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Assessment of C-band synthetic aperture radar data for mapping and monitoring Coastal Plain forested wetlands in the Mid-Atlantic Region, U.S.A.

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ABSTRACT

Multi-temporal C-band SAR data (C-HH and C-VV), collected by ERS-2 and ENVISAT satellite systems, are compared with field observations of hydrology (i.e., inundation and soil moisture) and National Wetland Inventory maps (U.S. Fish and Wildlife Service) of a large forested wetland complex adjacent to the Patuxent and Middle Patuxent Rivers, tributaries of the Chesapeake Bay. Multi-temporal C-band SAR data were shown to be capable of mapping forested wetlands and monitoring hydroperiod (i.e., temporal fluctuations in inundation and soil moisture) at the study site, and the discrimination of wetland from upland was improved with 10 m digital elevation data. Principal component analysis was used to summarize the multi-temporal SAR data sets and to isolate the dominant temporal trend in inundation and soil moisture (i.e., relative hydroperiod). Significant positive, linear correlations were found between the first principal component and percent area flooded and soil moisture. The correlation (r^2) between the first principal component (PC1) of multi-temporal C-HH SAR data and average soil moisture was 0.88 (p=<.0001) during the leaf-off season and 0.87 (p=<.0001) during the leaf-on season, while the correlation between PC1 and average percent area inundated was 0.82 (p=<.0001) and 0.47 (p=.0016) during the leaf-off and leaf-on seasons, respectively. When compared to field data, the SAR forested wetland maps identified areas that were flooded for 25% of the time with 63–96% agreement and areas flooded for 5% of the time with 44–89% agreement, depending on polarization and time of year. The results are encouraging and justify further studies to attempt to quantify the relative SAR-derived hydroperiod classes in terms of physical variables and also to test the application of SAR data to more diverse landscapes at a broader scale. The present evidence suggests that the SAR data will significantly improve routine wooded wetland mapping.

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1. Introduction

The biologic, aesthetic, and economic values of wetlands are now known to be disproportionately large compared to the often small percentage of the landscape they occupy. Wetlands in the Chesapeake Bay Watershed are especially vital as they help maintain water quality in one of the Nation's most productive estuaries (Chesapeake Bay Program, 1998; Tiner, 1987). Because of the high density of wetlands in the Mid-Atlantic Coastal Plain and development resulting from rapid population increase, this region is at high risk for future wetland loss. Forested wetlands, the most common type of wetland in the Chesapeake Bay Watershed, are especially at risk (U.S. Fish and Wildlife Service, 2002).

Wetland hydroperiod, or temporal variations in inundation and soil moisture, is the single most important factor in the formation and functioning of a wetland. Hydroperiod may result from complex and often small topographic variations in floodplain geomorphology, the type of soils present, and transfers of water into and out of the ecosystem. Small changes in water regime can cause large changes in wetland functioning, such as the potential of wetlands to transform and reduce nutrients (i.e., N and P) in ground and surface waters (Hamilton et al., 2007; Hattermann et al., 2006; Mitsch & Gosselink, 2000). These nutrients are responsible for water quality reductions in the Chesapeake Bay and have been the focus of numerous research studies and a high level of public and governmental concern (Boesch et al., 2001).

Although nutrient dynamics in the Chesapeake Bay itself have been rigorously studied, the fate and transport of nutrients in the Chesapeake Bay Watershed have not been given as much attention (Boesch et al., 2001). Presently, the Chesapeake Bay Program and other management agencies are working to estimate pollution reduction rates attributable to wetlands (J. Okay, personal communication,). However, accurate and timely information on wetland extent and hydroperiod is needed to fully integrate these estimates into decision support tools. Anticipated changes to the Mid-Atlantic climate (Mid-Atlantic Regional Assessment Team, 2000) could alter the

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water balance in this region's wetlands (Moore et al., 1997), further emphasizing the need for a means of continuously monitoring forested wetland hydrology.

Federal and State governments have sponsored wetland mapping programs, but many of the resultant maps are out of date, especially in areas, such as the Mid-Atlantic, that are undergoing rapid development. In addition, these maps are static and do not represent the dynamic nature of wetland hydrology. Field monitoring of forested wetlands is costly at the broad scales required for ecosystem management and regulation. While aerial photography is used to map forested wetlands, this method is often limited by cloud cover and the need to photograph forested wetlands during the leaf-off period. Furthermore, aerial photograph acquisition and necessary human interpretation are time-consuming, somewhat subjective, and expensive (Lunetta & Balogh, 1999; Tiner, 1999), especially since many forested wetlands are difficult to identify in aerial photographs (Sader et al., 1995; Tiner, 1990).

Synthetic aperture radar (SAR) imaging systems have the capability to detect key hydrologic characteristics of wetlands: namely, the spatial and temporal patterns of inundation and soil moisture. The Wetlands Subcommittee of the Federal Geographic Data Committee (1992) found that the difficulty of acquiring cloud-free imagery during the optimal time period was a key obstacle to mapping wetlands with optical satellite data. However, SARs can collect imagery regardless of solar radiation and cloud cover because these systems provide their own energy for surface illumination at wavelengths that penetrate clouds (Hess et al., 1995; Kasischke et al., 2003; Morrissey et al., 1994; Townsend, 2002; Townsend & Walsh, 1998; Wang et al., 1995). For this reason, SAR data can be used to produce wetland maps during optimal time periods and with greater frequency than optical images. Another advantage is that radar data can be processed semi-automatically using image processing software and batch programming and do not require the same level of expertise needed for aerial photograph interpretation, which is often done by hand. In contrast, aerial photographs are better suited for distinguishing different types of vegetation and for the mapping of herbaceous wetlands (i.e., marshes).

Although previous studies (Townsend, 2000; Townsend & Walsh, 1998) have demonstrated that C-band SAR data (wavelengths of ~6 cm) can detect relatively large areas of inundation beneath the forest canopy, these data have not been used to map less extensive flooding beneath forest canopies in the smaller floodplains that are more typical of the Chesapeake Bay Watershed. Nor have these data been compared to detailed field measurements of inundation and soil moisture. Little is known about the ability of C-band SAR data to distinguish different amounts of inundation (i.e., percent area inundated) and levels of soil moisture below the forest canopy that are indicative of hydroperiod.

The goal of this research study was to investigate the utility of C-band SAR data in mapping forested wetlands and monitoring forested wetland hydroperiod in the Mid-Atlantic U.S., and whether optical data can be used to enhance classification accuracy. This study provides a general approach to forested wetland mapping that builds upon documented relationships between inundation and SAR data response (Townsend, 2002; Townsend & Walsh, 1998) and moves towards an operational wetland hydrology monitoring solution. The contribution of Landsat Enhanced Thematic Mapper imagery to the forested wetland mapping process was determined. Maps created with multi-temporal ERS-1/2 (i.e., AMI — Advanced Microwave Instrument) and ENVISAT Advanced Synthetic Aperture Radar (ASAR) data were compared with direct observations of hydrology (i.e., inundation and soil moisture) and U.S. Fish and Wildlife Service (FWS) National Wetland Inventory maps. The utility of incorporating digital elevation data into the wetland mapping process was also explored. This mapping exercise was primarily conducted over a wildlife preserve near Laurel, Maryland, located on the upper Coastal Plain of the Mid-Atlantic, U.S. This analysis constitutes a necessary step towards improved forested wetland monitoring and provides ecologists and managers with vital information that is often missing or inferred using less direct means.

2. Background

2.1. Conventional mapping of forested wetlands

Since the 1970's, wetlands have been mapped using combinations of optical imagery and field data. In the U.S. the majority of wetland maps are produced by government agencies, such as the FWS, National Oceanic and Atmospheric Administration (NOAA), and Environmental Protection Agency (EPA). The most comprehensive national mapping effort was undertaken through the FWS's National Wetlands Inventory (NWI). The NWI produces wetland maps using interpretation of mid- to high altitude aerial photographs combined with field verification and collateral data (Federal Geographic Data Committee, 1992). The NWI maps usually err less by commission and more by omission; thus, if a wetland is indicated on a NWI map, there is a high probability that one exists or did at the time the photograph was taken (Nichols, 1994; Stolt & Baker, 1995). Forested wetlands are one of the most difficult types of wetlands to map using NWI's aerial photograph approach (Tiner, 1990). Estimates of the extent of NWI's forested wetland omission errors vary widely (Kudray & Gale, 2000; Rolband, 1995). The majority of NWI maps for the Mid-Atlantic Coastal Plain were generated using aerial photographs that are at least 20 years old. These maps are frequently out of date in areas undergoing rapid changes in wetland extent, such as that caused by beaver activity, forestry, drainage for agriculture, and various forms of construction. However, regardless of NWI's imperfections, NWI maps are one of the most commonly relied upon sources of wetland information in the U.S. and have been used to support management and regulatory decisions (Kudray & Gale, 2000).

Due to the high costs in time and money required to map wetlands with aerial photography, newer techniques are being developed by the FWS and others to update wetland maps (U.S. Fish and Wildlife Service, 2002), including utilization of satellite data. The advantages of using satellite data for wetland mapping include timeliness and cost savings, along with an inherently digital format that facilitates integration with other types of geospatial data and analyses using a geographic information system (Dobson et al., 1995; Federal Geographic Data Committee, 1992; Li & Chen, 2005). Unfortunately, visible and near-infrared satellite data alone have generally not produced adequate results without additional aerial photography and ground data, particularly for forested wetlands (Federal Geographic Data Committee, 1992; Li & Chen, 2005; Sader et al., 1995; Tiner, 1990). Although mid-infrared satellite data provide some increased sensitivity to spatial variations in hydrology (National Research Council, 1995), these data still do not provide the sensitivity to soil moisture (Neusch & Sties, 1999) or relatively small areas of inundation necessary to distinguish forested uplands from forested wetlands and to map hydroperiod. While Landsat Thematic Mapper data are usually not used alone to map forested wetlands, they have proved suitable for updating wetland maps. For example, techniques known as cross-correlation analysis (CCA) use multi-spectral satellite data to detect changes in land cover that have occurred since the wetland map was produced (Koeln & Bissonnette, 1999). However, CCA and other similar methods are limited to detecting changes within existing mapped wetland polygons. Therefore, these techniques are dependent on the existence of an accurate baseline map with low omission errors and cannot be used to detect newly formed wetlands.

2.2. Mapping forested wetlands using C-band SAR data

The scattering and reflection of microwave energy is sensitive to variations in soil moisture and the presence/absence of surface water, primarily due to the high dielectric constant of water. Microwave