College of Agriculture and Life Sciences
Proposal for Research Funds
Administered by the Office of Academic Programs
and the Cornell University Agricultural Experiment Station

Cover Sheet

Research Title:  **Quantifying hydrologic source areas and flowpaths in a complex landscape.**

Name of funding program(s) applying to:
- [ ] CALS Charitable Trust Research Grants
- [ ] Hatch/Multistate Supplement
- [X] Dextra Undergraduate Research Endowment Fund
- [ ] Arthur Boller Apple Research Grants
- [ ] Kieckhefer Adirondack Fellowships
- [X] Andrew W. Mellon Student Research Grants

Student’s Name:  **Adrian A. Harpold**

Degree status:
- Graduate student:
  - Degree currently pursuing:  **Ph.D.**
  - Number of years already completed in current program:  **1**

- Undergraduate student:
  - Current class:  **-**
  - Major:  **-**

Local Address  **30 Riley-Robb Hall Ithaca, NY 14850**

Telephone Number:  **(607) 342-3353**

E-mail Address:  **aah38@cornell.edu**

Name and Department of Faculty Research Mentor:  **Tammo Steenhuis, Biological & Environmental Engineering**

Signature of Faculty Research Mentor:  

1/9/2002
Quantifying hydrologic flowpaths and source areas in a complex landscape

A Grant Proposal Submitted To:
The Andrew W. Mellon Student Research Grant
February 16, 2007

Adrian A. Harpold
Biological and Environmental Engineering
30 Riley-Robb Hall
Cornell University
Ithaca, NY 14853
aah38@cornell.edu

Advisor: Dr. Tammo Steenhuis
204 Riley-Robb Hall
Cornell University
Ithaca, NY 14853
tss1@cornell.edu
Abstract

Water is the foundation of a society’s welfare, but world water resources are being stressed by population growth and environmental damage. The hydrologic sciences face many problems using conventional rainfall-runoff models (RRM) to solve emerging challenges. New RRM must incorporate hydrologic source areas and flowpaths to model nonpoint source pollution and landuse change. This research proposes a conceptual model of runoff generation and hydrologic connection for a 10 ha hillslope in the Catskill Mountains, N.Y. The conceptual model identifies spatial patterns, or ‘structure’, to better identify landscape units with similar hydrologic response.

The model will be tested using hydrometric, isotopic, and chemical signatures, as well as geophysical and vegetation surveys. Ultimately, the model will be validated for two gauged catchments and compared to conventional RRM.

Introduction and Justification

Sufficient and safe water is the underpinning of a society’s health, security, economy, and environmental condition [1]. Rainfall-runoff models (RRM) have been developed for operational purposes, including flood modeling, water quality permitting, and engineering structures, but their predictive abilities have long been questioned [2,3,4]. Population growth and its impacts are stressing the need for hydrologic prediction at every spatial and temporal scale [7], and often in ungauged basins (where surface water flow and other measures are lacking). Existing field measurement techniques are not capable of accurately and easily representing subsurface heterogeneities at scales of interest [5]. What is needed to revolutionize hydrological thinking, theory, and model development is an easily applied technique to quantify water storage and visualize water flowpaths beneath the subsurface [4,5,6].

A promising technique for improving prediction of flowpaths is recognizing patterns or ‘structure’ in the landscape that indicate dominant runoff processes [7,8]. Landscape heterogeneity is defined as randomness plus the structure imparted by the organized movement of water. Relevant landscape structures are better understood using knowledge from geomorphology [9], geology [10], pedology [11], and vegetation [12]. However, this more holistic view remains an emerging research area for the hydrologic sciences. In an effort to focus on these needs, the proposed research examines runoff generation on a complex landscape in N.Y. State. The research asks the question, can landscape structure be used to predict runoff source areas and flowpaths.

Brief Review of Literature

Current approaches to rainfall-runoff modeling are limited [13]. Systems-based models (‘black-box’) are based on relationships between input and output data and do not capture the internal workings of the catchment [6,13]. As a result, systems-based models require calibration of variables without physical meaning and cannot account for non-stationarity or threshold effects [6,13]. Physically-based models (‘white box’) use conservation equations and appropriate boundary conditions, but require the inclusion of all important hydrologic processes. Characterizing the landscape requires either extensive field measurements or the calibration of several parameters. Field measurement techniques are improving rapidly; however, it is unlikely there will ever be sufficient spatial data to constrain a complex model for even a small research
catchment [5]. Additionally, calibration of multiple parameters results in a non-parsimonious and uncertain final solution that cannot reliably be used for prediction [2,13]. More conceptual (‘grey-box’) models are the intermediary of the previous models and incorporate relevant physical processes in simplified forms [13].

Conceptual models are more compatible with the nonlinear, non-additive nature of hydrologic processes [4,6]. The conceptual model recognizes landscape structure (repeatable patterns) and a characteristic spatial scale [3,7]. Proposed conceptual models use a series of reservoirs with coupled unsaturated and saturated zones that connect in linear and nonlinear ways [4,6]. Hybrid metric-conceptual models [14] combine the use of observations to corroborate or reject hypothesized model structures. A hypothesis rejection approach makes better use of the scientific method [15], but is underutilized in hydrologic studies [16].

One difficulty facing development of new models is predicting heterogeneity [4], especially dominant subsurface flowpaths and travel times [5,7]. Pioneering field observations on runoff generation [17,18] have led to the development of variable source area (VSA) hydrology, the ‘current paradigm’ in hydrologic modeling [6]. Essentially, VSA was recognition that different parts of the landscape have different hydrologic function. However, a general understanding of how different landscape units contribute to the hydrograph remains unclear [19]. Conventional field measurement at the catchment outlet and select internal point measurements cannot identify specific flowpaths [20]. Until flowpaths and source areas are identified, catchment position cannot be related to stream effects, which is crucial for modeling nonpoint source pollution and land-use change [19].

Research Objectives and Significance

The goal of this research is to develop a simple, parsimonious model for representing hydrologic flowpaths and source areas in a complex landscape. This research utilizes a hypothesis-testing framework [15] to better use the scientific method in hydrologic field work [5,16]. Thus, a model is developed using field observations and tested using a focused field measurement scheme. Three research objectives were developed to meet the goal and complete the requirements for a dissertation.

1. **Develop a conceptual model of runoff generation based on preliminary field surveys.**

Preliminary field surveys focused on spatial data collection, including soil, vegetation, hydrometric, and geophysical surveys. The insight gained about form and function of the hillslope was used to develop a conceptual model of landscape connection and runoff generation. In addition, the model produced quantitative hypotheses that could be tested using field measurements.

2. **Collect geophysical, hydrometric, geochemical, and isotopic measurements at the hillslope-scale.**

Conceptual models must be constrained with water flow, source, and age together to robustly describe processes [5]. A range of sensor and water quality sampling locations have been identified (explained subsequently) to test the hypotheses in a robust way. Improved knowledge of flowpath locations increases sampling efficiency, which reduces costs and enhances the repeatability of this research.
3. **Verify if a network-based landscape model is capable of predicting the importance of lateral flowpath networks on a hillslope or watershed.**

Experimentalists must look past characterizing an individual hillslope and instead focus on simple ways to predict disparate hillslope response [6,15]. The data collected for the hillslope model will be used to improve and evaluate a conceptual model. In addition, the model will be applied to watersheds where landscape characteristics are similar. Does the model represent an improvement in predictive uncertainty over conventional RRM?

**Research Methodology**

A 10 hectare hillslope in the Townbrook watershed in the Catskill Mountains, NY has been the subject of detailed hydrologic field measurements. Initial work on the site investigated the spatiotemporal response of saturated areas near the stream [21]. A geoseismic survey was performed to determine the soil depth and restricting layers at the toe-slope [22]. This work showed that soil depth is correlated to soil moisture, and by inference hydrometric gradients and flowpaths. In addition, a vegetation survey showed that areas measured as ‘wet’ encouraged the growth of vegetation adapted to saturated conditions [22]. This work led to the discovery of toeslope soil pipe outlets and upslope flowpath networks fed by springs and seeps.

1. **Develop a conceptual model of runoff generation based on preliminary field surveys.**

A conceptual model is proposed that explains source areas and flowpaths based on geological and geomorphological controls (Fig. 1). The model combines the ideas of hydrologic landscape units, HLU [19], in a network-node framework. This model simplifies the system from many heterogeneous grid squares to several HLU where stores and fluxes are known or can be estimated with conventional closure equations (e.g. Darcy flow or Manning equation). The HLU are determined spatially across the landscape based on topography, vegetation, aerial photographs, and ground-truth observations [19]. In addition, ‘soft’ information, such as geophysical and vegetation surveys, is used to better define the HLU. The result is a model capable of predicting flowpaths and source areas based on readily available information.

![Figure 1](image-url)

**Figure 1.** a) Network conceptualization of hydrologic landscape units (source areas) and flowpaths, b) two-dimensional hillslope view showing corresponding HLU and observed flowpaths.
2. Collect geophysical, hydrometric, geochemical, and isotopic measurements at the hillslope-scale.

The formation of hydrologic structure and flowpaths is controlled by complex interactions of meteorological, biological, chemical, and geological features on the landscape [7]. Preliminary investigations have led to three process-based hypotheses:

1. Geologic controls on seep locations influence lateral flowpath development.
2. Confining layers (e.g. fragipan) are controls on soil pipe formation.
3. Vegetation increases water residence time.

Several field measurement tools are being used to test these hypotheses. Ground-penetrating radar (GPR) has been used to measure depth to the fragipan layer in the toe-slope region. The GPR was also used to locate soil pipes of up to 12 cm in diameter. This work will be continued to the midslope, where subsurface flowpaths occur at seeps and springs. The GPR will be validated by constructing a 3-m trench face on the upper hillslope. The trench provides quantitative measurement of lateral subsurface flow and provides a means for validating the GPR measurements. Testing the third hypothesis will require the use of chemical and isotopic measurements to determine water residence time.

A fundamental premise of hydro-chemical studies is that the source, pathway, and residence time of water in the catchment exert a strong control on water chemistry [20]. Testing quantitative hypotheses will require careful integration of the results of hydrometric, isotopic and geochemical methods:

1. Seeps and saturated areas dampen (‘buffer’) rain inputs and increase residence time before a threshold storage is exceeded.
2. Connection of saturated areas to the stream is a major control on runoff generation.
3. Upslope hillslope contribution will be minimal in all but the largest storms.
4. Groundwater flow is chemically distinct and important for chemical transport at low-flows.

An integrated sampling scheme has been developed to perform an end-member mixing analysis (EMMA) using geochemical and isotope signals. In addition, hydrometric methods and introduced tracer techniques (e.g. nontoxic dye) will increase the ability to reject the proposed hypotheses. Several end-members will be sampled, including rain, stream, surface, shallow ground, deep ground, soil pipes and spring outlets (Fig. 2). Water quality samples will be collected weekly and during three storm events at high temporal resolution (about 30 minutes). The anion and cation analysis will be performed using an Ion Chromatograph (IC) and Inductively Coupled Plasma (ICP), respectively, in the Soil and Water Laboratory in Riley-Robb.
Hall. Preliminary results indicate that EC, Ca, Na, Dissolved Organic Carbon (DOC), P, and N may differentiate end-members. Simultaneous collection of isotope signals can provide additional information on the age of water [20]. The isotope analysis of O\textsuperscript{18} and H\textsuperscript{2} will be completed in the Water Resources Department at the University of Arizona.

Hydrometric measurements will be used to further constrain the EMMA, including water table height, soil moisture, soil matrix pressure, and surface flow (Fig. 2). Detailed explanation of field equipment is beyond the scope of this proposal, however the equipment was selected based on available resources and automation. The preliminary work [21,22] reduced the sampling locations necessary to deduce hydrologic connections. In addition, introduced tracers, including Cl\textsuperscript{−} and nontoxic dye, will be used to estimate instantaneous travel time between landscape areas. Dye tracers also indicate what flowpaths are active on a trench face. All of these measurements will be incorporated to test the hypotheses presented and the mixing assumptions inherent in EMMA.

3. Verify if a network-based landscape model is capable of predicting the importance of lateral flowpath networks on a hillslope or watershed.

The conceptual model will be adjusted based on the results of the field measurements and hypothesis rejection. Subsequently, the conceptual model will be validated for two adjacent USGS watersheds (1 km\textsuperscript{2} and 30 km\textsuperscript{2}), where geology and landuse are similar. Three hypotheses will be tested to assess the applicability of the conceptual model to future studies:

1. Soil and geologic information can be used to better predict flowpaths and source areas.
2. Distributed hydrologic models need to account for ‘fast’ lateral subsurface flow.
3. Network models might be a simple alternative to distributed models.

### Timeline for Completion

<table>
<thead>
<tr>
<th>Winter 2007</th>
<th>Gather bi-weekly collection of snow samples</th>
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<tbody>
<tr>
<td></td>
<td>Collection of samples during snow runoff events</td>
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<td>Continue geophysical survey using GPR and EMI</td>
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<tr>
<td>Spring 2007</td>
<td>Perform 1 high-resolution storm runoff event sampling</td>
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<td>Begin weekly sampling from pizeometric equipment</td>
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<td>Begin rain depth and quality measurement</td>
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<td>Install subsurface trench face</td>
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<td></td>
<td>Gather weekly water quality samples</td>
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<tr>
<td>Summer 2007</td>
<td>Perform 1 high-resolution storm runoff event sampling</td>
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<tr>
<td></td>
<td>Gather weekly water quality samples</td>
</tr>
<tr>
<td></td>
<td>Continue geophysical methods using GPR</td>
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<tr>
<td>Fall 2007</td>
<td>Gather weekly water quality samples and finish analysis</td>
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<td>Remove sampling devices and equipment before freeze</td>
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<td></td>
<td>Send samples for isotopic analysis</td>
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<td>Finish preliminary analysis for presentation at AGU</td>
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<td>Winter 2008</td>
<td>Finish model development</td>
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<td></td>
<td>Validate for two nearby watersheds</td>
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<td>Spring 2008</td>
<td>Finish manuscripts and dissertation</td>
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## Budget

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<tr>
<td>Field equipment</td>
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<td>Water quality samples and analysis</td>
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<td>Part-time field work staff</td>
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<td><strong>Total Costs</strong></td>
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<table>
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<td>National Science Foundation Graduate Fellowship</td>
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<td>Departmental Funding</td>
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| **Amount Requested**                                      |        |

## Literature Cited

ADRIAN A. HARPOLD
30 Riley-Robb Hall, Cornell University
Ithaca, New York, 14850
(607) 342-3353  aah38@cornell.edu
soilandwater.bee.cornell.edu/People/adrian.htm

EDUCATION

<table>
<thead>
<tr>
<th>Year</th>
<th>Institution</th>
<th>Location</th>
<th>Major</th>
<th>Thesis Title</th>
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<tbody>
<tr>
<td>2005-Present</td>
<td>Cornell University</td>
<td>Ithaca, NY</td>
<td>Ph.D. Candidate in Biological and Environmental Engineering</td>
<td>Characterizing water transport pathways within small upland catchments in the Catskill Mountains, New York, advisor Tammo Steenhuis</td>
</tr>
<tr>
<td>2003-2005</td>
<td>Virginia Polytechnic Institute (Virginia Tech)</td>
<td>Blacksburg, VA</td>
<td>M.S. in Biological Systems Engineering</td>
<td>Stream discharge measurement using a large-scale particle velocimetry (LSPIV) prototype, advisor Saied Mostaghimi</td>
</tr>
<tr>
<td>1999-2003</td>
<td>Virginia Polytechnic Institute (Virginia Tech)</td>
<td>Blacksburg, VA</td>
<td>B.S. in Biological Systems Engineering</td>
<td>Summa cum laude</td>
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</table>

RESEARCH AND TEACHING EXPERIENCE

<table>
<thead>
<tr>
<th>Year</th>
<th>Institution</th>
<th>Location</th>
<th>Position</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005-Present</td>
<td>Biological and Environmental Eng. Dept., Cornell University</td>
<td>Ithaca, NY</td>
<td>Graduate Research Fellow</td>
<td>Funded by the National Science Foundation</td>
</tr>
<tr>
<td>2006-Present</td>
<td>Cornell Outdoor Education</td>
<td>Ithaca, NY</td>
<td>Outdoor Instructor</td>
<td>Rock climbing instructor on multi-day trips</td>
</tr>
<tr>
<td>2003-2005</td>
<td>Biological Systems Eng. Dept., Virginia Tech</td>
<td>Blacksburg, VA</td>
<td>Graduate Teaching Assistant</td>
<td>Departmental assistant ship for teaching an undergraduate thermodynamics course</td>
</tr>
<tr>
<td>Summer 2003</td>
<td>Forestry Dept., Virginia Tech</td>
<td>Blacksburg, VA</td>
<td>Hydrologic Field Technician</td>
<td>Research funded by the Bureau of Land Management (BLM) collecting water quality samples</td>
</tr>
<tr>
<td>Summer 2001</td>
<td>Biological and Env. Eng. Dept., Virginia Tech</td>
<td>Blacksburg, VA</td>
<td>Undergraduate Research Fellow</td>
<td>Funded by the National Science Foundation Research for Undergraduates (REU) program</td>
</tr>
</tbody>
</table>

AWARDS AND LEADERSHIP POSITIONS

- National Science Foundation Graduate Research Fellowship, 2005 – present
- Vice-President Department Graduate Student Association, 2006 - present
- Virginia Conservationist of the Year, Soil and Water Conservation Society (SWCS), 2005
- President Student Chapter of SWCS, 2003-2004
- 2nd Place Student Poster, 2004 SWCS Meeting
- Virginia Tech Biological Systems Engineering Sophomore of the Year, 2002

PROFESSIONAL AND HONOR SOCIETIES

American Geophysical Union (AGU), American Society of Agricultural and Biological Engineers (ASABE), Soil and Water Conservation Society (SWCS), Engineer-in-Training (EIT), Alpha Epsilon Honor Society, Phi Kappa Phi Honor Society, Golden Key Honor Society, National Society of Collegiate Scholars
PUBLICATIONS


CONFERENCE PROCEEDINGS


PROFESSIONAL SERVICES

Journal manuscript reviewer for Water Resources Research, Hydrological Processes, and Transactions of ASABE

GRANTS AND SCHOLARSHIPS


INTERNATIONAL EXPERIENCE

Served as a consultant to US AID for a project related to improving water management in Mali, July-August 2004

VOLUNTEER WORK

Big Brother, Big Sisters (BBBS) of Tompkins Co. NY, volunteer 2005 – present, BBBS of Southwest Virginia, volunteer 2003-2004, Apple Ridge Farm, Virginia, volunteer 2003-2004