Measurements of infiltration by accounting for the role of management practices

Thanos N. Papanicolaou and Lee Burras
IHR-Hydroscience and Engineering, The University of Iowa
And
Dept. of Agronomy, Iowa State University

Madison
June 6, 2007
EWRI
Support

- Dr. David Hammer
  National Leader, Soil Survey Investigations
  NRCS-National Soil Survey Center

  Dr. Jonathan Hempel
  Natural Resources Conservation Service
  NRCS National Geospatial Development

  Mike Sucik
  NRCS Iowa State Soil Scientist
Key Dynamic function K-sat

- Hydraulic conductivity can be defined as a measure of the ability of soil to transmit water. Under saturated conditions this parameter is usually denoted as K-sat or (Ks) and is assumed to be constant for a given space and time within a soil (Amoozegar and Wilson, 1999).

- The knowledge of K-sat for a specific soil is too important for instance in drainage design, the saturated hydraulic conductivity is used to compute the velocity in which water can move toward and into the drainlines below the water table (Amoozegar and Wilson, 1999).

- Laboratory determined values rarely agree with field measurements, the differences often being on the order of 100 fold or more. Field methods generally are more reliable than laboratory methods due to the closer approximation to natural conditions (Scott, 2000).
Key-challenges for K-sat

• K-sat measurements are typically point measurements. How can we do the integration of the point measurements over an area??

• Frequency of measurements?
Scales

After Papanicolaou (2006), Geomorphology
Key-questions towards the spatial/temporal integration

This collaborative investigation between UI and the Iowa State University (ISU) will examine the following research questions (Qs):

Q-1) Is the increase (decrease) in the hillslope gradient going to have an adverse (inverse) effect on the conductivity magnitude?

There are contradictory findings concerning the effects of slope gradient and landform geometry on infiltration rate. For example, Zaslansky and Sinai (1981) found that the infiltration rate decreased as the slope increased while Poesen (1986) reported an increase in infiltration as the slope increased.
Key-questions towards the spatial/temporal integration

Q-2) How slope, soil type and management practices collectively affect infiltration?

The effects of slope on infiltration rate for different soil types and land-use have not been thoroughly examined (Kidwell et al. 1997). More work is required to evaluate the cumulative effects of management practices and soil type on infiltration for different slopes. Furthermore, the role of soil microstructure on infiltration rate needs to be examined carefully as most of the studies thus far have focused only on the macroscopic properties of soil.
Shano very fine sandy loam.

Column 1: conventional tillage

Column 2: no-till

Column 3: CRP
Key-questions towards the spatial/temporal integration es and Tasks

Q-3) Rainfall intensity and raindrop size relate to the rate of infiltration by affecting the porous microstructure of the soil. Do changes in rainfall intensity and therefore raindrop terminal velocity affect significantly the rate of infiltration? How significant these changes need to be in order to cause delay or acceleration of the infiltration process?

Conductivity relations that account for the changes in rainfall intensity and the kinetic energy of the raindrops need to be developed.
Key-questions towards the spatial/temporal integration

Q-4) There is still a need to define spatial variability of infiltration and runoff along a hillslope using new research methodologies and techniques.
Hollistic approach

• Use geospatial tools and watershed models as a first step to identify the hotspots and address spatial/temporal variability.

• Perform continuous measurements using sensor technology at the hotspots to refine our existing understanding.

• Integration of point measurements.
Study Site

• South Amana catchment of Clear Creek watershed, IA
• The area of the catchment is approximately 6400 acres
• Primarily agricultural, with 60% of land cover being row crops and about 20% in pasture/hay
The Clear Creek Testbed, IA

Clear Creek Watershed - Gross Soil Loss (ton/acre/year)

Targeted Area

Iowa

0 - 1.3
1.301 - 3.3
3.301 - 5.3
5.301 - 7
7.001 - 13.7
13.71 - 30.8
30.81 - 55.2
55.21 - 150.1

Feet
Clear Creek Digital Watershed

Data sources: third-party geo-physical measurements

DEM: National Elevation Dataset
  Topography (10m and 30m resolution)

Hydrography: National Hydrography Dataset
  River networks for 8-digit HUC watersheds

Rainfall data: Iowa Environmental Mesonet & Nexrad NOAA
  Rainfall estimates

Stream data: National Water Information System
  Discharges and stream gage locations
Clear Creek Digital Watershed

**DW Application:** Rainfall from NEXRAD

**Data source 1:** Iowa Mesonet (daily)
**Data source 2:** NOAA (5 min)
Clear Creek Digital Watershed

Data sources: third-party geo-bio-chemical measurements

Soil type: STATSGO
- USDA-NRCS Soil Survey Division
- IDNR - Iowa Geological Survey (30-m grid)

Land use/cover:
- National Land Cover Dataset
- USDA-NRCS office, Williamsburg (IA)

Water Quality:
- IowaStoret - DNR
- IowaWater
Table: Crop Rotations in South Amana Catchment.

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Code</th>
<th>Areal Extent in Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall Till Corn -&gt; No-Till Bean</td>
<td>FTC-NTB</td>
<td>31.1 %</td>
</tr>
<tr>
<td>No-Till Bean -&gt; Spring Till Corn</td>
<td>NTB-STC</td>
<td>25.1 %</td>
</tr>
<tr>
<td>No-Till Corn -&gt; Fall Till Bean</td>
<td>NTC-FTB</td>
<td>22.8 %</td>
</tr>
<tr>
<td>Spring Till Corn -&gt; No-Till Bean</td>
<td>STC-NTB</td>
<td>4.5 %</td>
</tr>
<tr>
<td>Fall Till Bean -&gt; Spring Till Corn</td>
<td>FTB-STC</td>
<td>4.1 %</td>
</tr>
</tbody>
</table>
Clear Creek Digital Watershed

**DW Application: Water Quality**

**Iowa Storet:** 8 long-term stations and 24 newer stations (snap-shots)

**Measured Parameters**

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Creek</td>
<td>952024</td>
</tr>
<tr>
<td>Clear Creek (down)</td>
<td>952009</td>
</tr>
<tr>
<td>Clear Creek (up)</td>
<td>952008</td>
</tr>
<tr>
<td>Clear Creek at Tiffin</td>
<td>952019</td>
</tr>
<tr>
<td>Clear Creek South Trib</td>
<td>948057</td>
</tr>
<tr>
<td>Clear Creek/Jasper Street (Tiffin)</td>
<td>992002</td>
</tr>
</tbody>
</table>

* Not always available
Clear Creek Digital Watershed

USGS Stream discharge network

Near Oxford (0545220)
Near Coralville (0545200)
Oxford (0545200)
Coralville (0545280)

Clear Creek

Instantaneous and daily discharges are acquired real-time from NWIS
Welcome to Hydro-NEXRAD, a prototype system that allows hydrologists to obtain user-specified rainfall data for their research. These data are based on observations collected by the national network of WSR-88D radars, known as NEXRAD. Currently, raingauge observations are not available through this website. Hydro-NEXRAD is developed by researchers from The University of Iowa, Princeton University, UCAR’s Unidata Program Center, and the National Climatic Data Center, with funding from The National Science Foundation through award ATM 0427422. (For more information and contacts, check here.)

e-mail: anton-kruger@uiowa.edu
password: ******

Hydro-NEXRAD. Copyright © 2006 The University of Iowa
Last Updated on 22-06-2006
Preliminary coupling scheme

- Iterated process
- 30 arc-sec DEM
- 30m DEM
- ArcGIS
- 30 arc-sec DEM
- Soil profile
- Adjusted erodibility, friction factors, & random roughness
- WEPP-HE Code
- Daily climate forcing
- Hourly precipitation
- Soil & vegetation
- Precipitation & runoff output
- VIC
- Incremented for sampled slopes
- Original input data
- Intermediate data
- Data for WEPP-HE
- Data processing
- Iterated process
<table>
<thead>
<tr>
<th>Digital Domain</th>
<th>Natural pattern</th>
<th>Measuring</th>
<th>Representation</th>
<th>Measurement Scale</th>
<th>Pre-processing</th>
<th>Discretization</th>
<th>Modeling</th>
<th>Prediction Scale</th>
<th>Post-processing</th>
<th>Assessment Scale</th>
<th>Evaluating</th>
<th>Measurement Scale</th>
<th>Measuring</th>
<th>Process Scale</th>
</tr>
</thead>
</table>
Hotspots
NTB-STC and FTB-STC Crop Rotations Sampling Locations

Ridge
Soil moist & temp station

Floodplain
Soil moist & temp station

Soil Types
- ADAIR
- COLO OVERWASH
- COLO-ELY Sicl
- DOWNS
- ELY
- JUDSON
- NODA WAY CANTRIL
- OTLEY
- SHELBY
- TAMA

Clear Creek
Farm Borders

Scale: 0 625 1,250 2,500 Feet
Clear Creek sensors

In-situ data collected with conventional and custom-built instruments & laboratory analysis (selection):

- Wireless sensor network for moisture and water quality data (Nitrates)
- Non-intrusive stream flow monitoring techniques (ADCP and LSPIV)
- Sources of sediment & pathways (stable isotope tracers & radionucleids)
- Rainfall (disdrometers, rain gages)
- Bed load and suspended sediment (ISCO, sedimeters)
- Permeability
- Hydraulic conductivity (via in-situ instrumentation and lab-based CT)
- Enrichment ratio
- Phosphorus (particulate and dissolved)
Ongoing Field Work

Double-ring infiltrometer
Ongoing Field Work

Tensiometer & soil moisture probes
## Watershed Soil Characterization

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Corn</th>
<th>Soybean</th>
<th>CRP</th>
<th>Floodplain</th>
<th>Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>%</td>
<td>65.4</td>
<td>59.2</td>
<td>63.3</td>
<td>70.0</td>
<td>66.4</td>
</tr>
<tr>
<td>Clay</td>
<td>%</td>
<td>29.5</td>
<td>34.7</td>
<td>30.3</td>
<td>26.4</td>
<td>26.7</td>
</tr>
<tr>
<td>Sand</td>
<td>%</td>
<td>5.10</td>
<td>6.10</td>
<td>6.40</td>
<td>3.60</td>
<td>6.90</td>
</tr>
<tr>
<td>Water Content</td>
<td>%</td>
<td>21.5</td>
<td>20.0</td>
<td>25.36</td>
<td>16.1</td>
<td>18.35</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>---</td>
<td>2.56</td>
<td>2.73</td>
<td>2.46</td>
<td>2.54</td>
<td>2.50</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>%</td>
<td>26.70</td>
<td>27.00</td>
<td>24.20</td>
<td>32.35</td>
<td>24.36</td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>%</td>
<td>36.34</td>
<td>38.07</td>
<td>38.59</td>
<td>47.00</td>
<td>37.68</td>
</tr>
</tbody>
</table>
# Watershed Soil Characterization

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Corn</th>
<th>Soybean</th>
<th>CRP</th>
<th>Floodplain</th>
<th>Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>---</td>
<td>7.70</td>
<td>7.75</td>
<td>6.05</td>
<td>6.45</td>
<td>6.95</td>
</tr>
<tr>
<td>Buffer pH</td>
<td>---</td>
<td>7.30</td>
<td>7.35</td>
<td>6.70</td>
<td>7.00</td>
<td>7.13</td>
</tr>
<tr>
<td>Exch. K</td>
<td>cmol/kg</td>
<td>0.749</td>
<td>0.639</td>
<td>0.431</td>
<td>1.154</td>
<td>0.248</td>
</tr>
<tr>
<td>Exch. Ca</td>
<td>cmol/kg</td>
<td>21.21</td>
<td>31.13</td>
<td>10.82</td>
<td>12.52</td>
<td>12.00</td>
</tr>
<tr>
<td>Exch. Mg</td>
<td>cmol/kg</td>
<td>3.63</td>
<td>3.26</td>
<td>2.18</td>
<td>3.36</td>
<td>2.98</td>
</tr>
<tr>
<td>Exch. Na</td>
<td>cmol/kg</td>
<td>0.07</td>
<td>0.10</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Zn</td>
<td>g/kg</td>
<td>0.0021</td>
<td>0.004</td>
<td>0.0011</td>
<td>0.0052</td>
<td>0.0016</td>
</tr>
<tr>
<td>Fe</td>
<td>g/kg</td>
<td>0.070</td>
<td>0.098</td>
<td>0.116</td>
<td>0.140</td>
<td>0.088</td>
</tr>
<tr>
<td>Mn</td>
<td>g/kg</td>
<td>0.013</td>
<td>0.010</td>
<td>0.018</td>
<td>0.021</td>
<td>0.017</td>
</tr>
</tbody>
</table>
## Watershed Soil Characterization

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Corn</th>
<th>Soybean</th>
<th>CRP</th>
<th>Floodplain</th>
<th>Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic Matter</td>
<td>g/kg</td>
<td>43.55</td>
<td>54.85</td>
<td>53.85</td>
<td>74.70</td>
<td>30.52</td>
</tr>
<tr>
<td>Total C</td>
<td>g/kg</td>
<td>23.85</td>
<td>30.05</td>
<td>29.59</td>
<td>40.96</td>
<td>16.71</td>
</tr>
<tr>
<td>Total N</td>
<td>g/kg</td>
<td>2.061</td>
<td>1.964</td>
<td>2.672</td>
<td>3.496</td>
<td>1.638</td>
</tr>
<tr>
<td>NO$_3$-N</td>
<td>g/kg</td>
<td>0.0036</td>
<td>0.0022</td>
<td>0.0026</td>
<td>0.0027</td>
<td>0.0038</td>
</tr>
<tr>
<td>NH$_4$-N</td>
<td>g/kg</td>
<td>0.0013</td>
<td>0.0140</td>
<td>0.0040</td>
<td>0.0050</td>
<td>0.0080</td>
</tr>
<tr>
<td>CEC</td>
<td>cmol/kg</td>
<td>25.660</td>
<td>35.120</td>
<td>17.089</td>
<td>17.069</td>
<td>15.266</td>
</tr>
<tr>
<td>SAR</td>
<td>$\sqrt{\text{cmol/kg}}$</td>
<td>0.0191</td>
<td>0.0236</td>
<td>0.0205</td>
<td>0.0123</td>
<td>0.0135</td>
</tr>
<tr>
<td><strong>Biological</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photosynthetic Pathway</td>
<td></td>
<td>---</td>
<td>C4</td>
<td>C3</td>
<td>C3</td>
<td>---</td>
</tr>
</tbody>
</table>

---
DSD Generated by the Rainfall Simulator

M-P = Marshall Palmer DSD
Fig. 3. Field measurements.
Hollistic approach

• Use geospatial tools and watershed models as a first step to identify the hotspots and address spatial/temporal variability.

• Perform continuous measurements using sensor technology at the hotspots to refine our existing understanding.

• Integration of point measurements using .
Ensembled averaging at the hillslope scale

\[ \frac{\partial \langle h_r \rangle \langle c_{rl} \rangle}{\partial t} + \frac{\partial}{\partial x} \left[ K_r \left( \langle r \rangle \right) \frac{\langle w_r \rangle^{1/2} \langle h_r \rangle^{3/2} \langle c_{rl} \rangle}{\left( \langle w_r \rangle + 2 \langle h_r \rangle \right)^{1/2}} \right] \]

\[ + \frac{1}{2} \sum_i \sum_j \text{cov}(r_i, r_j) \times \frac{\partial^2}{\partial r_i \partial r_j} \left[ K_r \left( r \right) \frac{\langle w_r \rangle^{1/2} \langle h_r \rangle^{3/2} \langle c_{rl} \rangle}{\left( \langle w_r \rangle + 2 \langle h_r \rangle \right)^{1/2}} \right]_{r=\langle r \rangle} \]

\[ = \langle D_{rl} \rangle + 2 \rho_r \left( \frac{\pi}{2} \right)^{3/2} K_y \left( \langle r \rangle \right) \langle h_o \rangle^{3/2} \langle c_{rl} \rangle + 2 \rho_r \left( \frac{\pi}{2} \right)^{3/2} \]

\[ \times \frac{1}{2} \sum_i \sum_j \text{cov}(r_i, r_j) \frac{\partial^2}{\partial r_i \partial r_j} \left[ K_y \left( r \right) \langle h_o \rangle^{3/2} \langle c_{rl} \rangle \right]_{r=\langle r \rangle} \]
A baseline effective conductivity, $K_b$, (mm/hr) is measured as a function of the soil properties such as cation exchange capacity (CEC) and clay content (Onstad et al. 1984):

For clay content $\leq 40\%$

$$K_b = -0.265 + 0.0086 \left( 100 \text{ sand } \right)^{1.8} + 11.46 \text{ CEC}^{-0.75}$$  \hspace{1cm} (1a)

For clay content $> 40\%$

$$K_b = 0.0066 e^{(2.44/\text{clay})}$$  \hspace{1cm} (1b)

where $K_b$ is the baseline effective hydraulic conductivity, sand and clay are the fractions (%) of sand and clay, and CEC (meq/100g) is the cation exchange capacity of the soil.
Problem Statement and Background

If $K_{bare}$ (mm/hr) denotes the effective conductivity for any given event, then $K_{bare}$ is given by the following relation:

$$K_{bare} = K_b \left[ CF + (1 - CF) e^{-C.Ea(1 - RR_t / 0.04)} \right]$$

where $K_b$ is the baseline hydraulic conductivity (mm/hr), CF is the crust factor which ranges from 0.2 to 1.0, C is the soil stability factor ($m^2/J$), $Ea$ is the cumulative kinetic energy of the rainfall since the last tillage operation ($J/m^2$), and $RR_t$ is the random roughness of soil surface (m).
Problem Statement and Background

Because the canopy cover and plant root density affect the path of flowing water in a hillslope, the effective conductivity of the bare area, $K_{\text{bare}}$, is corrected for the percentage of the plot that is covered by vegetation (Kidwell et al. 1997):

$$K_e = K_{\text{bare}} (1 - scovef) + (c \text{ rain scovef})$$

(3)

where $K_e$ denotes the effective conductivity of the covered area (mm/hr), $c$ is a regression coefficient and rain is the storm rainfall amount (mm). This equation assumes that $K_e$ for any given area can be conceptualized as the area-weighted average of $K_{\text{bare}}$ and $K_e$ in the covered area. For the fallow case, above eqn. reduces to $K_e = K_{\text{bare}}$
CN & $K_{ef}$ Relationships

<table>
<thead>
<tr>
<th>Hydrologic Soil Group</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$K_{ef} = 14.18$</td>
</tr>
<tr>
<td>B</td>
<td>$K_{ef} = 1.17 + 0.072 \times %sand$</td>
</tr>
<tr>
<td>C</td>
<td>$K_{ef} = 0.50 + 0.032 \times %sand$</td>
</tr>
<tr>
<td>D</td>
<td>$K_{ef} = 0.34$</td>
</tr>
</tbody>
</table>

Table 1. Relationships for calculating curve number optimized Green and Ampt Effective Conductivity for fallow conditions, $K_{ef}$ (=1/2 $K_{sat}$)

$K_e$ for the cropped conditions is related to the curve number by the equation

$$K_e = \frac{56.82 K_{ef}^{0.286}}{1 + 0.051 e^{0.062 CN} - 2}$$

where $K_{ef}$ is the effective conductivity for fallow conditions and CN is curve number.
Outlook for the Holistic Approach

- **Advanced specialized cyber-tools and methods** (sensors, sensing networks, numerical and data models) are increasingly available, and sufficiently developed to aid **quantifiable understanding of the watershed processes** and their interactions with the bio-geo-chemical and socio-economic activities dependent on them.

- **Parallel advances** in high-performance computing, communication technologies, GIS along with innovative statistical, data-driven, and knowledge discovery models, enable **characterization of physical-biochemical habitat with increased spatial resolution over large-scale areas**.

- Collectively, these advances facilitate **adoption of a “information-centric” investigative and management approaches** enabling to understand and predict watershed ecosystem changes, protect the environment, and prevent natural and human disasters through knowledge-based adaptive management.

- The time is ripe for **WM and WS communities to coordinate and synergistically integrate their efforts** in a long-term, mutual-gain collaboration.
Field Site and In-situ Instrumentation

Figure 6 (a) An Amoozemeter (side view).

Figure 6 (b) The Amoozemeter method for determining $K_{sat}$.
**Water Cycle** (including internal & external interactions)

**Critical issues**

- Watershed water balance

- Water pathways, residence times, vertical and horizontal fluxes over a variety of spatial-temporal scales

- Water cycle interaction and feedback with chemical reactions, microbial activity, food chains, ecological evolution, and human land and water choices