Pennsylvania Water Resources Research Center, Penn State Institutes of Energy and the Environment
Annual Technical Report
FY 2008

Introduction

Research Program Introduction

The FY 2008-09 Annual Report for the Pennsylvania Water Resources Research Institute at Penn State University includes information about four research projects that were supported with small grants from the 104B base funding program, following a peer-reviewed, state-wide competition process. All of the research projects address water resources problems of importance to the state of Pennsylvania.

A project entitled "Mercury in Pennsylvania Forest Streams: Do Hotspots Exist?" by Dr. Elizabeth Boyer and David DeWalle within the School of Forest Resources at Penn State, provides baseline data on the accumulation of mercury in forested streams throughout the state, in response to atmospheric emissions of mercury. Another project focusing on streams in Pennsylvania was conducted by Dr. Michael Gooseff, a new faculty member with the Department of Civil and Environmental Engineering at Penn State completed a study entitled "Controls on nitrogen and phosphorus transport and fate in northern Appalachian streams," which compared and contrasted responses of upland forest and agricultural stream ecosystems to nutrient additions that typically can lead to eutrophication of downstream water bodies. A third project, "Seeing into the subsurface: Detecting and visualizing preferential flow in situ using innovative approaches," was completed by Dr. Henry Lin with the Department of Crop and Soil Sciences at Penn State, who developed state-of-the-art research techniques to map the movement of water in a forested landscape that is typical of the Ridge & Valley region of Pennsylvania. Finally, Dr. Mira Olsen, a young investigator with Drexel University, Department of Civil, Architectural and Environmental Engineering, completed a study entitled "Impact of Infiltrating Runoff on Ground-Water Recharge Quality" which determined the amount and water quality of ground-water recharge from constructed detention basins typically used to control storm-water peak flows in urbanizing environments.

Within these four research projects, ten students (from three universities) were supported or partially supported in 2008-2009. They are listed below in the format: Principal Investigator, Student, Major, Degree:

- Boyer; Christopher Grant; Forest Resources; Ph.D.
- Gooseff; Patrick Kerr, Civil & Environmental Engineering, M.S.
- Gooseff; Ryan Furtak, Civil & Environmental Engineering, B.S.
- Lin, Jun Zhang, Soil Science, Ph.D.
- Lin, Ken Takagi, Soil Science, M.S.
- Lin, Kristen Jurinko, B.S., Geosciences
- Lin, Laken Roberts, B.S., Environmental Resources Management
- Olson, Laura A. Klinger, Environmental Engineering, MS student
- Olson, Haibo Zhang, Environmental Engineering, PhD student
- Olson, David Burgy, Engineering, B.S. student

Mercury in Pennsylvania Forest Streams: Do Hotspots Exist?

Basic Information

Title:	Mercury in Pennsylvania Forest Streams: Do Hotspots Exist?
Project Number:	2008PA85B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	5th
Research Category:	Water Quality
Focus Category:	Water Quality, Surface Water, Ecology
Descriptors:	None
Principal Investigators:	Elizabeth Boyer, David Russell DeWalle

Publication

1. Sebestyen SD, JB Shanley, and EW Boyer (2009). Documenting effects of atmospheric pollutants on stream chemistry using high-frequency sampling. In press, Proceedings of the Third Interagency Conference on Research in the Watersheds.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Mercury is a persistent element in the environment that has the ability to bioaccumulate and biomagnify up the food chain, with potentially harmful effects for human health and ecosystems. Mercury emissions to the atmosphere are the largest source of mercury pollution globally and in most areas of the northeastern USA. Concern for increased environmental Hg levels and effects led to the development of a Mercury Deposition Network (MDN) that is operated by the National Atmospheric Deposition Program, which provides monitoring of mercury in precipitation at sites across the US and southern Canada. The Pennsylvania Water Resources Research Institute contributes to the operation of the 9 mercury deposition monitoring sites in the state. Results from the MDN monitoring show that Pennsylvania receives among the highest rates of Hg deposition of any location in the northeastern USA, experiencing wet atmospheric deposition rates of 7-10ug Hg/m2 in precipitation in 2006. Watersheds in Pennsylvania receive mercury that is emitted from the smokestacks of coal-fired power plants and other sources then is deposited to the landscape. Some mercury runs off into nearby streams where it can accumulate in the sediments and biota. Human exposure to Hg occurs mostly through fish consumption, and currently fish eating advisories due to mercury have been posted for over 877 stream miles and 28 lakes (28,500 acres) across Pennsylvania. Stream Hg levels are believed to be a key indicator for concentrations of mercury available for uptake by biological organisms.

In this project, baseline data on mercury accumulation was collected from 40 forested watersheds throughout the state, spanning gradients of climate and geology. These watersheds are minimally disturbed (e.g., no direct impacts of agriculture, urbanization, or mining) and are able to support fish populations. Mercury was measured in stream water, fish tissue (from brook trout), aquatic mosses, and in stream-

Measurement-inerpolated atmospheric deposition of mercury in precipitation in PA for 2007

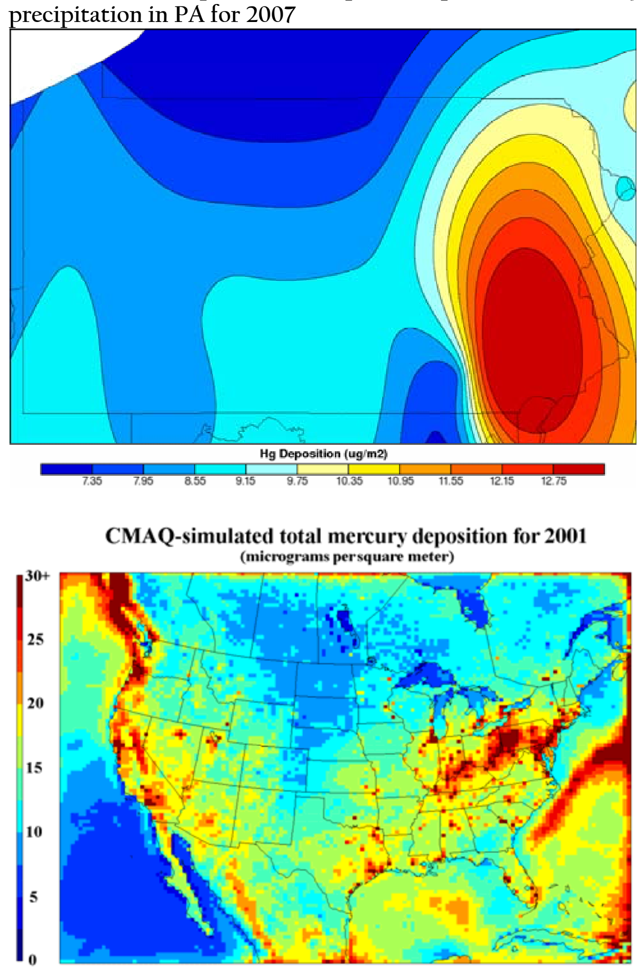

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Figure 1. (top:) Wet Hg deposition from interpolation of measurement data across PA in 2007 based on an interpolation of data from monitoring sites in PA & surrounding states. (bottom): Modeled total (wet+dry) total Hg deposition with the CMAQ model for the USA in 2001 (from US EPA).

bed sediments. Preliminary data suggest that mercury is accumulating at trace levels in these aquatic environments. Highest concentrations were found in the mosses and sediments, suggesting their potential utility for integrating long term watershed responses. Mercury levels in fish samples are very low in concentration with respect to human health concerns. However, mercury levels in fish samples suggest potential ecosystem level concerns in some of the watersheds, with concentrations in fish approaching the US Fish and Wildlife Service fish-eating bird and wildlife advisory. The findings of this study suggest that mercury deposition is reaching remote watersheds all across the state and is affecting aquatic ecosystems.

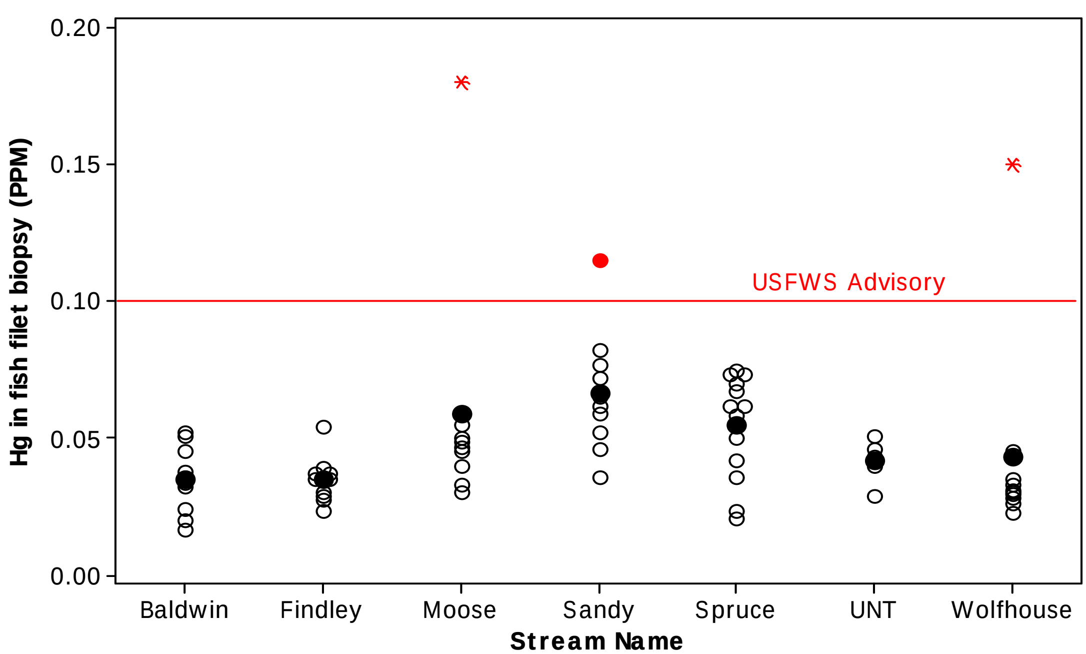


Figure 2. Total mercury levels in individual fish tissue samples in brook trout collected from seven forested streams. Overall, the low concentrations observed in fish are not a human health concern. The samples relative to USFWS fish eating bird &wildlife advisory (for ecosystems). Blackened circles are mercury averages in fish tissue, red symbols are above limit with red stars indicating outliers.

Controls on nitrogen and phosphorous transport and fate in northern Appalachian streams

Basic Information

Title:	Controls on nitrogen and phosphorous transport and fate in northern Appalachian streams
Project Number:	2008PA87B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	5th
Research Category:	Ground-water Flow and Transport
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Mike Gooseff

Publication

1. Kerr, PC, and MN Gooseff. 2008.Comparison of model structure in multiple-transient storage modeling of solute transport in streams: Nested versus competing storage zones. American Geophysical Union Fall Meeting, San Francisco (H11B).
2. Gooseff, MN, MA Briggs, PC Kerr, MR Weaver, W Wollheim, BJ Peterson, K Morkeski, and CS Hopkinson. 2009. Separating in-channel and hyporheic transient storage processes in river networks - A path toward improved quantification of stream-groundwater interactions. Joint Assembly of the American Geophysical Union (H71D-02).

PRINCIPAL FINDINGS AND SIGNIFICANCE

In this project, we conducted repeated whole stream nutrient additions of NO_3 and PO_4, each individually and a third addition of the two combined (NO_3 + PO_4) to determine whether the presence of both nutrients would enhance uptake of one or the other (in all addition experiments NaCl was also added as a conservative tracer). We expected that the elevated presence of both nutrients would result in less potential for limitation or saturation of one nutrient or the other (i.e., as might be expected in single-nutrient addition experiments). We performed 5 'sets' of these 3 addition types in three small streams in central Pennsylvania (Table 1).

Table 1. Details of sites, conditions, and addition experiments.

Experiment	Date	Addition	Q (L/s)	Reach length (m)
Benner Run 1	06/15/08	NO_3	110	340
Benner Run 1	06/16/08	PO_4	110	340
Benner Run 1	06/17/08	NO_3+PO_4	110	340
Benner Run 2	07/14/08	NO_3	57	460
Benner Run 2	07/15/08	PO_4	57	460
Benner Run 2	07/17/08	NO_3+PO_4	57	460
Laurel Run 1	06/24/08	NO_3	70	460
Laurel Run 1	06/25/08	PO_4	70	460
Laurel Run 1	06/26/08	NO_3+PO_4	70	460
Laurel Run 2	07/21/08	NO_3	30	460
Laurel Run 2	07/22/08	PO_4	30	460
Laurel Run 2	07/23/08	NO_3+PO_4	30	460
Leading Ridge 1	08/09/08	NO_3	0.25	200
Leading Ridge 1	08/11/08	PO_4	0.25	200
Leading Ridge 1	08/14/08	NO_3+PO_4	0.25	200

Our analysis of computed uptake lengths (S_W – the average distance a nutrient molecule travels downstream before being taken up) suggests that, on average, NO_3 uptake is enhanced by the presence of elevated concentrations of PO_4. The average NO_3 S_W during NO_3-only injections was 32,567 m, whereas during the coupled NO_3+PO_4 additions, the average S_W for NO_3 was 14,077 m. However, both sets of NO_3 S_W data are quite variable, ranging from -5000m to 142,857m for NO_3-only injections and from -50,000 m to 50,000 m in coupled additions (Figure 1A).

Our analysis of computed S_W values for PO_4 suggests that, on average, there is little to no effect from the presence of elevated NO_3 concentrations. The average of PO_4 S_W during PO_4-only injections was 4,800 m, whereas during the coupled NO_3+PO_4 additions, the average S_W for PO_4 was 4,857 m. There is less variability in PO_4 S_W data, compared to NO_3 S_W data, ranging from -5000m to 25,000m for PO_4-only injections and from 44 m to 10,000 m in coupled additions (Figure 1B). It is interesting to note that during coupled additions, all PO_4 S_W values were greater than 0.

Accounting for stream flow velocity, we can compare nutrient uptake velocities ($v_f = (u*d)/S_W$, where u is stream flow velocity and d is average depth). For NO_3, this analysis suggests a reduced demand, on average, during coupled additions ($1.16x10^{-5}$ m/s) compared to during NO_3-only additions ($8.10x10^{-5}$ m/s). Uptake velocity values for NO_3 ranged from -$3.3x10^{-5}$ to $3.14x10^{-4}$ m/s for NO_3-only additions and from -$7.6x10^{-5}$ to $6.98x10^{-5}$ m/s for coupled additions (Figure 1C). The opposite interpretation comes from the analysis of PO_4 uptake lengths, which average $9.27x10^{-4}$ m/s for PO_4-only additions and $1.05x10^{-3}$ for coupled additions. This comparison of greater PO_4 demand in coupled additions is evident in 4 of the 5 addition experiments (Figure 1D).

The goal of this research project was to determine whether the interpretation of single nutrient addition experiments was likely to be modified significantly by co-addition of another typically limiting nutrient. Our results indicate that 1) uptake lengths are long and nutrient demand is fairly small in these streams, compared to values published in other temperate, forested catchment streams, and 2) there is not a consistent trend of increased NO_3 or PO_4 uptake during additions of both nutrients compared to the addition of each alone. Whereas these streams represent only a single stream type, the findings are significant in suggesting that single nutrient addition experiments are useful in characterizing the dynamics of that individual nutrient. Furthermore, the stoichiometry of uptake, beyond background ratios does not appear to dramatically influence nutrient demand. Given the challenges faced by resource managers as society deals with increased nutrient loading to streams and ultimately coastal areas, the findings from this research suggest that co-additions of nutrients as a means of exploring nutrient uptake dynamics is not likely to provide new breakthroughs. However, using the standard methods here, it was not possible to determine whether full cycling of N or P had been completed during the addition experiments. That is, we could not determine separately rates of uptake and production separately. Hence, it may be possible with the inclusion of isotopic tracers of NO_3 or PO_4 to further evaluate specific rates of N or P processing.

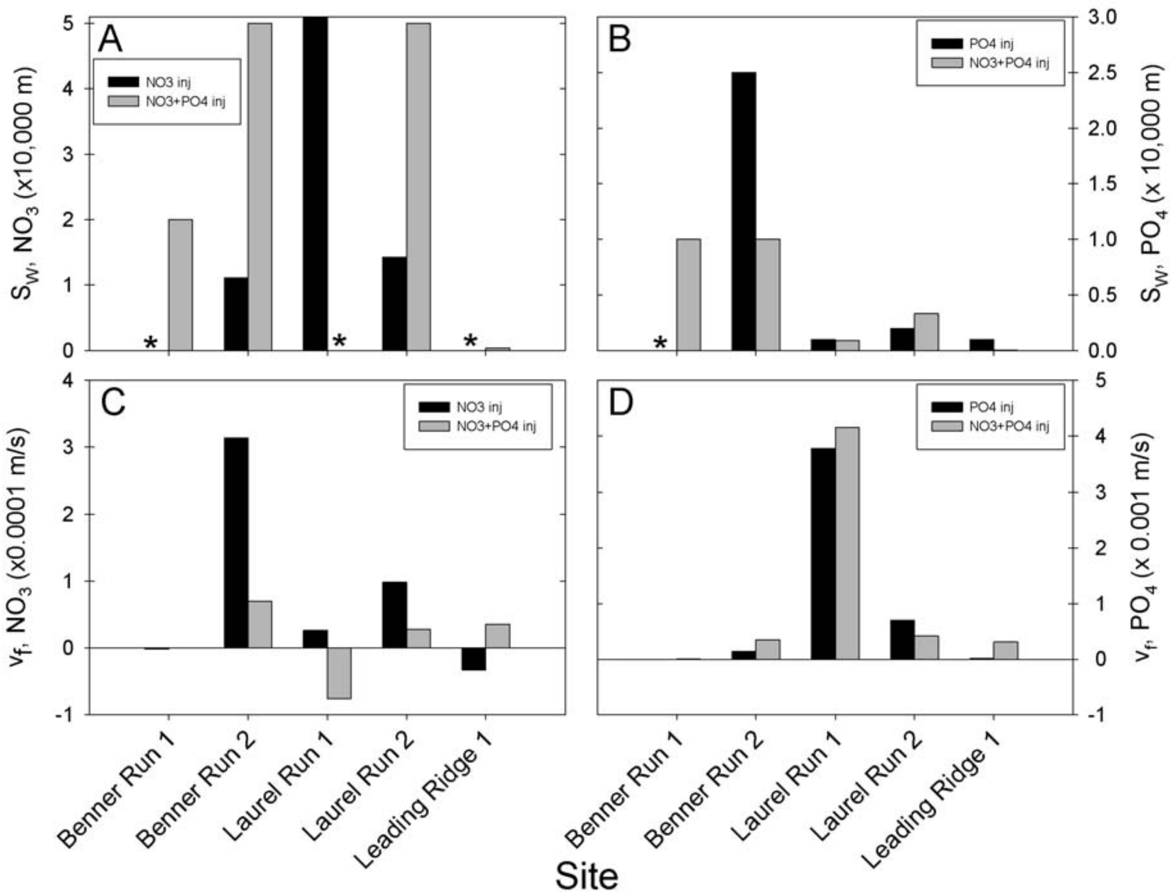


Figure 1. Summary results from 5 sets of whole stream nutrient addition experiments comparing A) nitrate (NO_3) and B) phosphate (PO_4) uptake lengths (S_W) and C) nitrate and D) phosphate uptake velocities (v_f) in nitrate-only and nitrate+phosphate addition experiments. * indicates that uptake lengths were negative (i.e., nutrient was indicated to be produced rather than taken up) over the reach length of interest. See Table 1 for addition experiment details. Note in panel A, the uptake length for Laurel Run 1 during the NO_3-only addition is 142,857 m.

Seeing into the subsurface: Detecting and visualizing preferential flow in situ using innovative approaches

Basic Information

Title:	Seeing into the subsurface: Detecting and visualizing preferential flow in situ using innovative approaches
Project Number:	2008PA88B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	5th
Research Category:	Ground-water Flow and Transport
Focus Category:	Hydrology, Methods, Solute Transport
Descriptors:	None
Principal Investigators:	Henry Lin

Publication

1. Lin, H.S. 2009. Earth s Critical Zone and Hydropedology: Concepts, Characteristics, and Advances. Hydrology and Earth System Science Dis. 6:1-37.
2. Lin, H.S., E. Brook, P. McDaniel, and J. Boll. 2008. Hydropedology and Surface/Subsurface Runoff Processes. In M. G. Anderson (Editor-in-Chief) Encyclopedia of Hydrologic Sciences. John Wiley & Sons, Ltd. DOI: 10.1002/0470848944.hsa306.

PRINCIPAL FINDINGS AND SIGNIFICANCE

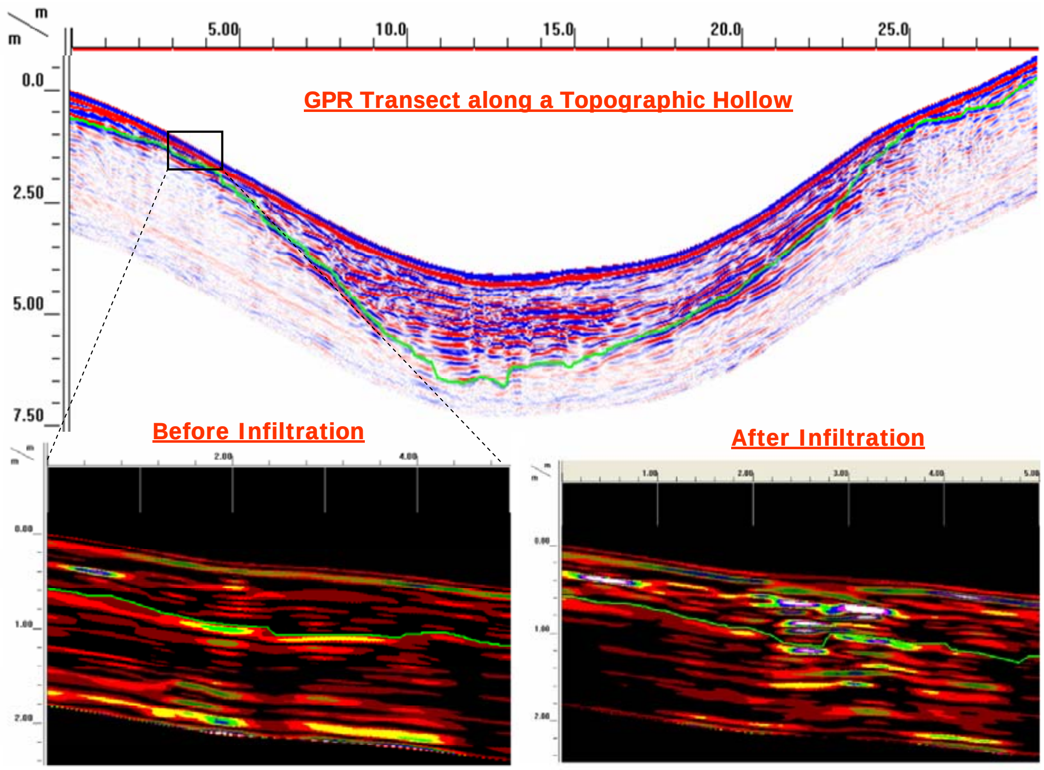
The lack of an effective means for detecting and visualizing subsurface flow dynamics has constrained our understanding and predicting of vadose zone processes such as subsurface stormflow and groundwater recharge. Growing evidence suggest that subsurface flow network is a key to understanding hydrologic processes including hillslope threshold behavior. The dynamic origin of network structures in soils and hydrologic systems and recurrent patterns of self-organization are the subjects of recent research and model development.

Subsurface lateral flow in the catchment has been observed to contribute substantially to direct runoff. But understanding the occurrence and intensity of subsurface lateral flow is difficult because of the subsurface complexity and the lack of appropriate tools to identify this complexity. In this study, we innovatively used time-lapsed ground penetrating radar (GPR) in combination with real-time soil water monitoring to identify subsurface flow regime in different hillslopes and soil types at the Shale Hills Catchment. The results of this study have significant implications for developing a next generation of hydrologic models that explicitly consider flow pathways, patterns, and flow configuration evolution.

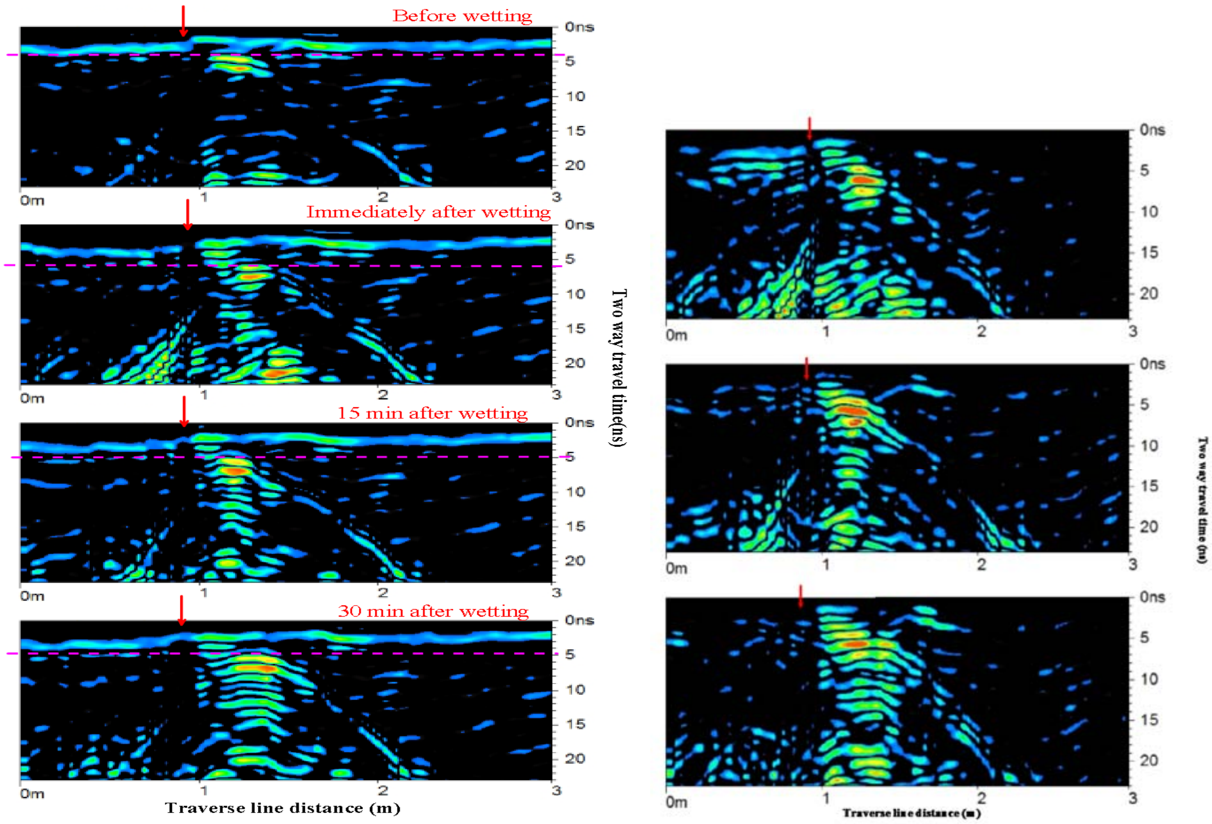
Ground Penetrate Radar provides a non-invasive way to reveal the subsurface complexity. We have demonstrated that GPR is suitable to identify subsurface structure in this landscape. However, static radargram only provides a qualitative description of subsurface characteristics. In this study, we developed time-lapsed GPR with soil water sensors to identify subsurface flow patterns in real time. A 3 by 4 meter grid was established along several hillslopes. In each grid, multiple ECH_2O-TE probes were installed at different depths (5, 10 and 30 cm) and the probes were connected to CR1000 datalogger to record the soil water dynamics at 2-minutes interval. The GPR scan was along downslope direction and the space interval was 0.1 m. The 400 MHz GPR was first used to scan the grid to obtain initial subsurface state. Then, a known volume of water waas carefully poured onto the soil surface at the upper portion of the grid. Subsequent GPR scans were then conducted along the same traverse line 5, 10, 20, 30, 40, 50 and 60 minutes later. Results indicated that radiograms were quite different before and after water infiltration. Electromagnetic velocity of GPR was obtained through the detection of direct ground wave, and then was transformed to water content using Topp's equation. Inverse distance weight method was used to interpolate the derived soil moisture and compared with the soil water content measured by ECH_2O-TE probes. By comparison with time-lapsed soil moisture map, it was possible to determine the subsurface flow pattern across the hillslope transects. This study improves the understanding of subsurface flow pattern in the Shale Hills Catchment and will enhance more realistic hydrological model development. In addition, we have developed many 3D (X, Y, Z; or X, Y, and time) and 4D (X, Y, Z, and time) animations of subsurface preferential flow at the pedon and hillslope scales based on the database collected from this project, which benefits classroom teaching and public education via "seeing is believing." For example, one of such animations is viewable and downloadable at http://hydropedology.psu.edu/.

Graduate student Jun Zhang and NRCS collaborator Jim Doolittle were working on GPR scanning of a hillslope at the Shale Hills Catchment.

Experimental setup of time-lapsed GPR scanning and real-time soil moisture monitoring with introduced water infiltration in a hillslope at the Shale Hills Catchment.



A terrain-corrected ground penetrating radar (GPR) image collected at the Shale Hills Catchment along a topographic hollow (orthogonal to its long axis). The green line indicates the interpreted approximate soil-bedrock interface. The zoom-in images show a section of the hillslope before (left) and after (right) ten gallons of water infiltrated into the soil between the 2 and 3 m distance marks.



A **B**

A: Time lapse GPR image before and after infiltration. Red arrow indicates the location of infiltration intake. Dash line is the two way travel time to the apex of hyperbola, which indicates the depth of buried metal plate used for GPR image calibration.

B: Difference between radargrams before infiltration and after 0, 15, 30 minutes infiltration, respectively (from top to bottom)

Impact of infiltrating runoff on groundwater recharge quality

Basic Information

Title:	Impact of infiltrating runoff on groundwater recharge quality
Project Number:	2008PA89B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	2nd
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Water Quality, Solute Transport
Descriptors:	None
Principal Investigators:	Mira Olson

Publication

PRINCIPAL FINDINGS AND SIGNIFICANCE

This project provided seed funding to start a long-term research endeavor exploring the impact of infiltrating storm-water runoff on the quality of ground water. The goal of this work was to quantitate pollutant loading to ground water beneath stormwater detention basins. During the project period, we began our analyses of infiltration rates and pollutant removal with depth beneath the surface, both in laboratory experiments and in the field. In addition, examined soil amendments which may be used as preferential sorbents for infiltrating contaminants and developed a spreadsheet model of ground-water infiltration following rainfall events. As managers prioritize resources for alternative water management practice and encourage aquifer recharge, it is important to identify regions of aquifer vulnerability to surface-derived contaminants and to develop best management practices for protecting ground water. To do this, a thorough understanding of pollutant transport during infiltration is required. It is our goal to optimize ground-water recharge management, preserving ground-water quality and quantity in urban and urbanizing areas of Pennsylvania.

<u>Field measurements of ground-water recharge quality:</u>

Suction lysimeters were installed at two depths beneath land surface in a stormwater detention basin in Philadelphia county to collect water samples during rainfall infiltration events. A great deal of heterogeneity was observed in the subsurface, and spatial analyses of surface infiltration rate measurements collected using a Cornell sprinkle infiltrometer are currently underway. A schematic of field instrumentation is provided in Figure 1. During rainfall events, grab samples are collected from ponded water in the detention basins and the pump to the suction lysimeters is turned on to collect water samples as the wetting front infiltrates through the unsaturated zone. Water samples are returned to lab and analyzed for pH, TSS, total phosphrous, total nitrogen, copper, lead, chromium, total coliforms and *E.* coli. Preliminary results suggest slight removal of TSS with depth. Experiments continue and field instrumentation of a similar detention basin in the Valley Creek Watershed is planned for Summer 2009.

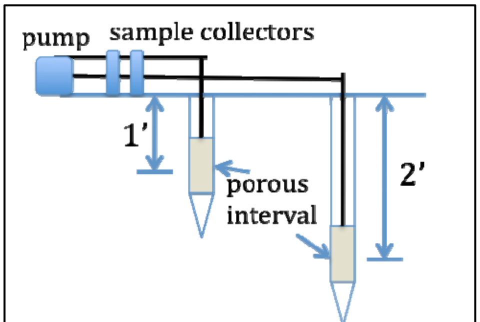


Figure 1. Field instrumentation for vadose zone water sample collection

<u>Development of a surface-water infiltration model:</u>

Localized recharge to ground water induced by infiltration from detention basins is a significant mechanism by which stormwater pollutants may be introduced to underlying ground-water supplies. The infiltration rate determines the rate at which surface water contaminants reach the underlying ground-water table. The Joint Green-Ampt infiltration was developed by combining two existing infiltration models into a fully explicit model. A comparison of the joint approach against an implicit model confirms that the accuracy of the joint model is sufficient for use. The fully explicit equations make it easy to perform calculations in a spreadsheet environment. The model can be used for a constant rainfall event in uniform soil. As part of this work, we developed a fully explicit spreadsheet model for estimating infiltration; we are currently updating this model to include contaminant transport and removal. The model is described as follows:

$$\text{When } r < Ks, \qquad q = r \qquad I = rt$$

$$\text{When } r > Ks \text{ and } t < t_0, \qquad q = r \qquad I = rt$$

$$\text{When } r > Ks \text{ and } t > t_0,$$

$$q = K_S\left(\frac{\sqrt{2}}{2}\tau^{-1/2} + \frac{2}{3} - \frac{\sqrt{2}}{6}\tau^{1/2} + \frac{1-\sqrt{2}}{3}\tau\right)$$

$$I = Ks\{(1-\frac{\sqrt{2}}{3})t + \frac{\sqrt{2}}{3}\sqrt{\chi t + t^2} + (\frac{\sqrt{2}}{3} - 1)\chi[\ln(t+\chi) - \ln\chi] + \frac{\sqrt{2}}{3}\chi[\ln(t + \frac{\chi}{2} + \sqrt{\chi t + t^2}) - \ln(\chi/2)]\}$$

$$\text{With} \qquad \chi = \frac{(h_s - h_f)(\theta_s - \theta_0)}{K_S}$$

$$\tau = \frac{t}{t+\chi}$$

$$t_0 = \frac{-K_s h_f(\theta_s - \theta_0)}{r(r - K_s)}$$

Where
q: surface infiltration rate (cm/h); I: Cumulative infiltration (cm),
r : constant water application rate at the surface (cm/h);
t : time (h); K_s : saturated hydraulic conductivity (cm/h);
θ_s: saturated volumetric water content (cm^3/cm^3);
θ_0: initial volumetric water content (cm^3/cm^3);
h_f: capillary pressure head (< 0) at the wetting front (cm);
h_s: ponding depth or capillary pressure head at the surface (cm);
t_0: time when surface saturation occurs(h)

Figure 2. *Laboratory infiltration columns.*

Laboratory studies of infiltration and pollutant removal:

Laboratory columns were designed and constructed to simulate surface recharge during infiltration of ponded water (Figure 2). Transient pore water pressures were measured using tensiometers evenly dispersed along the length of the column. Water samples were collected via syringes inserted into sampling ports along the length of the column. Synthetic stormwater amended with microorganisms was ponded at the top of the column and the infiltration front was measured. Modest improvements to bacterial removal rates have been observed when a layer of manganese-dioxide sand was packed in the column as a sorptive amendment.

PHOTOS OF PROJECT

Drexel University graduate student Laura Klinger installing suction lysimeters to measure ground-water quality versus depth beneath a Philadelphia stormwater detention basin.

Field installation of suction lysimters for ground-water sampling beneath a Philadelphia detention basin.


Field collection of stormwater infiltrating through the subsurface in a detention basin.

Information Transfer Program Introduction

None.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	3	0	0	0	3
Masters	3	0	0	0	3
Ph.D.	3	0	0	0	3
Post-Doc.	0	0	0	0	0
Total	9	0	0	0	9

Notable Awards and Achievements

- As managers prioritize resources for alternative water management practice and encourage aquifer recharge, it is important to identify regions of aquifer vulnerability to surface-derived contaminants and to develop best management practices for protecting ground water. Olson et al. developed a spreadsheet model of ground-water infiltration following rainfall events that is useful for watershed management considerations.
- The lack of an effective means for detecting and visualizing subsurface flow dynamics presents challenges for understanding the movement of water and pollutants in the subsurface. Lin et al. develop new methodology for tracking the movement of water and the fate of solutes in the landscape.
- Pennsylvania is blanketed with atmospheric emissions of mercury from multiple sources, including coal-fired power plants, resulting in mercury loadings in precipitation and in dry fallout. Boyer et al. show that mercury is found at low concentrations in sediments, mosses, fish tissues, and in the water column in 40 relatively unpolluted forested streams throughout the state; the levels of mercury do not pose a significant threat to human health, but may stress aquatic ecosystems.
- Nutrient pollution is a major water quality problem in Pennsylvania and beyond. Gooseff et al. quantify how streams and rivers process nutrient inputs from the environment and highlight the the importance of preserving, conserving, and restoring riparian zones to enhance natural processing of nutrient enrichments.

Publications from Prior Years