1965) noted that the catena concept was particularly valuable in the classification and mapping of soils in areas where hydrologic conditions are more variable than parent material. With the introduction of the catena concept, the relationship between soils and topography became more evident.

The utilization of the catena concept and soil-topography relationships in soil survey activities have since become essential to the development of soil maps and interpretations (Soil Survey Division Staff, 1993). Yet until the philosophical and scientific basis of soil survey was presented in written form as the soil–landscape paradigm, each soil surveyor learned a collection of conceptual mapping methods through their daily experience of delineating soils in the field. The soil–landscape paradigm refers to the use of landforms as a tool to predict the variation of soils across the landscape (Hudson, 1992). It can be considered to be a synthesis of the state factors of soil formation (Jenny, 1941) and the catena concept (Milne, 1936). The components of the soil–landscape paradigm (Hudson, 1992) can be summarized as follows.

(1) Within the soil–landscape unit, the five soil forming factors interact in a distinctive manner. As a result, all areas of the same soil–landscape unit develop the same kind of soil.

(2) The greater the difference between the conterminous areas of two soil–landscape units, the more abrupt and striking the discontinuity between them. The more similar the two conterminous areas of soil–landscape units, the less striking or abrupt the discontinuity tends to be.

(3) The more similar two landforms are, the more similar their associated soils.

(4) Adjacent areas of different soil–landscape units have predictable spatial relationships.

(5) Once the relationship among soils and landscape units have been determined for an area, the soil type can be inferred by identifying the soil–landscape unit.

The formalization of the soil–landscape paradigm was another significant advance in the evolution of pedology.

Advances in computer technology and software further enhanced the utility of soil–landscape relationships in soil resource inventory efforts. Terrain analysis, or topographic analysis, has become increasingly important in pedological research and soil survey activities. The pedological concept of terrain analysis may have begun with the work of Ruhe (1956) that first integrated the concepts of geomorphology and pedology. Terrain analysis has since been applied in a number of ways in terrestrial pedological applications including wetland delineation (Doolittle et al., 1995) and soil survey (Rahman et al., 1997). The soil–landscape relationship is now the formal basis for all soil resource inventory projects underway in the United States. The efficiency of present estuarine sediment sampling and mapping methods could be significantly improved once a similar landscape relationship could be confirmed and used to help develop a conceptual predictive model.

4. Difficulties in applying the soil–landscape paradigm to shallow water environments

Until recently, the application of the soil–landscape paradigm and terrain analysis techniques was severely limited by a number of factors associated with the examination of any permanently submersed environment. One of the problems is the relative imprecision of the location data linked to depth soundings. Compared to terrestrial situations where elevation transects can be precisely located, on open water bodies it is much more difficult to determine exactly where a depth sounding is taken. Thus, bathymetric studies have relied on a variety of methods to determine the location of each transect. For example, Katuna and Ingram (1974) utilized a series of buoys placed in line between two terrestrial landmarks to determine locations for depth data along cross-sections in Pamlico Sound, NC. Others have utilized laser-guided headings, terrestrial landmarks, and simple compass headings. To address this difficulty in our studies of Sinepuxent Bay, MD and Indian River Bay, DE, we utilized one of the most accurate GPS units available. The Rockwell PLGR + GPS has accuracy on the open water of ± 1 m in real-time without post-processing (Rockwell Staff, 1994). Each individual bathymetric sounding (1 cm accuracy) was linked directly to the location data through the use of mapping software (GeoResearch Staff, 1995).

Another problem encountered in the study of submersed environments is the relative dearth of detailed bathymetric data. Digital Elevation Models (DEMs) developed from existing USGS topographic data for terrestrial areas are commonly used in terrain analyses. But, the level of bathymetric data available for many estuaries is insufficient to confidently generate a DEM with detail equivalent to their terrestrial analogs. For example, bathymetric maps developed for Assawoman and Isle of Wight Bay, MD were based on 170 depth sounding within the 4560 ha study area, or 26.8 ha/sounding (Wells et al., 1994). In a study of the Chesapeake Bay, Ryan (1953) collected 213 soundings in 1.2 million ha, or 5354 ha/sounding. In contrast, terrestrial terrain analysis studies rely on elevation data typically representing < 1 ha/data point. To increase the level of detail needed for terrain analysis we collected over 23,000 depth soundings in the 1300 ha Sinepuxent Bay, MD study area or 0.06 ha/sounding (Demas and Rabenhorst, 1998). In a somewhat larger portion of Indian River Bay, DE, we have collected over 38,000 depth soundings (Demas and Rabenhorst, 1999a).

The last problem is that associated with tidal fluctuations. In a terrestrial environment, elevation data collected at one time of the day will be identical to data collected at any other time of the day (or month for that matter). In estuarine settings affected by tides, this is not the case. A depth sounding made from a boat at low tide may be significantly different than a sounding at the same location at high tide. Unless tidal range is extremely small or non-existent, normalization of depth soundings would need to be performed to create an accurate bathymetric map. Small tidal ranges (< 0.5 m) have occasionally been invoked to defend the use of uncorrected water depth data recorded at the time of sampling for the creation of bathymetric maps (Wells et al., 1994). To account for tidal fluctuations we utilized a digital tide gauge calibrated to 0

Mean Sea Level (MSL) through an elevation survey linked to permanent USGS benchmarks. Tide level was recorded during bathymetric sounding runs and later used to normalize all depth soundings to 0 MSL (Demas and Rabenhorst, 1998).

The protocol developed and applied for the acquisition and evaluation of bathymetry resulted in the identification of seven major subaqueous landforms (Demas and Rabenhorst, 1998) in Sinepuxent Bay, MD. Evaluation of transect data from each landform indicated a soil taxonomic (family level) purity of 50% to 100% (Demas and Rabenhorst, 1999a). While demonstrating that a sediment-landscape relationship exists, it became apparent that the systematic variation responsible for this relationship had not been sufficiently investigated for synthesis into a model. In addition, in order to incorporate pedologic concepts of systematic variation (i.e. Jenny's state factor equation), it would be necessary that estuarine sediment could be considered *soil*.

5. Shallow water environments and the concept of soil

Although there have been proposals to consider shallow water sediments as subaqueous soils, they were largely conceptual in nature, relying on subjective reasoning rather than analytical data (v.Post, 1862; Kubiena, 1953; Goldschmidt, 1958; Ponnamperuma, 1972; Demas et al., 1996). To consider estuarine sediments as soil, pedogenic processes (Simonson, 1959) should be responsible for horizon differentiation. Although differing layers within a sediment column are often identified, the critical question is whether the identified layers can be considered to be soil horizons. Demas and Rabenhorst (1999b) demonstrated that identified sediment layers are a function of pedogenesis and therefore could be considered subaqueous soil horizons. These observations led to a change to the definition of soil contained in *Soil Taxonomy* (Soil Survey Staff, 1999) to include soils in permanently submersed environments. This dramatic alternative to the present concept of sediment, along with the development of a subaqueous terrain analysis protocol, created an opportunity to evaluate the applicability of Jenny's state factors of soil formation on the genesis and distribution of subaqueous soils.

6. State factor approach to subaqueous pedogenesis

To adequately address a state factor approach, the work of sediment researchers needs to be incorporated along with classical pedologic concepts and models. Jenny's state factor equation:

$$\mathrm{S} = f(C, O, R, P, T)$$

suggests that subaqueous soil development could follow a similar genetic pathway.

Based on his compendium of sediment characteristics of United States estuaries, Folger (1972a,b) may have presented the first genetic model for estuarine sediments. He believed that sediment was a function of three factors: source geology (G), bathymetry (B), and hydrologic condition (H) (flow regime). Folger's concept of sediment genesis can be shown in written form as:

$$\mathrm{Se} = f(G, H, B).$$

Although limited in scope, it did help explain some fundamental observations about sediment attributes. Therefore, it is important that the components of the models of Jenny and Folger be evaluated concurrently.

6.1. Climate

The climate under which a terrestrial soil forms is classically conceptualized in terms of temperature and precipitation. Climate is known to significantly influence soil properties, but the effects are generally more visible only over a regional scale (Rabenhorst and Wilding, 1986). In a subaqueous environment, differences in precipitation are meaningless (unless one considers precipitation-driven erosion and delivery of terrestrial materials). The effect of climatic (principally temperature) variations may become apparent over greater distances (i.e. if the subaqueous soils of Sinepuxent Bay were compared to those of areas such as Naragansett Bay, RI or Pamlico Sound, NC). But, this has not been fully investigated. Nevertheless, the effect of climate can be seen in the subaqueous pedogenic transformation processes of sulfidization and organic matter decomposition (Demas and Rabenhorst, 1999b), which are known to be temperature dependant in a submersed environment (Odum and de la Cruz, 1967).

6.2. Organisms

The role of organisms in soil genesis has been widely documented and is a significant component of Jenny's model. Previous research has shown that biota can have a marked impact on subaqueous soil characteristics. Katuna and Ingram (1974) noted that vegetated shoals did not exhibit any distinct structure due to bioturbation and the presence of SAV roots. Rhoads (1974) suggested that benthic deposit feeders supplied a food source for bottom dwelling organisms by transferring organic matter from anaerobic layers to the surface. Submersed macrophytes have been shown to create iron rich plaques (oxidized root channels) in the adjacent sediment due to the pumping of oxygen to the roots (Chambers and Odum, 1990). These and other studies have shown that benthic organisms can alter the sediment in five ways. These include bioturbation, organic carbon depletion, the production of binding agents such as shells and mucous, biodeposition, and oxygenation of anaerobic sediments.

A number of our observations in Sinepuxent Bay provide additional evidence of the role of organisms in subaqueous soil genesis (Demas, 1998; Demas and Rabenhorst, 1999b). The accumulation of organic matter evident in Sinepuxent Bay surface horizons is a dramatic illustration of the effect of benthic organisms on subaqueous soil properties. Benthic organisms were also found to have increased the thickness of oxidized surface horizons over 10 times the typical depth (Fenchel and Riedl, 1970) through their burrowing activities in tandem with diffusion processes. Elevated levels of calcium carbonate were linked to the biogenic production of shells and subsequent incorporation into soil horizons after the death of the organism (Demas and Rabenhorst, 1999b). In addition, biomass production of submersed macrophytes were linked to subaqueous soil attributes in areas of similar water quality (Merrell et al., 1997; Demas et al., 1999), leading to higher levels of organic materials in the soils.

6.3. Parent material (source geology)

Subaqueous soil characteristics, as in their terrestrial counterparts, are related to the nature and origin of the parent material. A subaqueous soil derived from barrier island washover materials will be dominantly sandy, composed mainly of quartz, and be inherently infertile. In contrast, subaqueous soils derived from more loamy materials may exhibit finer textures, contain higher amounts of weatherable minerals, and exhibit higher levels of natural fertility. In Sinepuxent Bay, the influence of parent material is demonstrated in the characteristics of subaqueous soils in the shallow mainland coves. The parent materials of this landform are loamy estuarine sediments overlying soil materials previously in a terrestrial position. Landward erosion of the coves removed the upper horizons of the previously existing mainland soils, exposing their substrata to inundation. Subsequent deposition of water borne sediment resulted in a duality of parent material. Thus, values for organic carbon content in the substrata are very low ($< 0.10\%$) and are similar to those found in present day terrestrial soil substrata (Brady and Weil, 1996). These soils also had extremely low levels of pyrite ($< 0.01\%$), which again is a reflection of the terrestrial nature of the parent material (Demas and Rabenhorst, 1999b).

6.4. Time

The component of time, though difficult to evaluate, must be included in any subaqueous soil genetic model. Although often we were unable to directly quantify the effect of time, its role can be inferred from a variety of observations. For example, the degree of bioturbation will be related to the length of time organisms have been active in the sediment. The development of sedimentary structure and subaqueous landforms will also depend on the time available for the action of processes responsible for their expression. It could be said, however, that most subaqueous soils are probably relatively young, and may be somewhat analogous to the youthful alluvial soils of flood plains.

6.5. Relief

The role of relief (topography) in determining subaqueous soil characteristics is illustrated by a number of studies. In Chesapeake Bay, two of six noted sediment types occurred respectively on "broad flats" and on an underwater "terrace" (Ryan, 1953). Slumping or creeping of sediment has also been found to occur on slopes greater than 5% (Duarte and Kalff, 1986). Although a landform relationship was established in our study of Sinepuxent Bay, relief, as applied in Jenny's terrestrial soil model, is not directly applicable to submersed environments for a number of reasons. For example, in a terrestrial situation, relief helps determine the local expression of hydrology. In a submersed environment, the reverse may occur where the hydrologic conditions (flow regime) become a controlling factor in topographic expression.

6.6. Bathymetry

A number of studies have examined sediment attributes in relation to bathymetry. In Pamlico Sound, NC, particle size changes associated with textural transition zones were well sorted and not "smeared" across bathymetric gradients (Wells, 1989). This was believed to indicate that in shallow estuaries with low tidal ranges and low bottom current velocities, there is little large-scale dispersion of particles. The abrupt changes in particle size suggest a possible relationship between bathymetry and modal grain size. Louderback (1939) also recognized this relationship between bathymetry and particle size. Deepwater basin areas of San Francisco Bay were found to be finer in texture than shallow regions. Similar results were obtained in Sinepuxent Bay, MD where subaqueous soils of a broad deep (> 2.5 m) central basin were characteristically fine-grained while those located on shallow (< 1 m) overwash fans were typically sandy (Demas and Rabenhorst, 1998).

6.7. Flow regime (hydrologic condition)

Particle size distribution, which has been the focus of a large number of sediment studies, provides more clues concerning possible systematic relationships. Krumbein and Aberdeen (1937) examined the sediments of Barataria Bay, LA (USA) and found that high-energy channels were dominated by coarse-textured materials while more broad low-energy environments were characteristically silty. High organic carbon contents are associated with fine textured sediments while sandy textured sediments exhibited significantly lower levels of organic carbon. Similar results were obtained in Cape Cod Bay, MA (Hough, 1942) and Pamlico Sound, NC (Wells, 1989). Louderback (1939) had previously implicated flow regime as a controlling mechanism in particle size distribution based on similar results in a study of San Francisco Bay sediments. Flow regime here refers to the processes responsible for suspension, transportation, and deposition of particles as a result of internal waves (Cacchione and Southard, 1974), wind-induced surface waves, and currents (Sanford, 1994). Transect data from Sinepuxent Bay and Indian River Bay landforms demonstrated a topographic relationship and support other evidence of the influence of landscape position and associated flow regime on subaqueous soil properties. Subaqueous soil characteristics such as the depth to paleo-surfaces, number of discontinuities, depth to sulfidic materials, shell fragment content, and organic debris content were all found to be related to their position on the subaqueous landscape (Demas and Rabenhorst, 1999a).

6.8. The dot factor

In Jenny's (1980) treatise, the dot factor was introduced to accommodate other heretofore-unknown soil forming factors beyond the scope of the original five factors. The occurrence of catastrophic events might be such a factor that could be considered a component of subaqueous soil formation. A dramatic example of the impact of high-energy storm events on subaqueous soil properties was the opening of the Ocean City, MD inlet during the hurricane of 1933. In this case, large expanses of shallow habitat were eroded away and major bathymetric changes were induced. This in turn would have had a significant impact on the properties of the subaqueous soils in the immediate area.

7. A new model of subaqueous soil genesis

To propose a new model for describing the factors of subaqueous soil genesis, we must first acknowledge that Jenny's state factor equation, in its present form, does not adequately address permanently submersed systems. Jenny's equation is based on terrestrial soil genesis where precipitation and downward movement of water through the soil profile are significant driving forces. Folger's concept of sediment genesis is also inadequate. In its present form, it does not provide a reasonable explanation for horizon differentiation, the impact of organisms, or other subaqueous soil concepts.

Therefore, we propose a new state factor equation for the formation of subaqueous soils:

$$\mathrm{Ss} = f(C, O, B, F, P, T, W, E)$$

where Ss is subaqueous soil, C is climatic temperature regime, O is organisms, B is bathymetry, F is flow regime, P is parent material, T is time, W is water column attributes, and E is catastrophic events. While the model appears to simply combine the concepts of Jenny and Folger, the state factors and equation we present here do not necessarily function in the way they were originally conceived, and until this paper, have never been formally presented in either geologic or pedologic publications.

Climatic temperature regime (C), a factor not included in Folger's equation, does not include precipitation as in Jenny's model for terrestrial soils. The climatic component in the new model represents the impact of temperature regime on subaqueous soil genesis. An example of this is temperature's effect on the rate of organic matter decomposition.

Organisms (O), another factor not included by Folger, represents the role that biota play in subaqueous pedogenesis. The development of light colored, relatively thick surface horizons can be partially attributed to irrigation of benthic burrows with oxygenated water.

Bathymetry and flow regime $(B$ and $F)$ take the place of relief (R) in Jenny's equation. The catena concept, which manifests itself in Jenny's equation as relief, is not applicable in a permanently submersed environment. Thus, the bathymetry factor alone does not exclusively address subaqueous soil profile development in terms of its position on the underwater landscape. Instead, bathymetry helps to account for the effects of internal and wind generated waves on the subaqueous soil surface. Flow regime, which helps to shape underwater topography, accounts for differences in the energies associated with currents and tides. In tandem, bathymetry and flow regime play the same genetic role as relief does in terrestrial soil environments.

Parent material (P), a factor in both equations, explains the effect of the source material on subaqueous soil profile attributes. Subaqueous soils that develop in areas subject to barrier island washover events are predictably sandy textured.

Time (T) represents the amount of time available for the expression of subaqueous soil attributes.

Water column attributes (W), a factor in neither Jenny's or Folger's equations, is added here to account for variations in water column constituents that could have an impact on subaqueous soil characteristics. Subaqueous soil profiles developed in freshwater regions of estuaries may be significantly different than those in saline environments due to variations in sulfate, sodium, and other dissolved components. Dissolved oxygen levels could also play a role in the thickness and development of light-colored surface horizons.

Catastrophic events (E) in this equation is very similar to Jenny's concept of the dot factor. In this case, subaqueous soil profiles may be severely impacted by major storm events or other uncontrollable or unknown factors.

8. Conclusions

The change in concept from "shallow water sediment" to "subaqueous soil" could foster significant and far-reaching changes in the ecological, geological, and pedological communities. For the first time, data have been documented that show estuarine sediments undergo pedogenesis and therefore are actually subaqueous soils (Demas and Rabenhorst, 1999b). This has the potential to dramatically alter the conceptual basis for the mapping of estuarine bottom types in shallow water $(< 2.5$ m) environments.

The definition of soil, as published in *Soil Taxonomy* (Soil Survey Staff, 1999), now includes shallow water areas in estuaries that are capable of supporting rooted submersed aquatic vegetation. The definition had remained unaltered for nearly 50 years. This change expands the horizontal extent of pedology into shallow sub-tidal habitats.

The development of a state factor equation makes available a model to help understand the genesis and distribution of subaqueous soils. In conjunction with the soil–landscape paradigm (Hudson, 1992), a new more efficient predictive methodology is now available for the inventory of subaqueous soil resources.

The development of subaqueous soil surveys based on the new mapping protocol (Demas and Rabenhorst, 1998) could be a significant advance for estuarine restoration programs. Detailed mapping of different subaqueous soil taxonomic types could be utilized immediately to further define the habitat requirements of benthic flora and fauna, and ultimately help target suitable restoration sites for clams, oysters, scallops, and SAV.

The challenge now is for pedologists, geologists, estuarine scientists, and ecologists to begin to test the model, quantify the factors, and ultimately utilize the model to develop accurate subaqueous soil inventories in shallow water estuarine habitats.

References

Brady, N.C., Weil, R.R., 1996. The Nature and Properties of Soil. Prentice-Hall, Upper Saddle River, NJ.

Brown, J.H., 1995. Soil Survey of Montgomery County, Maryland. USDA-Natural Resources Conservation Service, Washington, DC.

Cacchione, D.A., Southard, J.B., 1974. Incipient sediment movement by shoaling internal gravity waves. Journal of Geophysical Research 79, 2237–2242.

Chambers, R.M., Odum, W.E., 1990. Porewater oxidation, dissolved phosphate and iron curtain. Biogeochemistry 10, 37–52.
Demas, G.P., 1998. Subaqueous Soils of Sinepuxent Bay, Maryland. PhD Dissertation, Dept. of NRSL, University of Maryland, College Park.
Demas, G.P., Rabenhorst, M.C., 1998. Subaqueous soils: a resource inventory protocol. Proceedings 16th World Congress of Soil Science, Montpellier, France. August 20–26, 1998. Symp. 7, on CD.
Demas, G.P., Rabenhorst, M.C., 1999a. The soil–landscape paradigm in a submersed environment. 1999 Soil Science Society of America Annual Meeting, Salt Lake City, UT. Agronomy Abstracts, p. 267.
Demas, G.P., Rabenhorst, M.C., 1999b. Subaqueous soils: pedogenesis in a submersed environment. Soil Science Society of America Journal 63, 1250–1257.
Demas, G.P., Rabenhorst, M.C., Stevenson, J.C., 1996. Subaqueous soils: a pedological approach to the study of shallow water habitats. Estuaries 19, 229–237.
Demas, G.P., Stevenson, J.C., Merrel, K.C., 1999. The relationship between subaqueous soil types and SAV production in a coastal estuary. 16th Biennial Estuarine Research Foundation Meeting, New Orleans, LA. Conference Abstracts, p. 29.
Dokuchaiev, V.V., 1948. Russian Chernozem (Russkii Chernozem). Selected Works of V.V. Dokuchaiev, Volume 1. English translation by N. Kaner published by U.S. Department of Commerce, Springfield, VA. Volume in Russian reproduced from 1883 edition.
Doolittle, J., Ealy, E., Secrist, G., Rector, D., Crouch, M., 1995. Reconnaissance mapping of a small watershed using electromagnetic induction and global positioning system techniques. Soil Survey Horizons 36, 86–93.
Duarte, C.M., Kalff, J., 1986. Littoral slope as a predictor of the maximum biomass of submerged macrophyte communities. Limnology and Oceanography 31, 1072–1080.
Fenchel, T.M., Riedl, R.J., 1970. The sulfide system: a new biotic community underneath the oxidized layer of marine sand bottoms. Marine Biology 7, 255–268.
Folger, D.W., 1972. Characteristics of estuarine sediments of the United States. Geological Survey Professional Paper 742. United States Department of the Interior, Washington, DC.
Folger, D.W., 1972b. Texture and organic carbon content of bottom sediments in some estuaries of the United States. Geological Society of America Memoir 133, 391–408.
GeoResearch Staff, 1995. Geolink/PLGR PPS+ GPS/GIS Mapping System XDS Manual. GeoResearch, Billings, MT.
Goldschmidt, V.M., 1958. Geochemistry. Oxford Univ. Press, Ely House, London, 730 pp.
Hough, J.L., 1942. Sediments of Cape Cod Bay, Massachusetts. Journal of Sedimentary Petrology 12, 10–30.
Hudson, B.D., 1992. The soil survey as a paradigm-based science. Soil Science Society of America Journal 56, 836–841.
Inman, D.L., 1952. Measures for describing the size distribution of sediments. Journal of Sedimentary Petrology 22, 125–145.
Jenny, H., 1941. Factors of Soil Formation: A System of Quantitative Pedlogy. McGraw-Hill, New York, 281 pp.
Jenny, H., 1980. The Soil Resource: Origin and Behavior. Ecological Studies, vol. 37, Springer-Verlag, New York.
Katuna, M.P., Ingram, R.L., 1974. Sedimentary structures of a modern lagoonal environment: Pamlico Sound, North Carolina. Sea Grant Publication UNC-SG-74-14, University of North Carolina, Chapel Hill, NC.
Kerhin, R.T., 1980. Chesapeake Earth Science Atlas Number 3: Eastern Bay and South River. Maps. Maryland Geological Survey, Baltimore, MD.
Krumbein, W.C., Aberdeen, E., 1937. The sediments of Barataria Bay. Journal of Sedimentary Petrology 7, 3–17.

Kubiena, W.M., 1953. Bestimmungsbuch und Systematik der Boden Europas, Stuttgart, 392 pp.
Louderback, G.D., 1939. San Francisco Bay sediments. Pacific Science Association. Proceedings of the Sixth Pacific Science Congress 2, 783–793.
Merrell, K.C., Stevenson, J.C., Demas, G.P., Rabenhorst, M.C., 1997. Seagrass production in relation to soil–landscape units: a pedological approach to understanding seagrass distributions. 14th Biennial Estuarine Research Foundation Meeting, Providence, RI. Conference Abstracts, p. 121.
Milne, G., 1936. Normal erosion as a factor in soil profile development. Nature 138, 148.
Odum, E.P., de la Cruz, A.A., 1967. Particulate organic detritus in a Georgia salt marsh-estuarine ecosystem. In: Lauff, G.H. (Ed.), Estuaries. American Association for the Advancement of Science, Washington, DC, pp. 383–388.
Ponnamperuma, F.N., 1972. The chemistry of submerged soils. Advances in Agronomy 24, 29–95.
Rabenhorst, M.C., Wilding, L.P., 1986. Pedogenesis on the Edwards Plateau, Texas: II. Formation and occurrence of diagnostic subsurface horizons in a climosequence. Soil Science Society of America Journal 50, 687–692.
Rahman, S., Munn, L.C., Vance, G.F., Arneson, C., 1997. Wyoming Rocky Mountain forest soils: mapping using an ARC/INFO geographic information system. Soil Science Society of America Journal 61, 1730–1737.
Rhoads, D.C., 1974. Organism–sediment relations on the muddy sea floor. Oceanography and Marine Biology Annual Review 12, 263–300.
Rockwell Staff, 1994. Operations and Maintenance Manual: Precision Lightweight GPS Receiver (PLGR+). Rockwell International, Cedar Rapids, IA.
Ruhe, R.V., 1956. Geomorphic surfaces and the nature of soils. Soil Science 82, 441–455.
Ryan, J.D., 1953. The sediments of Chesapeake Bay. Maryland Board of Natural Resources-Department of Geology, Mines and Water Resources Bulletin 12, Baltimore, MD.
Sanders, H.L., 1958. Benthic studies in Buzzards Bay: I. Animal–sediment relationships. Limnology and Oceanography 3, 245–258.
Sanford, L.P., 1994. Wave-forced resuspension of Upper Chesapeake Bay muds. Estuaries 18, 148–165.
Shepard, F.P., 1954. Nomenclature based on sand–silt–clay ratios. Journal of Sedimentary Petrology 24, 151–158.
Simonson, R.W., 1959. Outline of a generalized theory of soil genesis. Soil Science Society of America Proceedings 23, 152–156.
Soil Survey Division Staff, 1993. Soil Survey Manual. United States Department of Agriculture-Soil Conservation Service Agricultural Handbook 18. Washington, DC, 869 pp.
Soil Survey Staff, 1999. Soil Taxonomy. 2nd edn. Agricultural Hanbook AH-436, United States Department of Agriculture-Natural Resources Conservation Service, Washington, DC.
Trask, P.D., 1932. Origin and Environment of Source Sediments of Petroleum. Gulf Publishing, Houston, TX.
v.Post, H., 1862. Studier ofver nutidans kopregena jordbildningar, gytta, torf, mylla. Kgl. sv. Vetensk. Akad. Handl. 4. Stockholm.
Watson, J.P., 1965. Soil catenas. Soils and Fertilizers 28, 307–310.
Wells, J.T., 1989. A scoping study of the distribution, composition, and dynamics of water column and bottom sediments: Albemarle and Pamlico estuarine system. Albemarle-Pamlico Project Number 89-05, North Carolina Department of Environment, Health, and Natural Resources, Raleigh, NC, 39 pp.
Wells, D.V., Conkwright, R.D., Hill, J.M., Park, M.J., 1994. The surficial sediments of Assawoman Bay and Isle of Wight Bay in Maryland: physical and chemical characteristics. Coastal and Estuarine Geology File Report Number 94-2, Maryland Geological Survey, Baltimore, MD.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30, 377–392.

Wilding, L.P., Drees, L.R., 1983. Spatial variability and pedology. In: Wilding, L.P., Smeck, N.E., Hall, G.F. (Eds.), Pedogenesis and Soil Taxonomy. Concepts and Interactions, vol. I, Elsevier, Amsterdam, pp. 83–116.