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Tide Amplitude and Timing Variation Impacts on Remote Sensing of Emergent Wetlands on the Virginia Coast Reserve

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1.0 Executive Summary

This research addresses the magnitude of temporal and spatial tidal variations in tidal stage and their impact on the spectral characteristics of remotely-sensed wetlands. Specific research included:

- design and use of modular and integrated portable tide stations,
- creation of Cotidal maps for the Chesapeake Bay and Maryland and Virginia coasts,
- assessment of spectral changes in wetlands for different tidal stages,
- comparisons of satellite and photo-derived land-cover data layers for Hog Island, VA, and
- development of recommendations for modification of the C-CAP protocol to account for temporal and spatial differences in tidal inundation.

Specific results include:

- a full range of tidal phases are present in the Chesapeake Bay at any one time, but the differences in tidal stage throughout the Bay were usually less than 40 cm,
- spectral changes resulting from moderate tidal flooding of wetlands were comparable to those observed for many upland cover classes which were not subject to tidal flooding, and
- agreement between independent land-cover data layers was high for marsh areas.

2.0 Introduction

Coastal wetlands are important components of both terrestrial and marine systems. They mediate physical and chemical exchanges between terrestrial and marine systems. Additionally, the high productivity and physical structure of coastal wetlands make them important in their own right to the functioning of coastal marine systems, either as contributors of biomass or by serving as nursery areas and refuges. The unique position of coastal wetlands between the land and the sea makes them vulnerable to a variety of anthropogenic and natural forces. Among the forcing functions that impact coastal wetlands are sea-level rise (either as a result of anthropogenically induced atmospheric warming or long-term climatic trends), development of coastal lands, pollution, erosion and accretion.

The Coastwatch Change Analysis Program (C-CAP) was established by the National Oceanographic and Atmospheric Administration to assess changes in coastal land cover (Cross 1991). Procedures developed by C-CAP researchers emphasize the use of remotely-sensed data in assessing changes in land cover over periods of 1-5 years. An important component of the C-CAP land cover change classification scheme are estuarine and palustrine wetlands (Klemas et al. 1993). A protocol for the development of change maps and geographical information system data layers based on remotely-sensed data is under development by C-CAP researchers (Cross 1991, Dobson and Bright 1991, Klemas et al. 1993, Dobson et al., in review). The protocol allows the detection of land cover changes, while controlling for the temporary changes in image characteristics caused by differences in seasonality, sun angle, and atmospheric transmissivity. Coastal wetland classes can pose special problems for remote-sensing because of tidal fluctuations. As with many problems in change detection, the problem posed by tidal inundation is one of separating interesting and ecologically significant changes from transient or uninteresting changes, such as semidaily tidal flooding. During a course of a tidal cycle, tidal wetlands may go from being completely dry (land) to completely inundated (water). Despite the ecological importance of the tidal cycle to the functioning of the coastal systems, researchers depending on C-CAP products would be ill served by wetland classifications which were dictated by the level of tidal inundation at the time a particular satellite image was acquired rather than by the persistent character of the underlying land cover.

Assessment and amelioration of problems associated with remote-sensing of changes in coastal wetlands requires studies at two scales, that of a particular site and that of the scale of a remotely-sensed image. At the former scale, the degree of inundation (and hence the degree of distortion of vegetation spectra) at a given point and time is a function of a site’s elevation, tidal stage and vegetation height and density. Spectral signatures for wetland vegetation have been shown to be sensitive to a variety of factors including level of flooding, soil background reflectance, season, live and dead biomass, canopy height and moisture content (Ernst-Dattavio et al. 1981, Bartlett and Klemas 1981, Hardisky et al. 1983a, 1983b, 1984, 1986, Jenson et al. 1986). Mixing of the spectral characteristics of water and vegetation can lead to difficulties in classification. For example, Ernst-Dattavio et al. (1981) found that permanently flooded marshes could not be reliably distinguished from conifers using MSS data.

At a larger scale, remote sensing imagery is inherently synoptic. All points on a satellite the image are sampled at a common point in time. However, tide levels are a function of both location and time. The tidal phase angle relative to the adjacent open ocean may be as much as 1.5 hours within the lagoons and marshes of the Virginia Coastal Reserve. Thus, different parts of a remotely-sensed image are not contemporaneous with respect to the tide cycle and experience different levels of inundation. Tidal phase differences on the Virginia coast result in water elevation differences across the lagoon system of up to 1 m.

Specific research objectives are to:

- examine the relative magnitudes of temporal and spatial tidal differences at the scale of satellite images,
- assess the impact of differences in inundation on the spectral characteristics of remotely-sensed wetlands,
- use high-resolution imagery to evaluate a change map produced using the C-CAP protocol, and
- suggest modifications to the current C-CAP protocol to improve its reliability for tidal wetlands

3.0 Spatial and Temporal Components of Tidal Inundation

Relative to the complexities of spatial variations in tidal inundation, temporal differences are relatively simple to assess. In the simplest case, recorded tidal heights at a single station during the times when satellite imagery is acquired can be used to assess the degree to which tidal inundation of wetlands differs between images. If the tidal stage is similar for two images, change detection is simplified, even though spatial differences in inundation within images may interfere with generation of consistent spectral signatures for wetland areas. Change detection in areas where tide curves are markedly asymmetrical can be complicated by tidal phase differences, even if the tidal stage at a reference station is identical. In these cases, both tidal phase angle and stage must be considered if the area under analysis extends far from the reference tidal station, because of the confounding of temporal and spatial differences.

The maximum size of temporal variations in tidal stage can be assessed using tide tables by examining the mean tidal range. Tidal range in the continental United States can vary from almost 3 m to as little as 30 cm (Figure 1). Tides in the Chesapeake Bay area (represented in Figure 1 as Hampton Roads) fall in a the middle range with tidal extremes differing by about 1 m and a predominantly semidurnal tidal pattern (Browne and Fisher 1988).

Dealing with spatial variation in tidal stage is much more complex than dealing with temporal differences. Spatial differences are expressed both as changes in phase and in amplitude of tides across a coastline or estuary and can be quite distinct, even over distances of a few kilometers. For example, the Chesapeake Bay is sufficiently large and complex that the full range of tidal phases are expressed at any given time (Fisher 1986, Browne and Fisher 1988). Patterns are often complex because spatial differences in tidal stage are a function of the morphology and orientation of inlets, estuaries, and rivers. For this reason,

FIGURE 1. Typical tide curves for United States ports. Reprinted from NOAA Tide tables (National Ocean Service 1991).

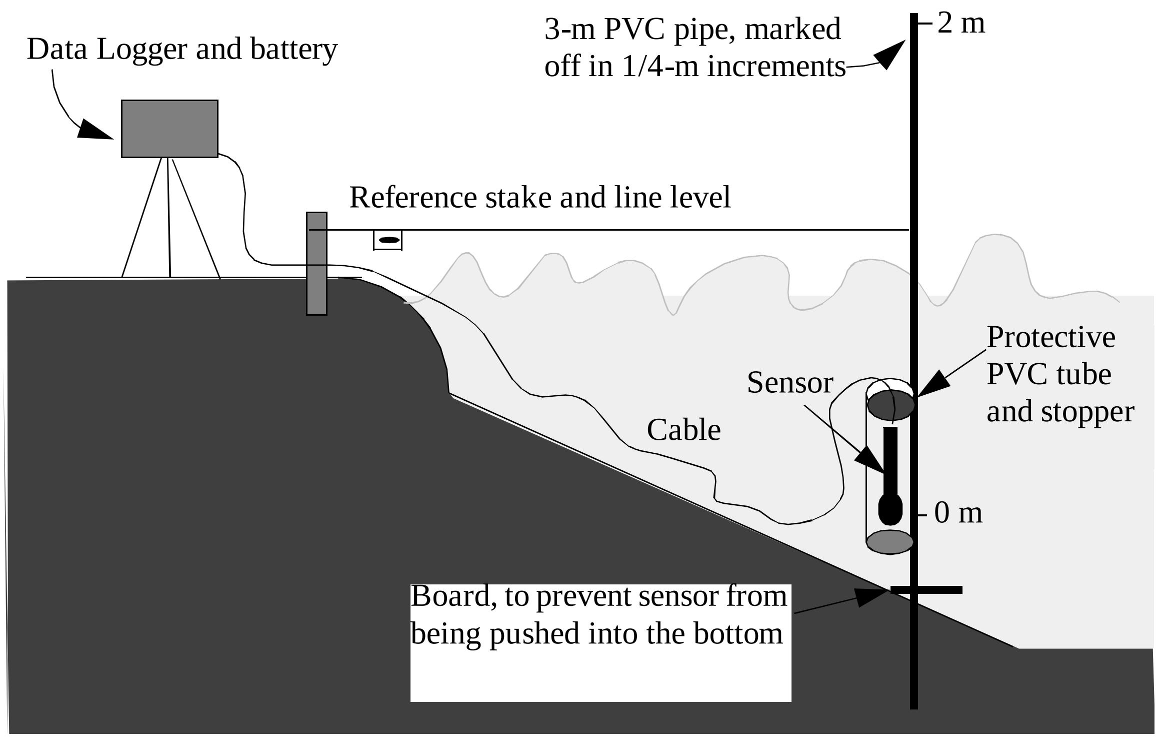
direct measurements, either in the form of tabulated measurements from NOAA tide stations or new measurements from temporary tide stations, are needed.

To assess the relative impact of temporal and spatial differences in tidal stage, we used data from two sources. NOAA tidal difference tables (National Ocean Service 1991) were used to obtain time and tidal range differences for 198 stations in the Chesapeake Bay area. These stations, which were based on three different reference stations (Baltimore, Hampton Roads and Sandy Hook), were standardized to the time base for Hampton Roads. Additionally, we assembled and deployed portable tide stations to provide more detailed information for a section of coastal Virginia.

3.1 Design of Portable Tide Stations

During this study we designed three types of digital tidal stations. All were based on pressure transducers used in association with digital data loggers. The first type used components commercially available from Leopold and Stevens (Figure 2). It consists of a

FIGURE 2. Portable, modular tide station (not to scale).



Stevens model 420 data logger with 12-volt lead-acid gell-cell power supply in a weatherproof enclosure. The logger unit is connected to a vented SDT-II pressure transducer by a 30-m cable. The cable contains both wires for sensor readings and a small semi-rigid tube. Atmospheric pressure is transmitted through the tube, providing automatic compensation for changes in atmospheric pressure. The sensor is hung by its cable inside a protective 3.8

cm diameter tube which is then attached to a 3-m pole. The pole is marked so that the level of the sensor relative to a monument on the adjacent land surface can be determined using a line level. This system provides high resolution (<1 cm over a range of 0 to 3 m), high accuracy (errors < 2.5 cm), long duration with high temporal resolution (over 100 days with measurements at 6 minute intervals). Its limitations are that it is relatively expensive (approximately $1,500 per station) and deployment is limited to places adjacent to an upland or marsh surface or piling.

The second and third types utilize an integrated sensor/logger combination. Its advantages are that it is inexpensive (<$350) and extremely portable. The Onset Computer's "Hobo" sensor combines a data logger with an 8-bit analog-to-digital converter and 1800 memory locations with a Motorola pressure transducer on a single small circuit board (5 cm on a side). The sensor, as currently configured by Onset, is designed for atmospheric pressure measurements. However, by substituting a differential Motorola pressure transducer (model MPX2050GP-9317) with a range of 50 kilopascals for the atmospheric sensor provided by Onset, it can be easily converted for use in a tide station. The resulting resolution is 2.5 cm, with a range of 0.15 to 6 m of water depth. Maximum duration of data collection is a function of measurement frequency. With measurements taken every 12 minutes, it can log for 15 days (or 7.5 days at 6 minute intervals), which is adequate for a temporary tide station. Power comes from a small lithium battery with a life-span of approximately 4 years. Its small size and light weight makes it possible to deploy the sensor away from land surfaces.

One way to utilize the integrated sensor/logger unit is to attach it to the top of a pole, which can then be inserted into the sediments (Figure 3). This system has the advantage that it can be deployed in shallow areas which are not adjacent to land or other fixed structures and can be leveled relative to survey monuments. The weatherproof enclosure can be vented to the atmosphere, permitting automatic compensation for air pressure changes.

The final configuration is to enclose the integrated data logger in a waterproof, pressure resistant case and completely submerge it (Figure 4). This configuration is usable in deeper water than either of the other configurations, but has the disadvantages that it is more susceptible to currents and does not automatically correct for atmospheric pressure. Additionally, failure of the seals in the waterproof enclosure can lead to severe damage to the logger.

3.2 Creation of Cotidal Data Layers

The components of two portable tide stations using Leopold and Stevens model 420 data

FIGURE 3. Rigid mounting system for integrated sensor/logger. Water flowing into opening near bottom of the tube pressurizes the air in the tube to provide pressure readings at the sensor.

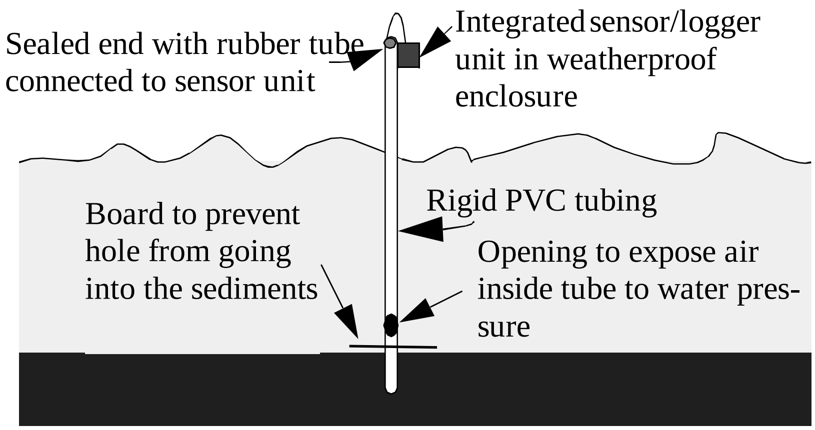
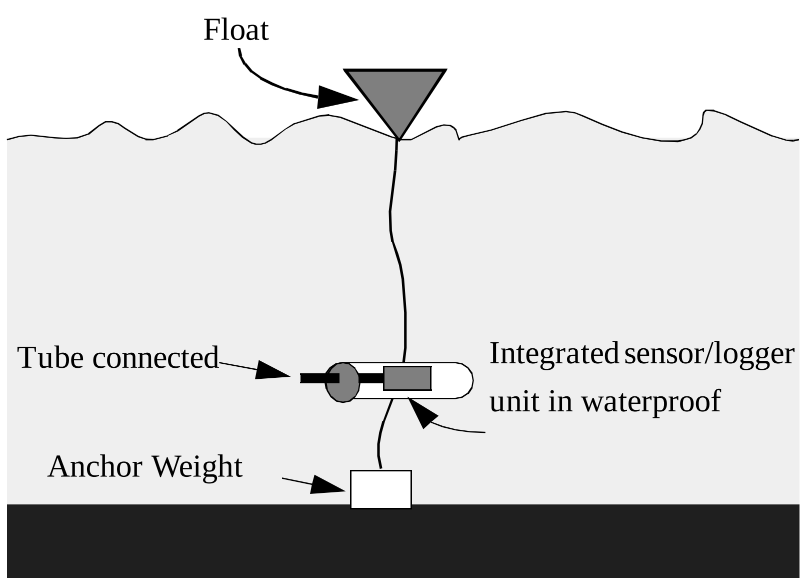


FIGURE 4. Submerged configuration for integrated sensor/logger.



loggers with SDT-II sensors were assembled during the winter of 1992-1993 and deployed during the spring and summer of 1993 (the integrated sensor/logger stations were a late development and data from them are not included here). Time and water level readings were recorded every six minutes, and were related back to contemporaneous readings at a permanent tide station in Redbank, VA. Individual stations were monitored for between two and 19 tidal cycles (mean = 7 tidal cycles). Phase angle, measured as the average time difference between the time of high tide at the reference station and each temporary location, was obtained for all stations. For most stations tidal range was also available. At some stations there was no deep water adjacent to a marsh surfaces, so it was not possible to obtain a range because the sensor was out of the water before low tide. In these cases, we approximated the range using adjacent stations.

Data from our tide stations was combined with data from NOAA tidal difference tables (National Ocean Service, 1991) by setting the tidal phase of Machipango Inlet in our data to correspond with the tidal difference table. We focused on the phase differences between stations at high tide, because this is when the tides are most likely to adversely affect remote-sensing of wetlands.

Browne and Fisher (1988) provide corange and cophase maps for the Chesapeake Bay and its major tributaries. Differences in tidal phase of up to 360 degrees and differences in tidal range of up to 60 cm occur between locations within the Chesapeake Bay (Fisher 1986, Browne and Fisher 1988). However, in assessing the magnitude of tidal differences between stations, information on both phase and amplitude differences need to be combined into an measure of actual differences in tide height. The phase of the tide can also be important. Two stations, with a 180-degree phase difference (roughly, 6-hours) between them and the same tidal range, can differ by as much as the full tidal range (if one is at low tide, while the other is at high) or as little as zero (if both stations are approaching mid-tide, albeit from different directions). Therefore, we estimated tidal stage at stations throughout the Chesapeake Bay and Virginia Coast Reserve for a full array of tidal phases in 45-degree increments. We interpolated between tidal extremes using an approximation based on the cosine function. Tidal stage was calculated as:

$$S = \left(\cos\left(\frac{\Delta t}{745} \times 6.2831\right)\left(\frac{A}{2}\right)\right) + \left(\frac{A}{2}\right)$$

Where: S is the tidal stage difference in meters,

A is the tidal range in meters, and

Δt is the time difference in minutes.

The term 745 is a constant, describing the duration of a tidal cycle at Baltimore, MD in minutes. The unit for the cosine function is radians.

Cotidal charts were produced for tidal phase angles of 0 through 315 degrees in 45 degree increments(Figure 5).

3.3 Spatial Variation in Tidal Stage

Spatial variation in tidal stage can be equal to the most extreme temporal variations. For the Chesapeake Bay all stations had tidal ranges less than 1 m, greatly restricting the range of any spatial variation, regardless of phase differences. The extreme range of tidal phases within the bay guaranteed that the largest spatial differences would be equal in magnitude to the largest temporal differences. Outside the confines of the Chesapeake Bay, the magnitude of tidal variation is higher, with tides frequently exceeding 1 m. However, synoptic tidal differences are comparable to those experienced in the Chesapeake Bay because the variation in tidal phase angles is smaller in the unrestricted waters adjacent to the open ocean.

Large (> 60 cm) spatial differences in tidal stage only occurred when open-ocean stations were compared with stations in lagoons or bays. The most extreme differences over short spatial scales occurred in Sinepuxent Bay, where a long island (Assateague) and restricted channels resulted in differences of up to 94 cm over only a few kilometers of distance. Smaller, but nonetheless, potentially serious, differences in tidal stage occurred across the Delmarva Peninsula if ocean-side and bay-side stations were compared (Figure 5).

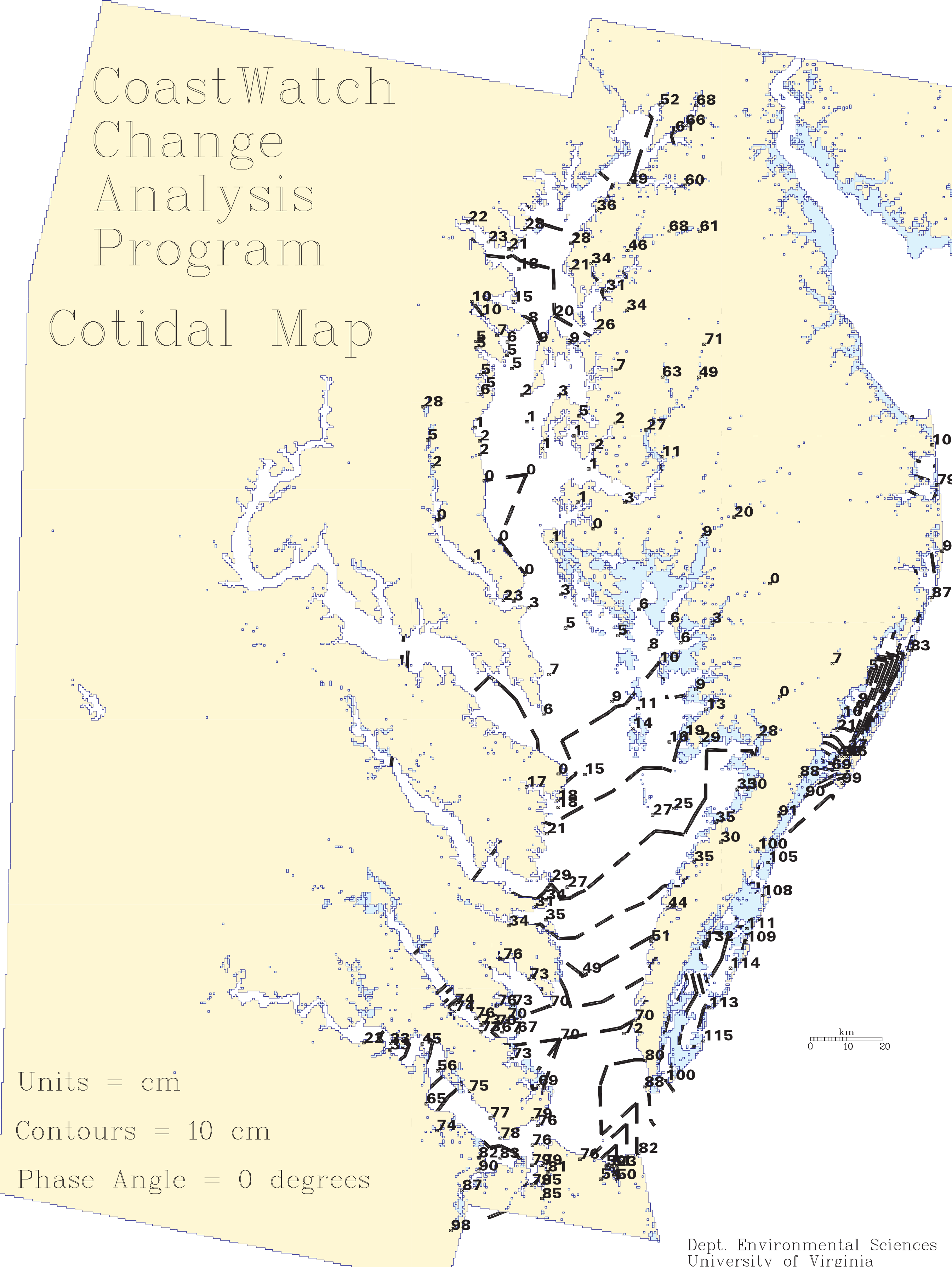
4.0 Impacts of Tidal Inundation on Remote Sensing

The potential for tidal inundation to alter spectral characteristics of wetlands is clear. However the extent to which that potential is expressed in spectral changes of wetland classes remains to be fully investigated. Jensen et al. (1993) observed a linear decline in areas classified as estuarine marsh across a temporal sequence of Thematic Mapper images spanning more than 2 m of tidal stage.

Here we investigate the potential of tidal differences, on the order of the spatially distributed tidal differences observed in the Chesapeake Bay, to adversely affect the classification of remotely-sensed images. Our examination focuses on tidally-induced changes in the spectral characteristics of wetlands, rather than on changes in classified data products. We take this approach because there are a large and growing number of processing schemes for classification of image data. However, whatever classifications methods are ultimately applied, they will have as their basis the raw spectral information. Factors, such as tidal inundation, which can alter the spectral characteristics of the wetlands cannot help but affect classifications based on those characteristics.

Spectral differences can result from a large number of causes. These include, sun angle,

FIGURE 5. Estimated tidal stages for the Chesapeake Bay and Atlantic Coasts of Maryland and Virginia. A phase angle of 0 degrees corresponds to full-high tide and a phase angle of 180 degrees corresponds to full-low tide for the Hampton Roads (Sewells Pt.) station. Tide stage is cm above the low tide at each station. Contour lines have an interval of 10 cm.



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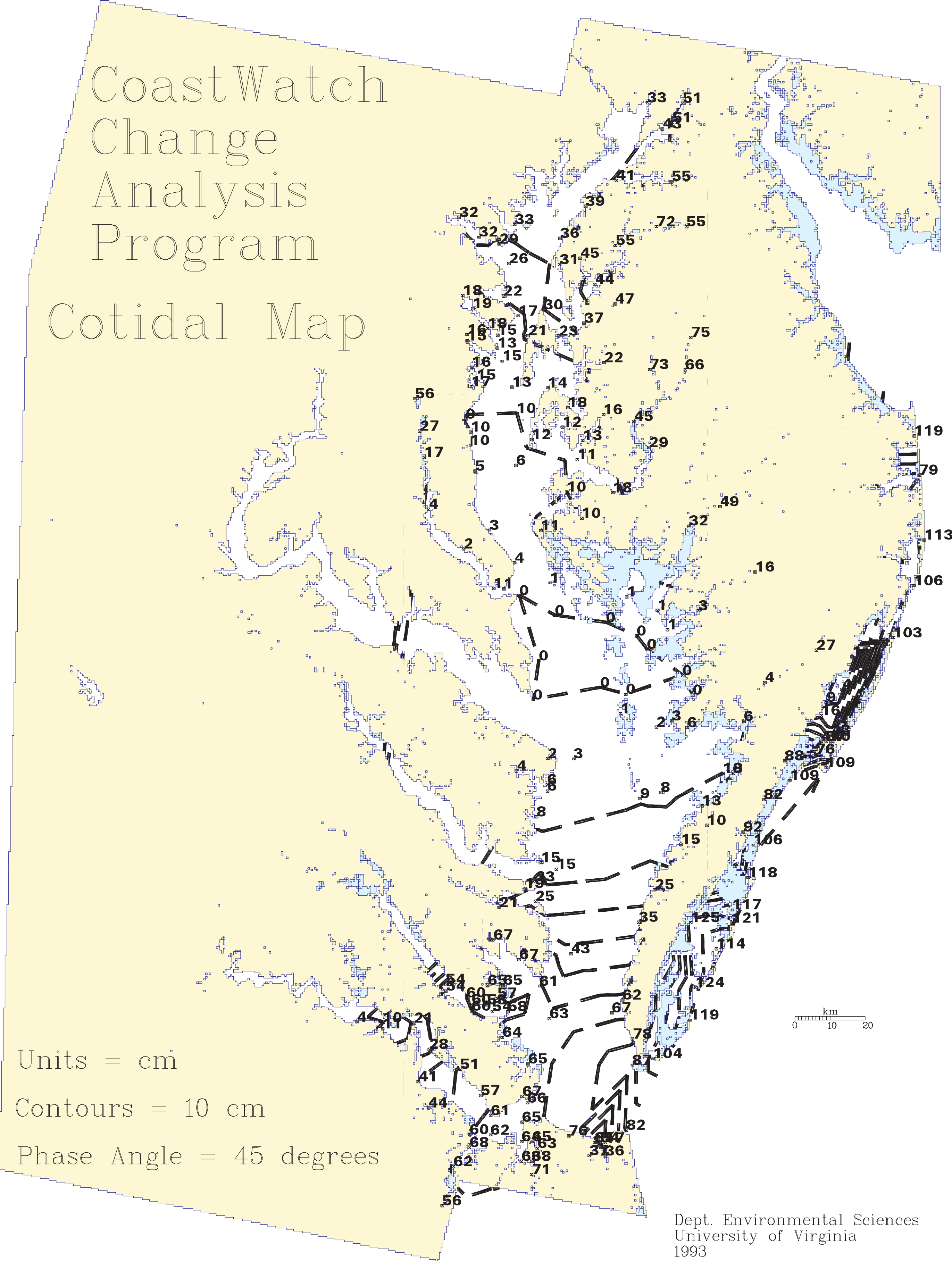
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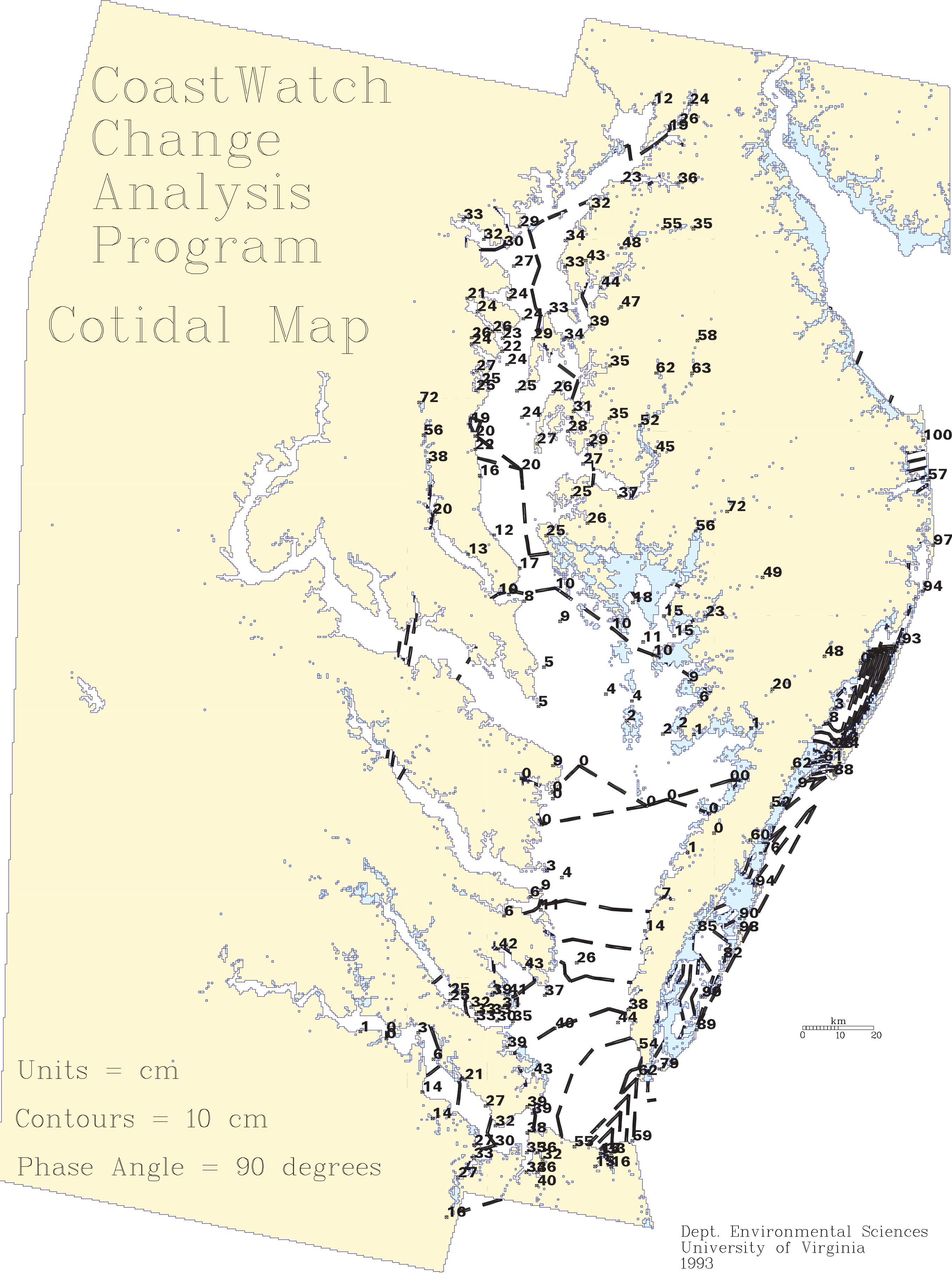
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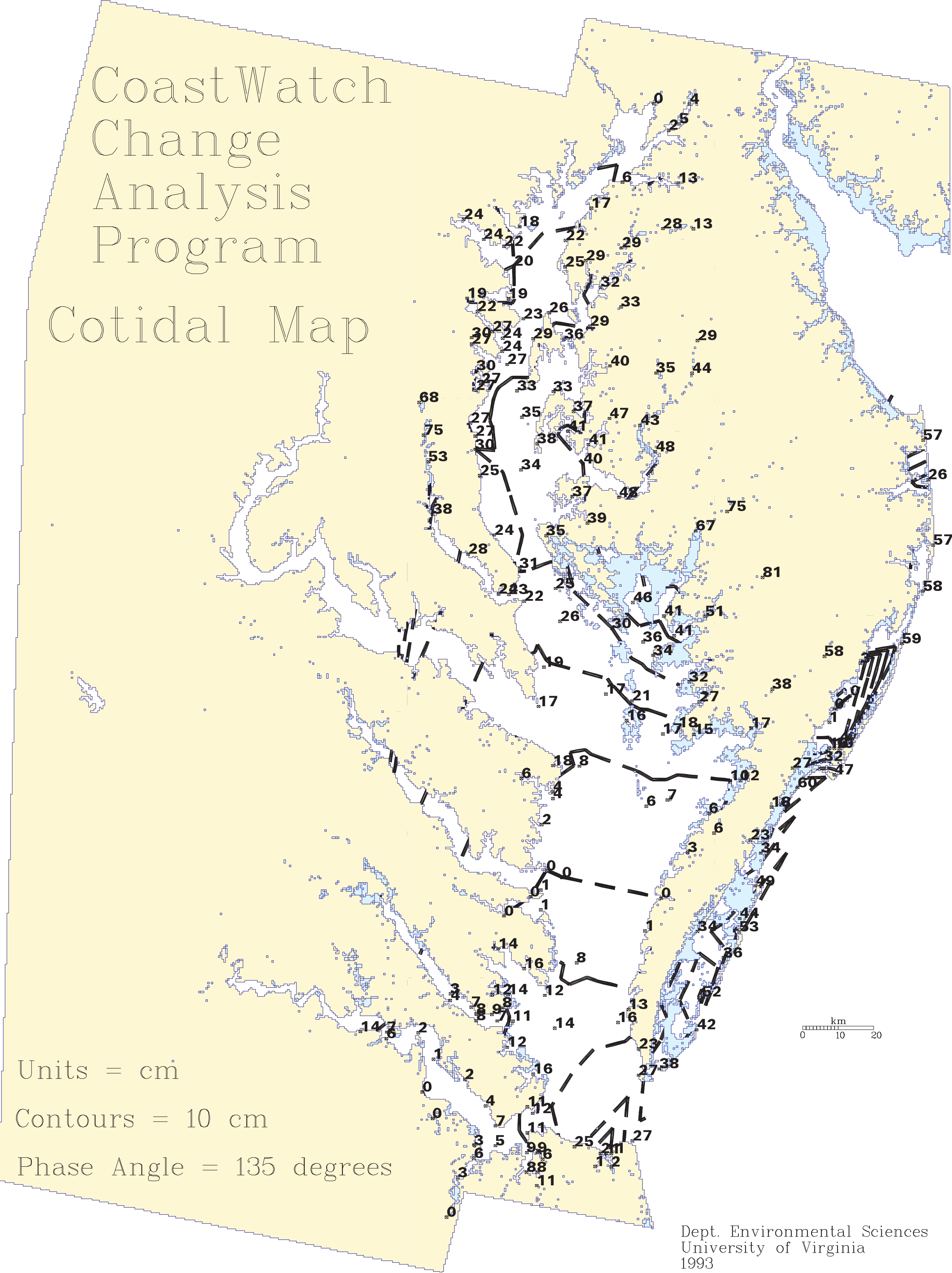
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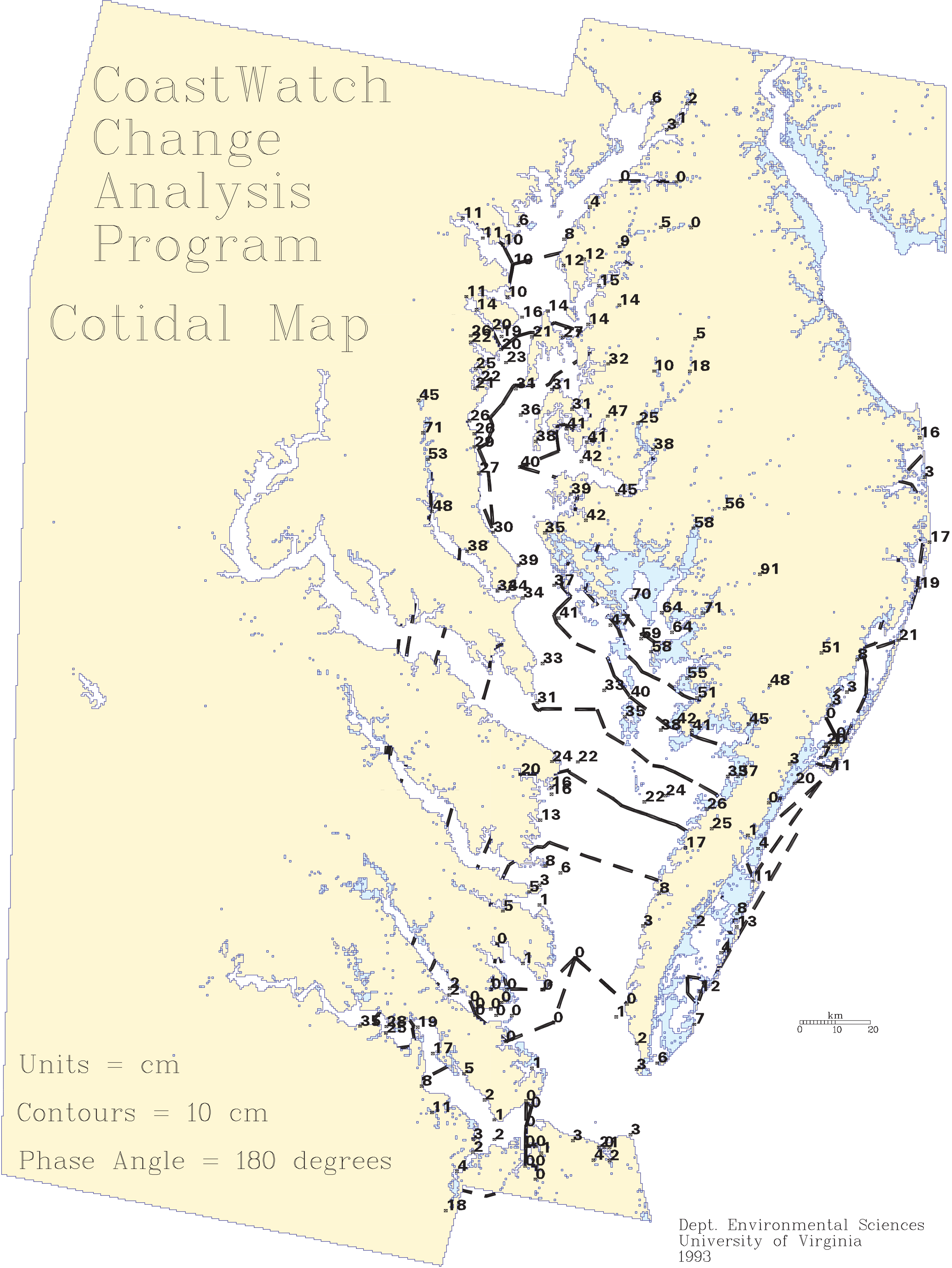
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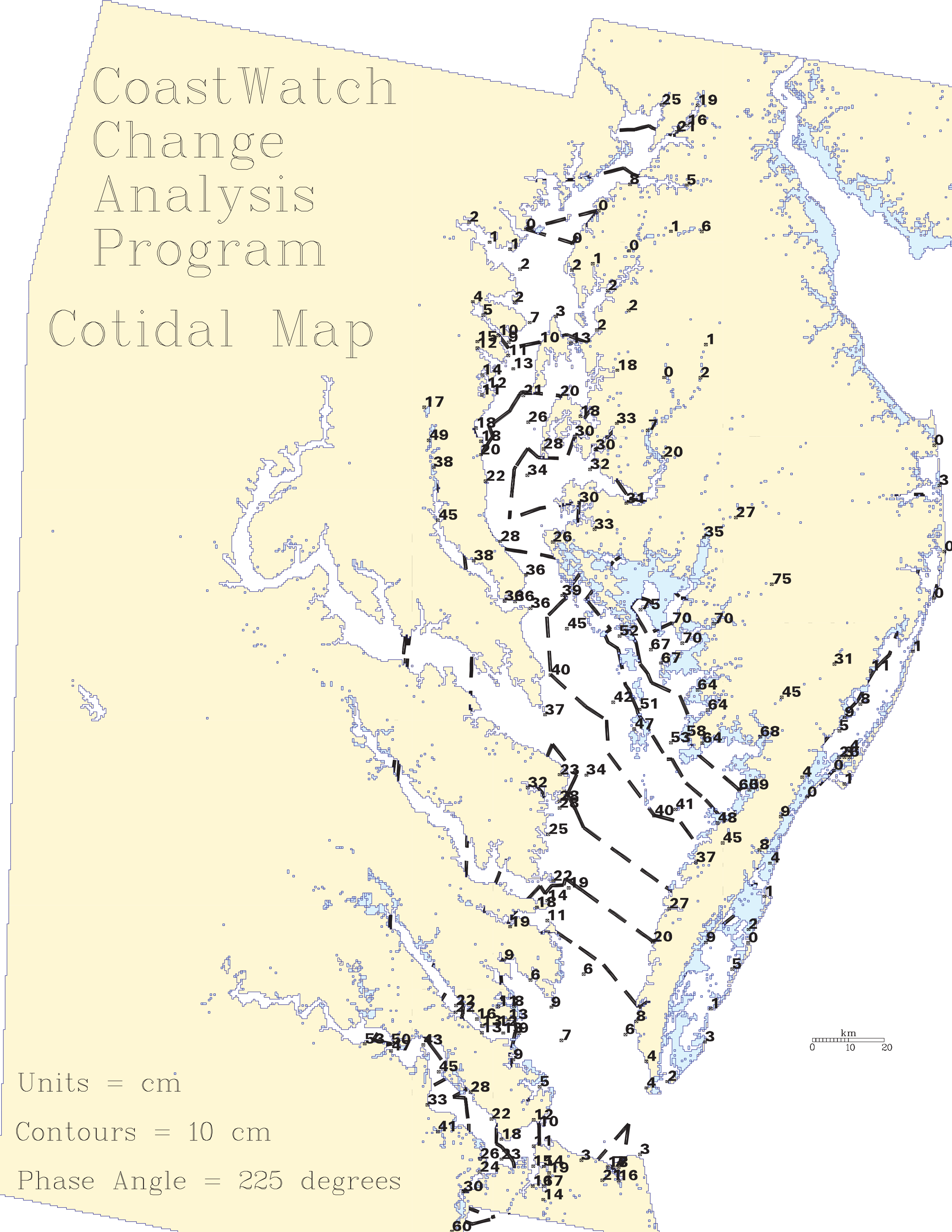

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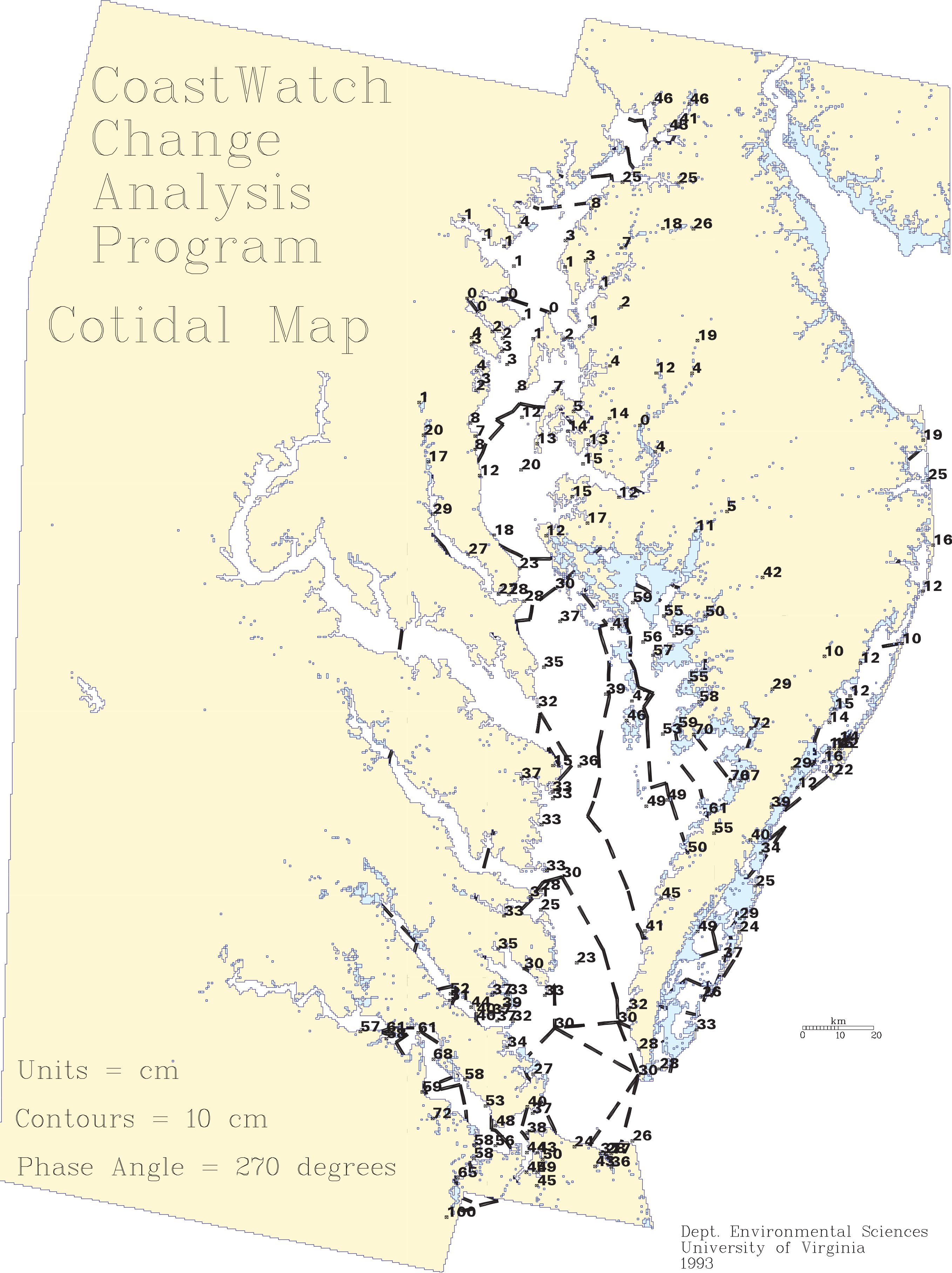
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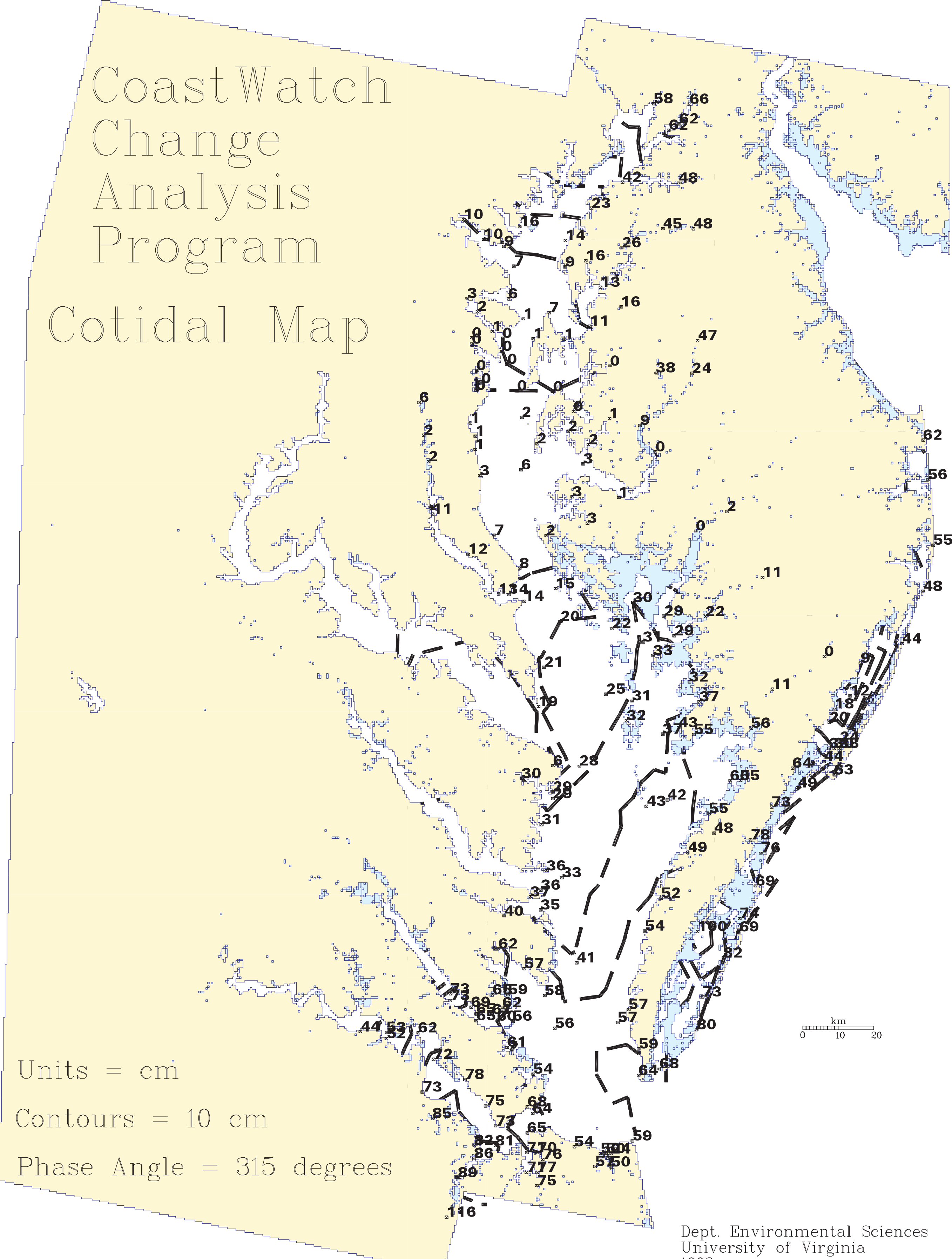

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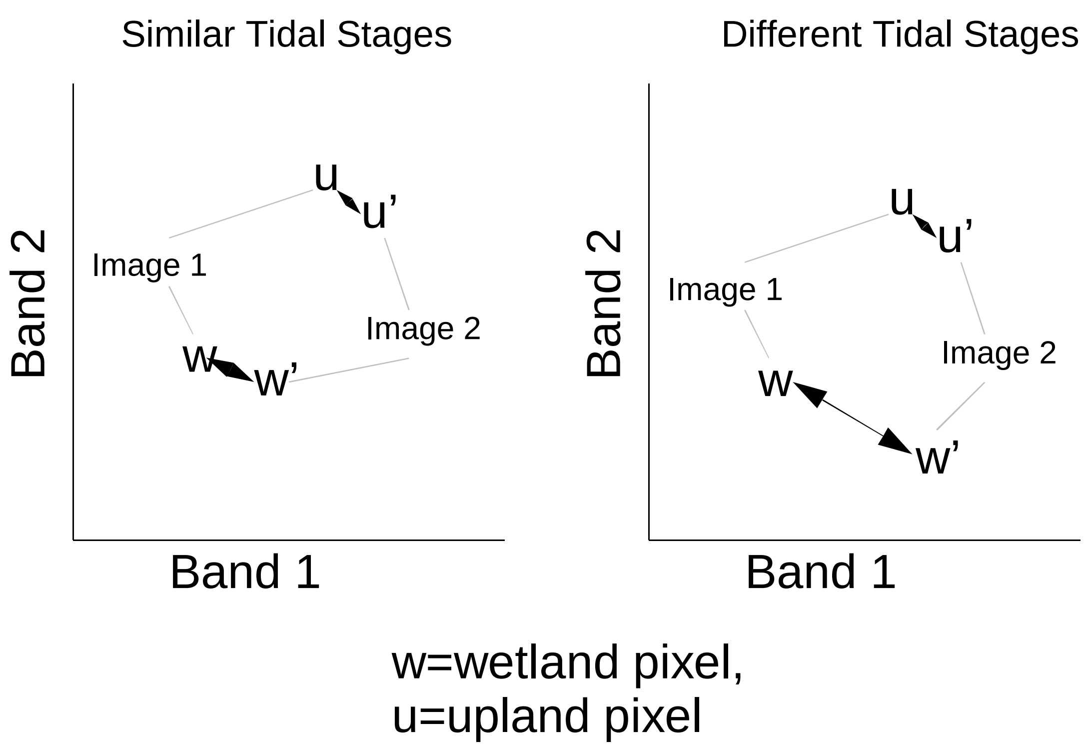
atmospheric transmissivity, and seasonal differences in the characteristics of vegetation among others (Jenson 1986). Thus, it is not possible to examine tidally induced spectral differences in isolation. Instead, they must be studied within a larger context. Non-tidal spectral changes are expressed throughout the entire image. In contrast, tidally-related changes are expressed only in areas where tidal flooding occurs. Thus, by comparing spectral shifts of tidally-influenced cover classes to those of upland classes, it is possible to isolate changes resulting directly from tidal actions (Figure 6). If tidal differences have

FIGURE 6. Spectral shifts between images for upland pixels are independent of tidal stage, whereas shifts for tidal wetland pixels are not.



little effect on the spectral properties of wetlands then we would expect to see result similar to the example in Figure 7. However, if tidal differences did impact the spectral characteristics of wetlands we would expect to see a result similar to the example in Figure 7.

4.1 Data Sources and Image Processing

We used the land-cover and change-analysis data layers produced by the Chesapeake Bay

FIGURE 7. Sample result for an analysis were tidal flooding was having little or no effect on the spectral characteristics of wetlands.

FIGURE 8. Sample result for an analysis were tidal flooding is substantially affecting the spectral characteristics of wetlands.

C-CAP prototype project (Dobson and Bright, 1991, NOAA 1992). Using predicted and observed tidal data Wachipreague, VA and Baltimore, MD as a basis of comparison, imagery sets used in the creation of the C-CAP change analysis exhibit two different tidal relationships between pairs of images (Table 1). The change analysis for Path 14, which spans

TABLE 1. Tidal stages during Landsat image acquisition.

Thematic Mapper Scene	Tide Level (cm above Mean Low Water)	Tide Difference[a] (cm)
Path 14/33 and 14/34 - 09/21/84	27[b]	0
Path 14/33 and 14/34 - 11/03/88	34[b]	7
Path 15/33 and 15/34 - 10/12/89	142[c]	33
Path 15/33 and 15/34 - 08/27/84	175[c]	0
Path 15/33 - 06/08/84[d]	134[c]	41

a. Differences between tide levels for the same satellite path.

b. Based on predicted tidal stage for Wachipreague, VA.

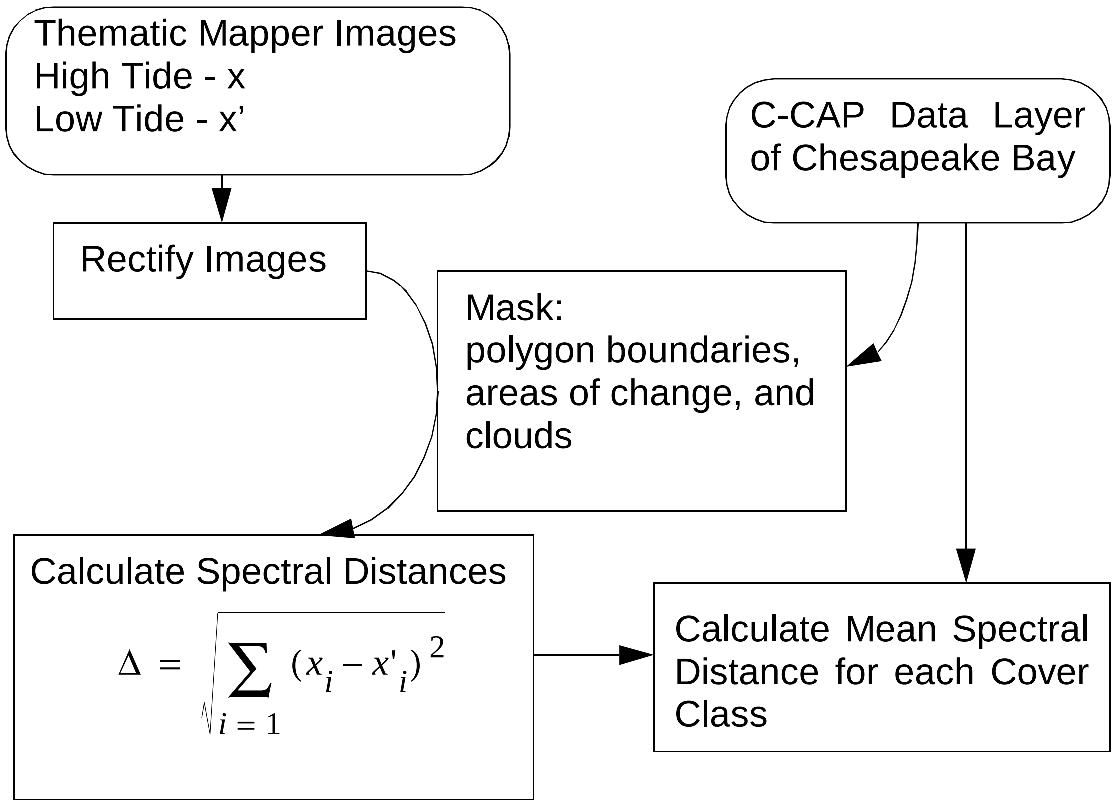
c. Based on observed tidal stages for Baltimore, MD.

d. Image obtained from NASA Pilot Land Data System. Not used in previous C-CAP analyses. Tide difference is versus 1984 image.

the Maryland and Virginia Coasts incorporates only a small (7 cm) tidal difference. However, the scenes for Path 15, which includes most of the Chesapeake Bay, spans a tidal range of 33 cm. An image for Path 15 of the northern Chesapeake, which was not previously used in C-CAP analyses, was obtained from the NASA Pilot Land Data System. It differs in time from the 1984 image used in the C-CAP analysis by only 3 months, but has a tidal stage offset of 41 cm. These differences allow us to examine tidally induced spectral changes while minimizing the effects of changes in the underlying system.

Our image processing used a multi-step process (Figure 9). Images for Path 14 were already rectified, however the images for Path 15 were unrectified. The 8/27/84 image was rectified to the 1984 C-CAP land-cover data layer with an RMS error of <0.75 pixels. The 6/8/84 image was then rectified to the previously rectified 8/27/84 image with an RMS error of <0.5 pixels. The C-CAP land-cover data layer was used to create a mask of polygon boundaries which was supplemented by a hand-digitized cloud mask. This mask was used to eliminate edge pixels and areas of cloudiness. For the Path 14 images, which spanned a 4-year period, a mask of change areas from the C-CAP change-analysis data layer was applied to eliminate pixels which had changed land-cover class. Thematic Map-

FIGURE 9. Image processing procedures. The process was repeated for two pairs of images, one pair with a small tidal difference and one pair with a relatively large difference in tidal stage. Change masks were only applied to image pairs which spanned more than a year.



per bands 2, 3, 4 and 5 were available for all image sources and were used for the computation of spectral distance. Spectral distances for both pairs of images were then computed using geographically coincident pixels from pairs of images.

4.2 Effects of Tides on Spectral Characteristics

The magnitude of spectral shifts varied widely between cover classes (Figure 10). Classes with the largest spectral distances (regardless of tidal differences) tended to be those characterized by high radiometric values. Less reflective classes had generally lower spectral distances. This reflects a well-known tendency for pixels in bright cover classes to be more variable than those in dimmer classes, and is not a function of tide.

The differences between the similar tide and different tide image pairs also varied between

FIGURE 10. Spectral distance by cover class. "Similar Tide" images differed in tidal stage for a centrally located tidal station by 7 cm. "Different Tide" images differed by 41cm.

cover classes (Figure 10). The largest single difference was for palustrine wetland, but was in the opposite direction expected if tidal differences were important. Spectral distances between images were *smaller* for different tides. We have been unable to generate any hypotheses wherein tidal differences promote spectral homogeneity, therefore non-tidal explanations (e.g., climate status, interannual changes in vegetation condition, and undetected cover change between "similar tide" images) must be invoked.

Several classes showed shifts in the expected direction (i.e., larger differences for different tides). Some classes with relatively large differences were upland, rather than wetland. It is not difficult to generate hypotheses as to why cropland and exposed land classes might be highly variable, regardless of tidal stage. However, more stable upland classes, such as deciduous, pine and palustrine forest, showed only small shifts.

The difference in tidal stage had little or no effect on the spectral characteristics of the estuarine emergent wetland class. Differences for that class were similar to those observed for some of the most stable upland classes. For tidal flats, the results are more equivocal. Differences in spectral distance between pairs of images was similar in magnitude to those observed for the brighter and most variable upland classes and roughly double those observed for more stable upland classes. This suggests that tidal differences, on the level of those observed here, may affect the classification of tidal flats. Of all the wetland classes, tidal flats are the most susceptible to flooding.

In this analysis we have dealt with the temporal, but not spatial components of tidal inundation. Nonetheless, the tidal difference used here was 41 cm which is larger than 57% of the tidal stages in Figure 5 where the median tidal stage, across all tidal phase angles, was only 30 cm. Obviously, our results cannot be uncritically applied to all regions, but they do suggest that the magnitude of spatial and temporal variations in tidal stage in the Chesapeake Bay are not sufficient to pose major obstacles to the remote-sensing of wetland classes. Our results are less applicable to the Virginia Coast Reserve, where tidal ranges were greater and a larger percentage of spatial and temporal differences exceed 41 cm. Application of our methodology to images with larger tidal stage differences would allow us to address the impact of these, more extreme, tidal differences.

5.0 Comparisons Between Image Sources

Comparisons of independent classifications of wetland areas are a fruitful way to highlight the strengths of different approaches and to identify cover types or special situations that may be problematical. High-resolution, false-color infrared photography has a much higher spatial resolution (<2 m) than satellite-based imagers. Porter and Callahan (in review) developed a land-cover data layer with a spatial resolution of 5 m for the north end of Hog Island, VA on the Atlantic coast of Virginia. Hog Island is a principle research site of the Virginia Coast Reserve Long-term Ecological Research Project (VCR-LTER) and has been the subject of intensive land cover mapping (Shao et al. 1993). The photograph on which the land-cover data layer was based was taken at near low tide, so it provides a way of examining how accurately wetland boundaries are captured using the C-CAP protocol.

The C-CAP prototype data layer, produced by Dobson and Bright (1991) for 1988, and the photo-based layer created by Porter and Callahan (in review) for 1989 did not use the same classification schemes. Nonetheless, both schemes could be aggregated into a 6-class classification scheme which focused on broad land-cover types (Table 2). Both data layers were recoded into the new classification scheme and compared on a pixel-by-pixel basis. A new data layer was created which had the class of each pixel in the photo-based data layer, but only for places where there was disagreement between it and the C-CAP-derived data layers.

There was high agreement between data layers for the interior of the extensive tidal wetlands on the western coast of Hog Island (Figure 11). The primary area of disagreement was the network of marsh creeks, which were too narrow to be detected by the satellite image. Similarly, there were disagreements around the border of the marsh, but these were limited to single-pixel distances for the satellite-derived data layer. Those few places in

TABLE 2. Classification Schemes

Classification scheme used for comparison	C-CAP (Dobson and Bright 1991)	Photo (Porter and Callahan, in review)
Wetland	Estuarine emergent wetland, Palustrine emergent wetland and Tidal flats	High marsh, and Low marsh
Woody	Deciduous forest, Pine forest, Mixed forest, Mixed shrub/scrub, and Palustrine forest	Shrub
Grass	Grass	Dense grass
Bare	Exposed land	Sand, Sand/sparse grass
Water	Water	Water
Other	Developed-high intensity, Developed-low intensity, and Cropland	None (Hog Island is uninhabited)

the interior of the marsh where there are disagreements occurred were at the ends of tidal creeks in areas occupied by frequently flooded flats.

There were a larger areas of disagreements for non-tidal wetlands, shallow ponds and flats in the interior of Hog Island. These areas are not subject to tidal flooding except during extreme storm events. Instead, flooding is controlled by recent climatic history (i.e., rain storms and strong winds). The water areas where disagreements occurred are shallow (<1 m) ponds, which can dry out on seasonal or annual basis.

6.0 Modifications to the C-CAP Protocol

The draft C-CAP protocol dictates that images for change analysis “should be selected to minimize tide stage, and tide stages for each time period should be as similar as possible” (Dobson et al., in review). A tentative standard is that low tide is preferred with a tidal stage of 30-60 cm preferred, with tides above 90 cm being unacceptable (Jensen et al. 1993). Such a standard works well in the Chesapeake Bay region. Differences in tidal stage of 41 cm (in the middle of the recommended range) showed only small spectral shifts for estuarine emergent wetlands, and slightly larger shifts for tidal flats. However, the protocol assumes that all portions of an image will be experiencing the same tidal

FIGURE 11. Comparison of photo-derived and C-CAP data layers for Hog Island, VA. Displayed are the classes from the photo-derived data layer for areas where there was disagreement between the two data layers.

stage. As our analysis shows, this assumption may not be reliable. Selecting an image based on the tidal stage at central point may not capture the true range of tidal variation within the image. Selecting images with similar tidal stage will help to mitigate some of the problems posed by tides to change analysis, but only if tidal phase, as well as tidal stage is considered. We propose these rules for selecting images for use in C-CAP analyses and for determining when spatial, as well as temporal, tidal shifts must be considered:

1. If the maximum tidal range (*T*) is less than or equal to 60 cm for the area covered by a Thematic Mapper scene, tides should not pose a problem for detecting changes in tidal wetlands. Low-tide images are still desirable for detecting tidal flats.

2. Given the fraction of a tidal wave that can occur in an estuary (*F*, computed as the maximum time lag between stations divided by the length of an entire tidal cycle) and the maximum tidal range (*T*), an index ($F \times T$)can be calculated. If $F \times T$ is less than or equal to 60 cm, then spatial variations in tidal stage can be ignored for examining tidal wetlands.

3. If $F \times T$ is greater than 60 cm, then only some portions of a satellite scene will be suitable for detecting wetland change and multiple images may be required to complete coverage of an area. This condition is likely to occur where tidal ranges are great, and/or in large estuaries, where a large fraction of a tidal cycle may be present. In such areas, cotidal maps similar to those in Figure 5, should be produced using data from NOAA tidal difference tables or, where sufficient data are not available, field surveys using portable tide stations. Such maps can be used to optimize image selection to maximize coverage in critical areas, and to guarantee complete coverage when multiple images are used. When use of multiple images to attain full coverage is impractical, it is especially important for change analyses that images with a comparable tidal stage and phase be used or that areas covered by the change analyses be restricted to areas for which $F \times T$ is less than 60 cm.

6.1 Research Directions

In the present study, we focused on periodic-tidal inundation: how it varies both spatially and temporally and what effects it has on the spectral characteristics of wetlands. We found that spatial variation in tide stage could equal the most extreme temporal differences, but that, at least within the Chesapeake Bay, most differences in tidal stage were less than 30 cm. Our comparative examination of the spectral characteristics of images differing in tidal stage by 41 cm indicated that moderate difference in tidal stage would not seriously impact change analyses of tidal wetlands. Additionally, we completed the technical development on highly-portable tide monitoring equipment. An individual equipped with such equipment can survey large areas because the equipment has self-contained data loggers that can record data for several weeks between data dumps and are relatively inexpensive. However, the integrated tide monitors still require additional field testing and the creation of manuals detailing operation.

Additional areas of research were not directly addressed in our work:

- What are the effects of wind-driven tides on the spectral characteristics of wetlands? Often the magnitudes of wind-driven tides can greatly exceed those of normal tides. Does the C-CAP protocol need to incorporate standards for meteorological effects on tides?
- How are the spectral changes caused by tidal stage related to the characteristics of the underlying vegetation and the elevational gradients across wetlands? Once such relationships are well understood, it may be possible to produce predictive, or at least proscriptive, models that go beyond the "60 cm rule" to precisely delineate acceptable limits for tidal flooding in change analyses.
- How are the spectral signatures of upland land-cover classes altered by recent climatological history? During our study, we found several indications that non-tidal wetlands experienced spectral shifts. For example, disagreement between the photo-derived and C-CAP data layers was highest in non-tidal areas. Similarly, the large spectral shift shown for palustrine wetlands with similar tides may also reflect differences in the rainfall-history. By using climatological indices, such as the Palmer Drought Index and Soil Conservation Service Soil Moisture Indices, procedures and protocols could be developed for minimizing the disruptive influences of short-term climate-induced spectral shifts on C-CAP data products.

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