Laramie Range
Upper Crow Creek Watershed nested design
Approximate location of Thunderstorm Large lag time

10 hours

Hydrograph of the Middle Crow Creek indicating a slow, subsurface response
Subsurface flow plays a critical role in the hydrology of the Laramie Range
Partitioning Surface and Subsurface Flow: Rainfall Simulation and Two-Dimensional Surface Electrical Resistivity Imaging

Austin M. Carey
Ginger B. Paige, Bradley J. Carr,
Scott N. Miller, W. Steven Holbrook
Hypothesis

Partitioning of surface and subsurface flow can be quantified through field measurements that couple a variable intensity rainfall simulator with electrical resistivity imaging.

Ecological sites in a given condition should have a specific hydrologic response which can be used to inform hydrologic models.
A Nested Watershed Design (94 km²)
Study Site - Upper Crow Creek Watershed (UCCW)

A Nested Watershed Design (94 km$^2$)
Study Site - Ecological Sites

Shallow Loamy (SL)
- > 40% of the ground cover is litter
- Blue gramma, Idaho fescue, fringed sagewort
- Moderately deep (0.75 - 1 m) soil profile

Loamy Upland (LU)
- > 90% canopy cover
- ~42% of the canopy cover is robust big sagebrush
- Moderately deep (0.75 – 1m), organic, highly porous soil profile

Shallow Upland (SU)
- Very shallow (< 0.5 m) soil profile
- large granite boulders exposed or buried at the near surface
- Bluebunch wheatgrass, Idaho fescue, fringed sagewort
- > 30% of the ground cover is lesser spikemoss

Coarse Upland (CU)
- Shallow soil profile (~ 0.5 m) that transitions into saprolite
- Sandberg bluegrass and bluebunch wheatgrass
- > 30% of the ground cover is lesser spikemoss
Methods - Experimental Setup

Walnut Gulch Rainfall Simulator (WGRS; Paige et al., 2003)

- Variable intensity
- Rainfall applied to a 2x6 m plot
- Runoff measured using pre-calibrated flume

Electrical Resistivity Tomography (ERT)

- AGI SuperSting R8/IP
- Injection of current into the subsurface
- Create 2D tomography of the electrical resistivity distribution of a bulk soil volume
Methods - Rainfall Simulation

- **Dry run:** 45 min of constant rain
- **Wet run:** step through five intensities: 49, 77, 112, 157 and 180 mm hr$^{-1}$
- **Measure steady state infiltration rate**
## Methods - Time Lapse ERT

### Event Hyetograph

<table>
<thead>
<tr>
<th>Intensity [mm hr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>75</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>125</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>175</td>
</tr>
<tr>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>120</td>
</tr>
</tbody>
</table>

- **Applied Rainfall**
- **Time Step**

### Resistivity -> complicated function of...
- Porosity
- Temperature
- Water content
- Pore fluid chemistry
- Resistivity of minerals
- Etc

### Methods - Time Lapse ERT

- **Rainfall Simulator Location**

  \[ T = 0 \text{ min} \] \( P = 0 \text{ mm} \) - \( Q = 0 \text{ mm} \) - \( F = 0 \text{ mm} \)

- **Change in Resistivity (%)**

  - **Iteration = 1**
  - **RMS = 0.00%**
  - **L2 = 0.00**
  - **Electrode Spacing = 0.50 m**
Methods - Wetting Front Evidence

- Resistivity - $\Theta$ relationships
- Bulk porosity
- Infiltration area from rainfall simulator
- Area of the -10% change in resistivity iso-contour
Oldenburg and Li (1999)

**ERT**

**GPR**

**Seismic Refraction**

Saprolite - ~500 m s⁻¹

Fractured Bedrock- 1200 m s⁻¹
Results - Surface Runoff

- Surface Runoff

**Graphs:**

- **Plot 1**
- **Plot 2**
- **Plot 3**
- **Plot 4**

**Intensities (mm/hr):**

- **CU**
- **SL**
- **SU**
- **LU**

**Time Since Start of Wet Run (min):**

- **CU-2**
## Results - Surface Runoff

<table>
<thead>
<tr>
<th>Ecological Site</th>
<th>Plot</th>
<th>$Q_{\text{peak}}$ (mm hr$^{-1}$)</th>
<th>C</th>
<th>$Q_{\text{peak}}$ Average (SE) CV (%)</th>
<th>C Average (SE) CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU</td>
<td>1</td>
<td>76.4</td>
<td>0.38</td>
<td>60.9 (9.8) 32.0</td>
<td>0.27 (0.05) 36.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>32.4</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>66.8</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>68.2</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL</td>
<td>1</td>
<td>31.5</td>
<td>0.10</td>
<td>29.9 (4.4) 29.5</td>
<td>0.09 (0.03) 56.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>39.5</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>30.6</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>18.1</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU</td>
<td>1</td>
<td>98.5</td>
<td>0.44</td>
<td>87.9 (3.6) 8.3</td>
<td>0.40 (0.01) 6.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>82.7</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>83.8</td>
<td>0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>86.5</td>
<td>0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CU-2</td>
<td>1</td>
<td>82.5</td>
<td>0.36</td>
<td>50.0 (15.8) 63.2</td>
<td>0.21 (0.07) 67.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>54.3</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.7</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>56.4</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Results - Multiple Linear Regressions

All models significant at the $p = 0.05$ level

<table>
<thead>
<tr>
<th>Variable</th>
<th>SS1 (mm hr$^{-1}$)</th>
<th>SS2 (mm hr$^{-1}$)</th>
<th>SS3 (mm hr$^{-1}$)</th>
<th>SS4 (mm hr$^{-1}$)</th>
<th>SS5 (mm hr$^{-1}$)</th>
<th>$Q_{\text{peak}}$ (mm hr$^{-1}$)</th>
<th>C (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>50.25***</td>
<td>78.73***</td>
<td>171.52***</td>
<td>168.01***</td>
<td>191.39***</td>
<td>-10.52</td>
<td>-0.57*</td>
</tr>
<tr>
<td>Variable 1 (beta weight)</td>
<td>0.34 Plant Base** (0.54)</td>
<td>-0.52 Moss*** (-0.79)</td>
<td>-1.53 Moss*** (-1.39)</td>
<td>-1.40 Moss** (-0.89)</td>
<td>-1.61 Moss*** (-0.91)</td>
<td>1.10 Moss** (0.63)</td>
<td>0.01 Moss*** (1.28)</td>
</tr>
<tr>
<td>Variable 2 (beta weight)</td>
<td>-0.41 Bare Soil** (-0.49)</td>
<td>0.87 Plant Base** (0.39)</td>
<td>-2.17 Bare Soil*** (-0.43)</td>
<td>-1.71 Bare Soil* (-0.24)</td>
<td>-1.98 Bare Soil* (-0.25)</td>
<td>3.48 Bare Soil** (0.47)</td>
<td>0.02 Bare Soil*** (0.60)</td>
</tr>
<tr>
<td>Variable 3 (beta weight)</td>
<td>-0.07 Moss* (-0.39)</td>
<td>-1.12 Bare Soil** (-0.37)</td>
<td>-0.54 Litter* (-0.55)</td>
<td>-1.52 Rock† (-0.29)</td>
<td>0.01 Litter* (0.58)</td>
<td>-1.52 Rock† (-0.29)</td>
<td>0.01 Litter* (0.58)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.62</td>
<td>0.84</td>
<td>0.85</td>
<td>0.78</td>
<td>0.82</td>
<td>0.84</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Significance Codes: *** $p \leq 0.0001$  ** $p \leq 0.001$  * $p \leq 0.01$  † $p \leq 0.05$

---

Results - Subsurface
Combined Results - CU Site

- **C** = 0.38
  - Moss Cover = 38%

- **C** = 0.14
  - Moss Cover = 12%

- **C** = 0.29
  - Moss Cover = 30%

- **C** = 0.30
  - Moss Cover = 46%

- **Moss Cover = 30%**
- **RMS = 2.23%**
- **DOI = 0.4**
- **Velocity [m s⁻¹]**
  - 500 m s⁻¹
  - 1200 m s⁻¹
Combined Results - CU Site

<table>
<thead>
<tr>
<th>Group</th>
<th>Plots</th>
<th>Slope (mm min$^{-1/2}$)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>LU Plot 2$^\dagger$</td>
<td>0.468</td>
<td>0.92</td>
</tr>
<tr>
<td>B</td>
<td>CU-2 Plots 1,3,4</td>
<td>0.346</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>CU Plots 2,4$^\dagger$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>SL Plots 1,2,4$^\dagger$, LU Plot 1</td>
<td>0.283</td>
<td>0.94</td>
</tr>
<tr>
<td>D</td>
<td>SL Plot 3</td>
<td>0.233</td>
<td>0.98</td>
</tr>
<tr>
<td>D</td>
<td>CU-2 Plot 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>SU Plots 2,3$^\dagger$, LU Plot 3</td>
<td>0.200</td>
<td>0.96</td>
</tr>
<tr>
<td>F</td>
<td>LU Plot 4$^\dagger$</td>
<td>0.156</td>
<td>0.99</td>
</tr>
</tbody>
</table>

- $\Delta t = 25$ min, $F = 22$ mm
- $\Delta t = 56$ min, $F = 81$ mm
- $\Delta t = 230$ min, $F = 92$ mm

RMS $= 2.23\%$, DOI $= 0.4$
Summary of ES Hydrologic Response

**LU**
- No runoff
- Very high infiltration capacity is a result of dense sagebrush cover
- Infiltration concentrated within a small area (high porosity)

**CU-2**
- Moderate runoff
- Variable runoff response can be explained by % moss and degrees of subsurface moisture
- Rapid wetting front movement (piston)

**SU**
- High runoff due to near surface impervious granite boulders and high moss cover
- Slow wetting front movement
- Very low variability across site

**SL**
- Low runoff
- Moderate wetting front movement
- Gopher holes promote infiltration

**CU**
- Moderate runoff
- Variable runoff response can be explained by % moss and degrees of subsurface moisture
- Rapid wetting front movement (piston)
Conclusions

1) Through hydrogeophysics field experiments we were able to quantify and characterize surface hydrologic response at the ES scale
   A. Simple parsimonious models of percent moss and bare soil coverage could explain a large degree of variability
   B. ANOVA analyses indicated statistically significant differences in the how these ES partition rainfall

2) Using time-lapse ERT we were able to track the movement of the wetting front through time
   A. ANCOVA results show that there are statistically significant differences in the rate of wetting front migration

3) Three geophysical methods provides a first order constraint on subsurface structure that explain differences in the hydrological processes
Acknowledgements

Ed Kempema, David Legg, Andy Parsekian, Mine Dogan, Elizabeth Traver, Thijs Kelleners

Andrew Annear, Tony Perlinski, Jeff Santos, Bea Gordon, Marc Peters, Michael Rider, Brady Flinchum, Jagath Vithanage, Niels Claes, Tegenu Engda, Alan Klatt, Shamila Kumara, Deni Voutchkova, Tom Moore, Landon Eastman, Suman Chitrakar, Ben Cook, Sam LaBarre, Clay Buchanan, Maneh Kotikian, Julia Workman, Will Rose, Rebecca Upjohn, Bujidmaa Borkhuu, Matt Provart and the Geophysics Team