Parameterization of the Rangeland Hydrology and Erosion Model (RHEM) using dynamic Landsat-based foliar cover estimates

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Research Problem

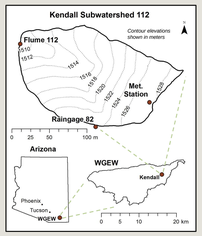
A key feature of the Rangeland Hydrology and Erosion Model (RHEM) is that routinely measured landscape characteristics (e.g., foliar and ground cover) are used to parameterize the model. This allows managers to easily conduct hillslope-scale runoff and erosion simulations using localized transect data. However, when conducting simulations at a larger spatiotemporal extent or within data-scarce regions these input data may be unobtainable.

Objectives

1. Develop a site-specific, long-term foliar cover time series based on field-calibrated Landsat imagery for a semiarid, grassland watershed.
2. Incorporate the remotely sensed foliar cover into RHEM and evaluate model performance for runoff simulation using gauged events from 1996-2014.

Study Site

This study was conducted on the Kendall subwatershed located within the Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona. The watershed has a drainage area of 2 ha and an average slope of 12.5%. The site is instrumented with a raingage (WGEW RG 82), meteorological station, soil moisture sensors and a weir (Flume 112) for measuring runoff and sediment. Two-thirds of the annual precipitation occurs in July-September during the North American Monsoon. Generally, runoff only occurs during this time period. The vegetation has historically been dominated by native grasses, with a transition to Lehmann lovegrass occurring after a period of drought induced mortality and forb-domination in 2006. A heavily vegetated swale at the base of the watershed serves as an area of increased infiltration and sediment deposition.



Modelling Environment

RHEM has been integrated with the USDA-ARS hydrologic and routing model, KINEROS2, and the Automated Geospatial Watershed Assessment (AGWA) tool to allow for watershed-scale analysis in a geospatial environment.

RHEM

http://apps.tucson.ars.ag.gov/rhem/

RHEM is an event-based, hillslope-scale runoff and erosion model developed specifically for rangeland use. Model inputs include: plant lifeform, foliar cover, ground cover (litter, basal, rock), soil texture and slope (Nearing et al., 2011).

KINEROS2

http://www.tucson.ars.ag.gov/kineros/

KINEROS2 is an event-based, watershed-scale runoff and erosion model. It allows for multiple RHEM/KINEROS2 hillslope simulations to be routed through connecting channels to the watershed outlet (Smith et al., 1995).

AGWA

http://www.tucson.ars.ag.gov/agwa/

AGWA is an ArcGIS-based application for model parameterization, data organization and visualization in which nationally available geospatial data can be used to populate model inputs. These data sets include: digital elevation maps (DEMs), soils maps and land cover classifications (Miller et al., 2007).

Watershed Geometry and Initial Model Parameterization Using AGWA

1. The watershed boundary was defined using a 1-m DEM.
2. The watershed was then broken into hillslope and channel elements.
3. Initial, static parameter values required by RHEM/KINEROS2 were assigned to each model element based on national geospatial data.
4. Select parameter values were refined using field-collected data from the site (e.g., rock cover, soil classification and channel width).

Watershed delineation | Watershed discretization | Unique parameter sets distributed to each element

Landsat-based Foliar Cover

Landsat Multispectral Satellite Imagery

- Spatial resolution of 30-m GMD is appropriate for watershed scale
- Spectral resolution adequate for detecting rangeland vegetation
- 16-day repeat cycle with one satellite in orbit, 8-days with two
- Landsat 5 (1984-2012), Landsat 7 (1999–present), and Landsat 8 (2013-present) were used in this study

Soil-Adjusted Total Vegetation Index (SATVI)

SATVI was used in this study due to its ability to detect both green and senescent (or brown) vegetation (Marsett et al., 2006).

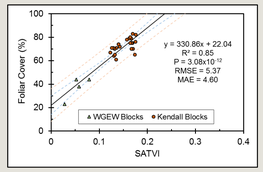
$$SATVI = \frac{\rho_{SWIR1} - \rho_{RED}}{\rho_{SWIR1} + \rho_{RED}}(1 + L) - \frac{\rho_{SWIR2}}{2}$$

L = Soil adjustment factor
A value of 0.5 was used in this study

Field Calibration of Landsat Imagery

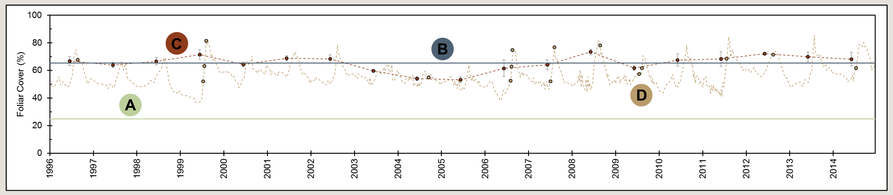
Repeat transect measurements of foliar cover at Kendall (Kendall Blocks) and grassland sites within WGEW (WGEW Blocks) were taken over the 2015 growing season. Each study block contained three 80-m transects designed to correspond with four Landsat pixels. Landsat 7 & 8 imagery were obtained from satellite overpasses that coincided with transect collection dates for calibration.

A linear relationship was developed between SATVI and the field-measured foliar cover. The resulting linear equation was applied to all cloud-free Landsat scenes covering the watershed from 1996-2014 to produce a long-term foliar cover time series (***shown by the gold dashed line on the chart below***).



Linear relationship between field-measured foliar cover and SATVI. Dashed lines show 95% confidence (pink) and prediction (blue) intervals.

Foliar Cover Scenarios For Model Input



The Landsat-based foliar cover values from the time series were used to generate three scenarios (B,C and D) for input into RHEM. Runoff simulation results from these scenarios were compared with those using a default, literature-based foliar cover value (A) provided by AGWA.

Foliar Cover Scenarios for Model Input

A — NLCD-based – Static Value of 25%
AGWA lookup table value associated with National Land Cover Database (NLCD) land cover Class 71: Grassland/Herbaceous. A static value of 25% foliar cover was applied to all simulated events.

B — Long-term Mean – Static Landsat-based Value of 66%
Average of annual monsoon season (July-September) cover values 1996-2014. A static value of 66% foliar cover was applied to all simulated events.

C — Annual Seasonal Mean – Annual Landsat-based Value
Average of cover values obtained between July-September each year. The annual value was applied to all storms for a given year. ***This value is indicated by red circles on the above chart. Error bars show standard error.***

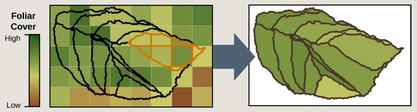
D — Event-based – Dynamic Landsat-based Value
The cover value obtained from the closest Landsat scene to a given runoff event. Images used were acquired no more than ten days from runoff events. ***Gold circles on the above chart denote images associated with runoff event(s).***

Foliar Cover Integration into Model

Twenty-eight precipitation events with gaged runoff quantities were used for simulation and model evaluation. The following procedure demonstrates how the model was parameterized using the foliar cover scenarios for each rainfall/runoff event that was modeled.

Foliar Cover Integration

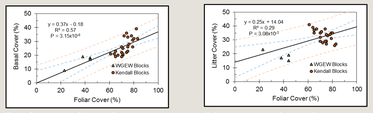
Landsat-based foliar cover values were applied to each hillslope element using a weighted average of the intersecting 30-m Landsat pixels. The elements were also populated with static parameters that had been assigned using AGWA.



Landsat pixel aggregation | Foliar cover distributed to elements

Basal and Litter Cover Estimates

Basal and litter cover are required inputs into RHEM, therefore allometric relationships were developed between foliar cover, and basal and litter cover using the transect data. These relationships were applied to the Landsat-based foliar cover to generate basal and litter cover model inputs.



Basal cover relationship | Litter cover relationship

Affected Model Parameters

The following RHEM/KINEROS2 parameters were altered by the foliar (or derived basal/litter) cover inputs:

- **Friction Factor:** $Ft = f(\boldsymbol{basal\ cover}, \boldsymbol{litter\ cover}, rock\ cover, cryptogram\ cover, slope)$
- **Effective Hydraulic Conductivity:** $Ke = f(\boldsymbol{basal\ cover}, \boldsymbol{litter\ cover}, soil\ texture, plant\ lifeform)$
- **Canopy Interception:** $In = f(\boldsymbol{foliar\ cover})$

Friction Factor (Ft)

This represents the frictional resistance to surface flow. As friction from ground cover and vegetation increases, flow velocity decreases resulting in reduced peak discharge and greater infiltration.

Hydraulic Conductivity (Ke)

This represents a soil's ability to transmit water through its pores. Increased vegetation can increase conductivity, leading to increased infiltration and lower runoff volume.

Canopy Interception (In)

This is the amount of precipitation captured by vegetation canopy before reaching the ground. Increased vegetative cover can capture more rainfall, decreasing the water available for runoff.

Model Performance

Performance Metrics Used for Evaluation

Nash-Sutcliffe Efficiency (NSE)

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right]$$

NSE indicates how well the observed verses simulated data fits the 1:1 line (***dashed gray line on charts below***) (Nash & Sutcliffe, 1970).

- Optimal value of 1
- A negative value indicates that the mean of the observed data is a better predictor
- Positive values indicate generally acceptable model performance

Percent Bias (PBIAS)

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right]$$

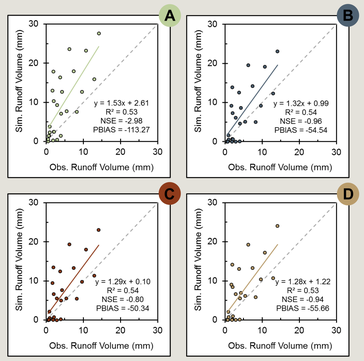
PBIAS is a measure of the average tendency of the simulated data to be larger or smaller than the observed data (Gupta et al., 1999).

- Optimal value of 0
- Lower magnitude of values indicate more accurate simulation
- Negative values show model overestimation
- Positive values show model underestimation

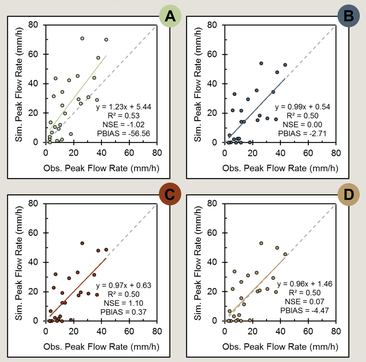
Runoff Simulation Results and Performance Evaluation

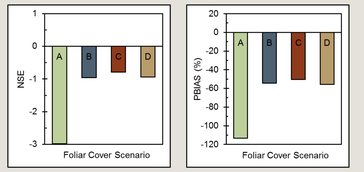
Precipitation-runoff simulations were conducted with RHEM/KINEROS2 using precipitation data from twenty-eight monsoon events occurring from 1996-2014. Gauged runoff data from Flume 112 was used to evaluate total runoff volume and peak flow rate at the outlet of the watershed.

Total Runoff Volume

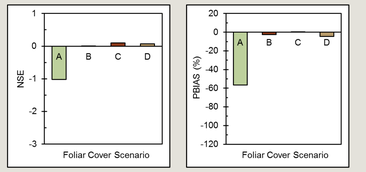


Peak Flow Rate





All scenarios showed model overestimation of runoff volume and negative NSE. However, use of the remotely sensed foliar cover inputs (B, C, and D) showed improved performance and decreased bias compared to the default, NLCD-based value (A).



Peak flow rate performance improved when using the remotely sensed inputs (B, C, and D), with positive NSE values and PBIAS magnitudes less than 5%.

Increasing the temporal resolution of the remotely sensed foliar cover data (i.e., long-term (B) to annual (C) to sub-annual (D)) showed negligible improvement in runoff simulation. Vegetative cover remained relatively constant over time at this site. It is hypothesized that the annual or sub-annual foliar cover measurements could further improve model results when applied to a site in which land modification occurred (e.g., fire, increased grazing, shrub encroachment).

Final Thoughts

- The Landsat-based foliar cover time series showed the ability to capture both inter- and intra-annual variability of foliar cover in a small, semiarid watershed over a 14-year period.
- Incorporating site-specific, Landsat-based foliar cover into RHEM/KINEROS2 improved model results compared to the NLCD literature-based value.
- The methodology outlined here provides a framework for improved hydrologic modelling in regions where field-based vegetative data may be unavailable.
- Further research goals include: uncertainty analysis of foliar cover inputs; evaluation of erosion/sediment simulations; further model calibration; and extrapolation of methodology to disturbed sites or different vegetation types.

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