# Watershed-Scale Sensing of Subsurface Flow Pathways at the OPE3 Site

## T.J. Gish, C.L. Walthall, C.S.T. Daughtry, G.W. McCarty, W.P. Dulaney

### Abstract

The Optimizing Production inputs for Economic and Environmental Enhancement (OPE3) research program focuses on developing strategies for meeting economic crop production goals while mitigating excess chemical loss to neighboring ecosystems. The OPE3 site has four hydrologically-bounded watersheds, about 4 ha each, which feed a wooded wetland and first order stream. Among the OPE3 watershed-scale research projects seeking to meet these goals are investigations focused on methods to quantify spatial variations of water and nutrients via characterization of subsurface flow pathways and analysis of crop response. Subsurface topography of the first continuous clay lens was determined by combining ground-penetrating radar (GPR) data with surface digital elevation maps to identify the spatial location of subsurface convergent flow pathways. Remote sensing provided information on crop nitrogen status and foliage density via spectral vegetation indices (SVI) from an airborne imaging system. Both the spectral and spatial information domains of imagery are being used to map LAI and leaf chlorophyll at high spatial resolutions (1 to 4 m pixels). These analyses provide links for mapping the impact of soil water dynamics over several growing seasons. The maturation and fusion of these technologies will permit an assessment of watershed strategies influencing water and chemical flows and their impacts on surrounding ecosystems while simultaneously assessing the effectiveness of management strategies on crop production.

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**Keywords:** subsurface water flow, yield patterns, remote sensing, preferential flow

### Introduction

Plant growth and chemical behavior are strongly influenced by surface and subsurface soil water dynamics. Classical quantification of field-scale subsurface water movement and chemical transport was dependent upon knowledge of the spatial distribution and autocorrelation of soil hydraulic properties and subsurface soil layering structures. Unfortunately, traditional methods to assess the spatial nature of soil hydraulic properties are of limited benefit because only a fraction of the subsurface is sampled. As a result, it is impossible to ascertain the spatial behavior of soil hydraulic properties using point data because the sampling density of soil core and well log data is below the inherent spatial variability of soil hydraulic properties.

Abrupt changes of soil texture or density across the boundary of two adjacent soil layers creates a discontinuity of pores. A mismatch of both pore-entry value and soil hydraulic conductivity across this boundary can trigger funnel flow (Kung 1990, Kung 1993, Ju and Kung 1993). Under this latter condition, uniform matrix flow processes could congregate and become a preferential flow process, especially when the subsurface restricting layer is inclined. By evaluating changes of soil dielectric properties Kung and Lu (1993) and Casper and Kung (1996) showed that GPR can detect the size, inclination, and spatial pattern of subsurface layers. Recently, Gish et al. (2002) showed that subsurface convergent flow pathways could be identified with GIS analysis of ground-penetrating radar data and digital elevation maps. A knowledge of the GPR-identified flow pathways was utilized to characterize corn growth pattern (Walthall et al. 2001) and to understand surface-subsurface nitrogen transport (Daughtry et al. 2001). In addition, Angier et al.

(2001) found that the GPR-identified flow pathways corresponded with the up-welling zones in the adjacent riparian ecosystem. These results may make it possible to accurately quantify subsurface water and chemical fluxes exiting agricultural land and entering neighboring ecosystems.

The objective of this paper is to present a brief overview of the OPE3 program and to show the relevance of subsurface flow pathways on crop yield during water-limited growing seasons.

## Materials and Methods

### Site description

The research site is a 25 ha agricultural production field located at the USDA, Beltsville Agricultural Research Center, Beltsville, Maryland (39$^{o}$ 01' 00" N, 76$^{o}$ 52' 00" W). The site is part of the **O**ptimizing **P**roduction inputs for **E**conomic and **E**nvironmental **E**nhancement program (OPE3) containing four small bounded watersheds, approximately 4 ha each, with earthen berms which feed a wooded riparian wetland and first-order stream (Fig. 1). The watershed has a sandy loam surface and is relatively flat with 73% of the site having slopes < 2% and 1% of the site having slopes > 3%. The watershed drains into a riparian wetland forest which contains a first-order stream.

For the first year of this study the same management treatment was applied to all four watersheds to assess watershed similarities. The variability of yields between watersheds was surprisingly similar (Table 1). The corn grain yield of each watershed ranges from < 900 kg/ha to over 7,900 kg/ha. Furthermore, the yield distributions for each watershed were normally distributed with a mean yield of about 3,750 kg/ha. Thus, the watersheds appear to behave similarly.

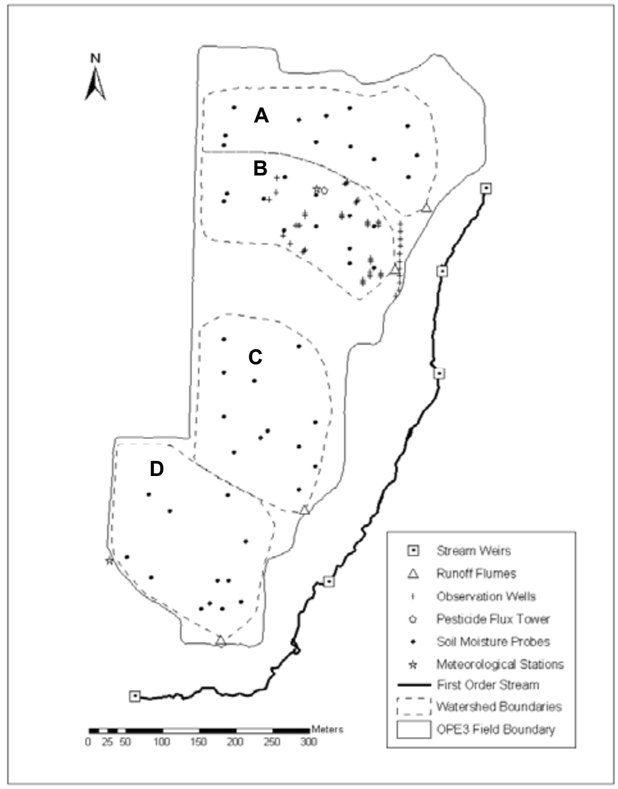


Figure 1. OPE3 schematic showing bounded waterdheds, first-order stream, and instrumentation.

Table 1. Corn Grain Yield Comparison Among Watersheds, 1998.

| *Watershed* | **Mean** (kg/ha) | **Std. Dev.** (kg/ha) | **Min.** (kg/ha) | **Max.** (kg/ha) |
|---|---|---|---|---|
| **A** | 4,076 | 1,442 | 878 | 7,964 |
| **B** | 3,700 | 1,568 | 627 | 8,466 |
| **C** | 3,449 | 1,693 | 377 | 8,654 |
| **D** | 3,763 | 1,630 | 876 | 8,027 |

### Data collection activities

OPE3 is a small watershed program that is intensively instrumented, and where all data is geolocated with a differential or kinematic global positioning system. Some of the data collection activities include:

- Over 40 km of ground penetrating radar (GPR) data have been collected and analyzed.

- Every two years, soil cores are extracted to determine the spatial correlations and distributions of organic matter, pH, and sand, silt, and clay percentages.
- Electromagnetic induction (EM-31 and EM-38) has been collected for two of the watersheds.
- 36,000 volumetric water content measurements at 48 locations are collected daily.
- Micro-meteorological stations with eddy covariance systems monitor climatic conditions.
- Multiple pesticide vapor flux towers are operational after application.
- Water and chemical (N, P, and pesticides) runoff fluxes are collected from each watershed.
- Watershed B is instrumented with 52 groundwater observation wells.
- Corn grain yields are measured using a grain a yield monitor.
- Aircraft and satellite remote sensing imagery are collected. Ground and tower-based reflectances are collected as needed.
- Plant growth and development are measured periodically during the growing season.
- 180 observation wells in the riparian wetland are monitored for anions and pesticide.
- Stream flows and chemical fluxes in the stream are measured at five stations within the riparian wetland.
- Wetland soil cores were extracted and analyzed for grain size, bulk density, carbon content, hydraulic conductivity, water content, and denitrification potential.
- Dissolved gas is measured in groundwater samples throughout the wetland, for evidence of denitrification and methanogenesis. Dissolved oxygen, dinitrogen, nitrous oxide, and methane are measured.
- Sap flow rates for estimating evapotranspiration are measured on ten trees within the riparian wetland.

The site is also the center of the NASA BARC-EOS and EO-1 Core validation site.

### Subsurface flow pathways

Soil moisture is a critical factor governing plant growth and chemical behavior and fate. Consequently, methods for determining the existence and location of subsurface flow pathways is important to optimizing production field management. At OPE3 over 40 km of digital GPR data were used to identify the location of potential subsurface convergent flow pathways. GPR data were acquired for the 25 ha site at two scales of observation: 1) parallel North-South transects, 25 m apart over the entire watershed; and 2) North-South transects, 2 m apart over forty-four, 25 m x 25 m plots within the watershed. The spatial autocorrelation of subsurface reflections potentially restricting water movement was determined using geostatistical software. Omnidirectional semivariograms were produced from point data derived from digitized traces of the depth to the first continuous restricting layer. Semivariogram models provided kriging parameters for subsequent spatial interpolation. The depth of these subsurface reflections was calculated for 10 m x 10 m cells over the entire watershed and subtracted from the DEM data. This calculated a subsurface topographic surface that restricts water flow. The Arc/Info GIS FLOWDIRECTION and FLOWACCUMULATION routines were applied to the subsurface topography to determine potential flow pathways (Gish et al 2002).

### Soil moisture monitoring

Two hundred fifty-six soil moisture sensors were distributed between 48 locations to independently monitor the spatial and temporal changes of soil water content throughout the top 1.8 m of the site. Each sensor was calibrated before installation, and programmed to record volumetric water content every 10 minutes (Gish et al. 2002).

### Airborne imagery

The Airborne Imaging Spectroradiometer for Applications (AISA) is used to collect visible-near infrared hyperspectral imagery of the site. Color infrared film is also used when very high spatial resolution is required.

Patterns of high crop density during water limited growing seasons have been observed in imagery for areas corresponding to the presence of GPR-identified subsurface flow pathways. Together with correspondingly high yield patterns from the yield monitor data, these crop density patterns are believed to corroborate the location of subsurface flow pathways. Imagery from dry and/or drought years appears especially useful for identifying areas of the field that appear to be continuously irrigated from subsurface sources.

Image-based procedures for chlorophyll density and leaf area index (LAI) mapping at high (1-4 m) spatial resolution are being developed for the hyperspectral data. Procedures to identify the subtle changes of canopy reflectance associated with leaf chlorophyll concentrations are also being developed as a tool for managing the spatial variability of crop N. Remotely sensed leaf chlorophyll concentrations were consistent with measured values over a wide range of soil reflectance and LAI values (Daughtry et al. 2000).

One LAI mapping procedure under investigation seeks to exploit the spatial information content by incorporating semivariograms of spectral vegetation index (SVI) maps with surface-based samples. Another procedure uses a hybrid approach that links SVI maps with radiative transfer model inversions to produce LAI maps. The LAI maps will serve as quantitative measures of crop variability.

The chlorophyll and LAI maps are being investigated as potential surrogate indicators of subsurface flow pathway locations. Image-based procedures may be applicable to other production fields in the absence of logistically difficult and expensive GPR data.

Crop foliage imagery is also being used to infer information about the underlying soil water holding properties. The spatial information of the remotely sensed LAI maps, coupled with weather data and a physical model are being used to investigate procedures for the inversion of soil water holding capacity.

## Discussion

A protocol for determining the spatial location of subsurface flow pathways based primarily on GPR and DEM data was developed and successfully tested at the OPE3 experimental research site. Although there is good visual agreement between remote sensing activities and the GPR-identified flow pathways, there is considerable amount of uncertainty due to the manner in which the GPR data were collected. Apparently, uncertainty in the areas where no GPR data were collected increases as the flow network moves downslope.

Confirmation of subsurface water movement through preferential flow pathways can be difficult to asses due to: 1) the spatial and temporal dynamics of water movement; 2) the relatively small volumes of soil used in preferential transport; and 3) the small volumes of soil being evaluated by the soil moisture sensors (i.e. 10 cm diameter). Nonetheless, representative subsurface soil water contents patterns occurring near (<5 m) or far away (>5 m) from the GPR-identified flow pathways are shown Figures 2 and 3. Soil moisture measurements, acquired every 10 minutes, provided a motion picture view of the soil water dynamics at the two locations during the growing seasons.

The soil moisture probe located near a GPR-identified flow pathway and where the GPR data indicated a clay lens at 1.54 m, is shown in Figures 2a and 2b. At this location, a layer of coarse sand and gravel is above the clay lens. In 1998, (d = 126) volumetric water contents changed abruptly at 1.5 m from 0.08 to 0.32 $cm^3\ cm^{-3}$ in less than an 24 h – while volumetric water contents at 1.2 m changed slowly even though both depths had a similar soil textures. Additionally, moisture contents at 1.5 m were more than twice the moisture content at 1.2 m. Thus, the soil water dynamics near a GPR-identified flow pathway fully support the hypothesis of horizontal water flow along the clay lens interface – funnel flow. During the 1999 growing season a large plume of water appears (d = 260) – a consequence of Hurricane Floyd. Although water contents at 1.2 m and 1.5 m rise simultaneously, they remain higher at 1.5 m, indicating a larger plume and potential horizontal water flow. When fluxes are monitored, abrupt changes in soil water content are common with preferential flow processes (Kung et al. 2000).

Since preferential flow typically occupies less than 1% of the available pore space, most of the watershed should experience water movement predominantly as a function of hydraulic conductivities and matrix potential gradients, and as such one would generally expect gradual changes in soil moisture with time. In

Figure 3a and 3b, the soil moisture probe is located > 5 m away from a GPR-identified flow pathway and where the clay lens is situated 1.6 m below the soil surface. Several rain events occurred in August of 1999 which increased the subsurface water contents by only a few percent. However, little increase in subsurface moisture was noted during Hurricane Floyd (d = 260), suggesting that subsurface water bypassed this site where the probe was located. Other than the soil moisture changes at d = 242 in 1999, all subsurface moisture observations changed gradually. In summary, no preferential flow was observed in the soil moisture probes located > 5 m from a GPR-identified flow pathway for identical weather patterns and similar soil conditions.

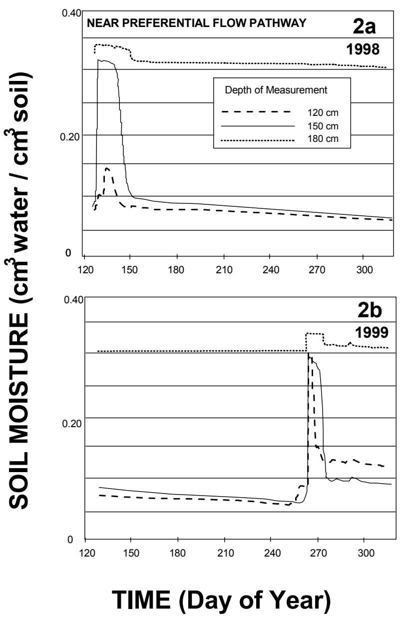


Figure 2. Real-time soil moisture observations near the GPR-identified flow pathway.

## Relationship between yield and flow pathways

Corn grain yields during a mild drought are also influenced by the GPR-identified flow pathways. Corn grain yields decrease with increasing distance from the subsurface flow pathways (Fig. 4).

Since corn grain yields are influenced by the subsurface flow pathways a moisture response index, MRI, is being developed and tested to identify those areas of the field and the degree to which they are influenced by subsurface soil moisture. The MRI uses yield monitor data from wet and dry years to generate an index that may help refine the location and shape of the GPR-identified flow pathways.

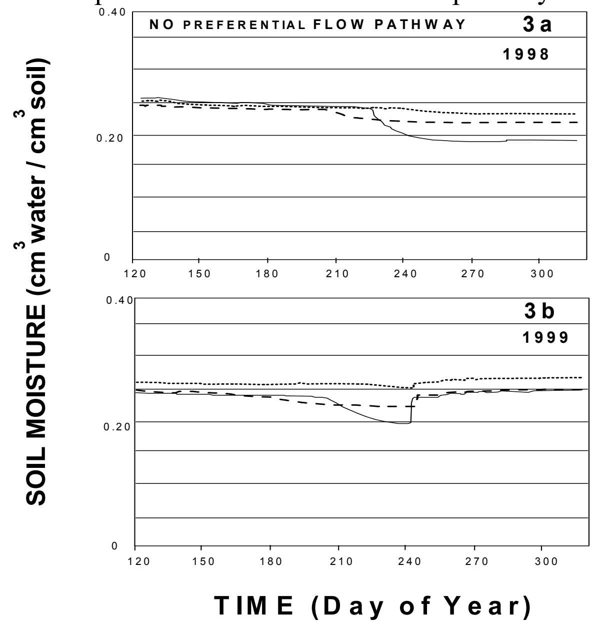


Figure 3. Real-time soil moisture observations >5 m from a GPR-identified flow pathway.

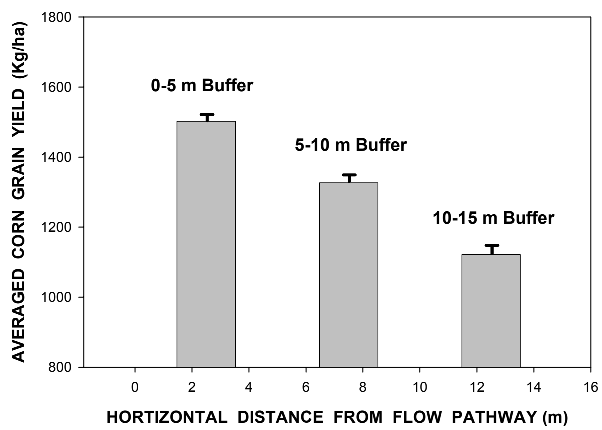


Figure 4. Impact of distance from subsurface flow pathways on corn grain yield during a mild drought. Data presented is for watershed B. Error bars indicate standard error of the means.

## Conclusions

The OPE3 program demonstrates that georeferenced GPR data sets on a sandy soil have great potential to locate soil layers which control subsurface water flow, crop yield patterns, and perhaps field-scale chemical behavior and fate. Real-time soil moisture data supported the existence of funnel flow processes, which indirectly confirmed the existence of restricting layers. These techniques may have the capacity to monitor and evaluate subsurface water pathways which are necessary to determine agrichemical fluxes beyond the root zone. Additionally, soil moisture data coupled with GPR-identified flow pathways suggest that: 1) a coupling of GPR data with real-time soil moisture monitoring may be an effective tool for evaluating and monitoring subsurface flow processes; 2) the spatial location of the soil moisture monitoring system is critical to monitoring water movement; and 3) real-time monitoring of water movement is critical if preferential flow pathways are to be accurately monitored.

## Acknowledgments

Manuscript reviews and help with the preparation came from Dr. Ali Sadeghi and Andrew Russ.

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