C-BAND RADAR MONITORING OF HYDROLOGY IN MID-ATLANTIC FORESTS: NEW INFORMATION FOR IMPROVED WATER QUALITY MANAGEMENT

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INTRODUCTION

Wetlands are at high risk for loss, due to inadequate legal protection, rapid population growth and climate change. Hydrology (i.e., flooding and soil moisture) controls wetland function, and must be better understood to improve watershed management. Broad-scale forested wetland hydrology is difficult to monitor using ground-based and traditional remote sensing methods (i.e., aerial photography). Satellite-borne C-band (5.6 cm wavelength) synthetic aperture radar (SAR) data could improve the capability to monitor forested wetland hydrology, but the abilities and limitations of these data need further investigation.

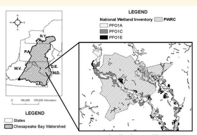
Imaging radars have the unique capability to monitor key hydrologic characteristics of wetlands throughout the year and with greater frequency, in part due to the ability of SAR to collect images regardless of solar illumination and cloud cover. SARs are active sensors, emitting and receiving energy at multiple polarizations and incidence angles. The orientation of the energy, perpendicular to the direction of travel, determines polarization. In operational spaceborne SAR systems, the energy is either emitted or received horizontally (H) or vertically (V), relative to the surface of the Earth. Energy can also be transmitted at different angles (incidence angles) relative to the Earth's surface. The energy that is returned to the sensor is called backscatter (σ^o) and is measured in dB.

Objective:
Examine the relationship between mid-Atlantic floodplain hydrology and climate, and the ability of ASAR data (C-HH and C-VV with a spatial resolution of 5.6 cm) to monitor hydrology beneath the forest canopy.

HYDROPATTERN IN MID-ATLANTIC FORESTS

What controls hydrology in Mid-Atlantic Floodplains?

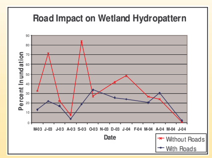
In situ data (e.g., inundation, soil moisture, basal area, tree height, and canopy closure) were collected coincident with ASAR images in 24 4-hectare forest plots located in backwater, levee, and uplands areas adjacent to the Patuxent River (lower-left). These data were collected from spring of 2003 to winter of 2004. Stream discharge and climate data were gathered online. Statistical analyses were used to determine the relationship between inundation and stream discharge, temperature (a proxy for evapotranspiration), and precipitation.



Palustrine forested wetlands at the Patuxent River study site as indicated by the National Wetlands Inventory.

- Inundation was strongly correlated with stream discharge, precipitation, and temperature
  - R^2 between 0.63 and 0.96 (average R^2 = 0.76)
  - A dirt road also influenced inundation (far right)

After the connection between hydrology and climate was elucidated, we investigated the ability of C-band SAR to monitor hydrology.

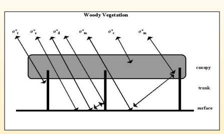


Percent area inundated in field plots that were and were not influenced by a narrow dirt road.

MONITORING HYDROPATTERN USING RADAR

Can C-Band SAR be used to monitor hydrology beneath the forest canopy in the mid-Atlantic U.S.?

Transmitted microwave energy (backscatter or σ^o) is attenuated and reflected from different elements, resulting in the microwave energy detected by the sensor (below).



$$\sigma^o = \sigma^o_c + \tau^2_c \tau^2_t (\sigma^o_m + \sigma^o_t + \sigma^o_s + \sigma^o_d)$$

Where:

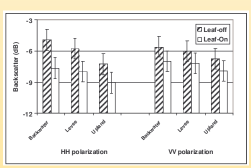
σ^o = total backscatter coefficient from a forest
σ^o_c = backscatter coefficient of the crown layer
τ_c = transmissivity of the crown layer
τ_t = transmissivity of the trunk layer
σ^o_m = multi-path scattering between the ground and canopy
σ^o_t = backscatter coefficient of the trunk layer
σ^o_s = backscatter coefficient of the surface

σ^o_d = double-bounce scattering between the trunk and surface

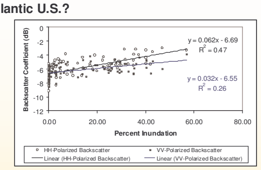
- **Variation in σ^o between backwater, levee, and upland plots**
  - C-HH & C-VV σ^o varies significantly between plot types (p <.0001)
  - C-HH & C-VV backwater & upland σ^o and levee & upland σ^o are significantly different (p < 0.05)
  - C-HH significantly different (p < 0.05) between backwater & levee

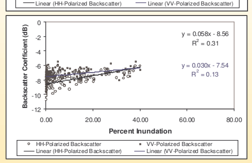
- **Inundation**
  - **C-HH:** Leaf-off: ~4dB; Leaf-on: ~2.5dB change with inundation (upper-right)
  - **C-VV:** Leaf-off:~1.5dB; Leaf-on: ~1dB change with inundation (lower-right)

- **Soil Moisture**
  - Large degree of collinearity between soil moisture & inundation
  - Variation between backwater & upland sites
    - 1.1dB C-HH & 0.9 dB C-VV during leaf-on season with no flooding



Mean backscatter in field plots during the leaf-off and leaf-on seasons. Error bars depict total uncertainty.





Regressions of σ^o against inundation during leaf-off (top) and leaf-on (bottom) seasons. Top equation and r^2 values within both charts correspond with C-HH σ^o and bottom with C-VV (p < 0.0001).

C-band SAR can be used to distinguish different levels of flooding and soil moisture. C-HH can monitor even relatively small changes in flooding during leaf-off & leaf-on seasons and the potential of C-VV is promising during leaf-off season.

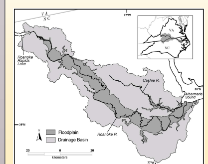
INFLUENCE OF INCIDENCE ANGLE

How does incidence angle influence the ability of C-band SAR data to monitor inundation beneath the forest canopy?

Multiple incidence angle Radarsat (C-HH) data (right) were collected over the Roanoke River (below) to determine the impact of incidence angle on ability of SAR to monitor inundation below the forest canopy.

Date	Average Incidence Angle
12/6/2000	23.5°
12/23/2000	27.5°
12/16/2000	33.5°
12/9/2000	39.0°
12/2/2000	43.5°
12/19/2000	23.5°
6/21/2000	27.5°
5/21/2000	33.5°
6/7/2000	39.0°
5/31/2000	43.5°
6/17/2000	47.0°

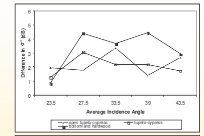
Dates and incidence angles for Radarsat acquisitions.

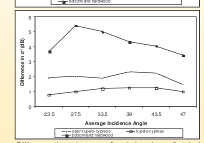


Roanoke River Study Site.

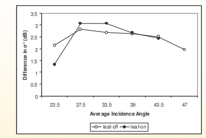
Hypothesis: the ability to detect inundation will decline with increasing incidence angle, regardless of forest type.

- Contrary to our hypothesis, we found:
  - The ability to monitor hydrology was highly dependent on forest type
  - Smallest incidence angle was least preferable
  - Larger incidence angle data were better suited for inundation monitoring than expected





Difference in σ^o between flooded and non-flooded forests as a function of incidence angle during leaf-on (top) and leaf-off (bottom) seasons.



Difference in σ^o between flooded and non-flooded areas as a function of incidence angle (forest types averaged).

A wider variety of incidence angles and times of the year should be considered when monitoring inundation.

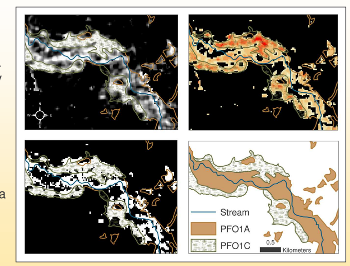
This should increase temporal resolution of future studies.

FORESTED WETLAND MAPPING

Can C-Band SAR be used to monitor forested wetland hydrology and map forested wetlands?

Maps were produced using multi-temporal SAR images and compared to field observations and U.S. Fish and Wildlife Service National Wetland Inventory (NWI) maps.

Multi-temporal SAR data were calibrated and georegistered, filtered, and stacked to form one image file before running a principal component analysis. Principal component 1 (PC1) was thresholded to produce the multi-class wetland map (hydropattern) and PC1 was used with elevation data in a decision tree classifier to produce the binary forested wetland map.



ASAR wetland maps. PC1 (top, left), binary forested wetland map (bottom, left), and the multi-class forested wetland map (top, right) over-laid with the NWI boundaries for palustrine, broad-leaved deciduous, forest with either seasonally (PFO1C – flooded longer) or temporarily (PFO1A – flooded shorter) flooded wetlands and the Patuxent River. Both types of wetland polygons are shown alone at the bottom right.

- **Comparison with *in situ* inundation**
  - Maps compared well; C-HH leaf–off map identified 95% & C-HH leaf-on 88% of areas inundated 15% of the time.
- **Comparison with NWI**
  - On average, binary maps agreed with NWI 90% of the time.
  - Areas identified as being inundated for longer periods of time by NWI were identified more often as wetlands.

Improved method for gathering information on forested wetland hydropattern & the influence of climate and anthropogenic forces on hydrology.

CONCLUSIONS AND FUTURE DIRECTIONS

This study provides new technology to monitor forested wetland hydrology and changes to forested wetland hydrology, caused by climatic and anthropogenic forces.

Previous studies have shown that C-band SAR can map inundation (0% versus 100%) in large forested wetland systems. This study was conducted at a finer scale with detailed measurements of inundation. It directly compared the abilities of C-HH & C-VV data to detect flooding and soil moisture throughout the year, tested the ability of C-band SAR to detect varying amounts of flooding (at relatively low levels), and used C-band SAR to link levels of inundation to weather conditions in the Mid-Atlantic.

We are currently mapping forest hydrology in the Choptank River Watershed on the Eastern Shore of Maryland. Efforts are being made to stream-line this process and enhance the applicability of this information to management issues, including water quality monitoring.

Although some water quality models, such as AnnAGNPS, are spatially explicit, they do not incorporate many of the parameters that can be derived with remotely sensed data. Maps of forest hydrology are expected to improve model estimates of water quality by identifying candidate locations where denitrification, and other chemical transformations that rely on aerobic condition, may occur. We are working to incorporate forest hydrology maps and other remotely sensed parameters into water quality models at multiple scales, ranging from local to National. Modeling the impact of watershed management, including the implementation of agricultural best management practices, with improved landscape information will help improve water quality in freshwater ecosystems, such as the Chesapeake Bay.

Acknowledgements: Initial research conducted while the first author was a student at the University of Maryland under the direction of Eric Kasischke. This research was supported by a NASA Earth System Science Fellowship and the Mid-Atlantic Regional Earth Science Applications Center. SAR data were provided by the European Space Agency (ENVISAT AO GRANT 733) and the Application Development and Research Opportunity (ADRO) program.