Using GSSHA, a Two-Dimensional Gridded Distributed Hydrologic Model for Floodplain Management

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Todd Cochran, PE, CFM
Jeff House, CFM
Annje Dodd, PhD, PE
Today’s Agenda

• Overview of GSSHA model

• Example of it’s use for the Truckee River Flood Project
Today’s Agenda

• GSSHMA Overview
• TRFMA Model Development
• Modeling Challenges
• Future Uses
GSSHA

- Gridded Surface Subsurface Hydrologic Analysis
- Based on the CASC2D model (Ogden and Julien) developed in the 1990’s
- Now developed by USACE’s Engineer Research and Development Center (ERDC)
- [http://www.gsshawiki.com/gssha/Main_Page](http://www.gsshawiki.com/gssha/Main_Page)
- FEMA Approved
WMS
GSSHA Overview

- A physics-based, distributed, hydrologic and sediment and constituent fate and transport model

- Features include
  - 2D overland flow
  - 1D stream flow
  - 1D infiltration
  - 2D groundwater
  - Snowmelt, Gridded & Temporal Precipitation
  - Full coupling between groundwater, shallow soils, streams and overland flow
Spatially Distributed Parameters

- Gridded Model Input
  - Elevations
  - Land Use
  - Soils
  - Impervious Area
Physics-based Model

• Values are based on physical conditions in the computational element
  • Requires less calibration data (values are quantifiable from time step to time step from cell to cell)
  • Extendable beyond calibration range (e.g., addition of a subdivision, parameters are changed only for cells that include the land use change)
• Tie to physical conditions provides a means to logically alter parameters based on changing conditions
  • Land use changes, project alternatives, etc.
Processes Simulated

- Precipitation
- Infiltration
- Overland Flow
- Channel Flow
- Reservoir Simulation
- Evapo-transpiration
- Soil Moisture Accounting
- Closed Systems
- Snowmelt and Accumulation
- Groundwater
- Sediment Erosion
- Sediment and Nutrient Transport
PRECIPITATION

Spatially Varied or Uniform
- For calibration and validation use
- For future planning
  - Hypothetical “Impact” Storm(s)
Running Models with NYE 2005 Event for the Calibration Storm
Running Models with NYE 1997 Event for one of the Validation Storms
Running Models with Jan. 2008 Event for the other Validation Storm
Infiltration

• Green & Ampt
• Green & Ampt with Redistribution
  • Redistribution of soil moisture during periods of no rainfall
• Multi-layer Green & Ampt
• Richards Equation
Overland Flow Routing

- 2D grid of interconnected cells
- Four direction flow
2D Diffusive Wave

• Diffusive wave in x and y directions

\[ S_{f_x} = S_{o_x} - \frac{\partial h}{\partial x} \quad S_{f_y} = S_{o_y} - \frac{\partial h}{\partial y} \]

• Manning’s equation to relate friction and flow

\[ q_x = \frac{1}{n} h_i^{2/3} S_{f_x}^{1/2} \quad q_y = \frac{1}{n} h_j^{2/3} S_{f_y}^{1/2} \]

• Continuity equation to relate flow and depth at next time step

\[ \frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial x} = 0 \]
Channel Routing
1D Unsteady Streamflow

Diffusive Wave

\[
S_{f_{i-1/2}}^k = S_{o_{i-1}}^k - \frac{d_i^k - d_{i-1}^k}{\Delta x}
\]

\[
S_{f_{i+1/2}}^k = S_{o_i}^n - \frac{d_{i+1}^k - d_i^k}{\Delta x}
\]

Manning’s

\[
Q_{i-1/2}^k = \frac{1}{n} A_i^k \left( R_i^k \right)^{2/3} \left( S_{f_{i-1/2}}^k \right)^{1/2}
\]

\[
Q_{i+1/2}^k = \frac{1}{n} A_{i+1}^k \left( R_{i+1}^k \right)^{2/3} \left( S_{f_{i+1/2}}^k \right)^{1/2}
\]

Continuity

\[
v_i^{k+1} = v_i^k + \Delta t \left( q_{\text{lat}_i}^{k+1} \Delta x + q_{\text{recharge}}^{k+1} \Delta x + Q_{i-1/2}^k - Q_{i+1/2}^k \right)
\]
TRUCKEE RIVER WATERSHED REGIONAL HYDROLOGIC MODEL

TRFMA
TRUCKEE RIVER FLOOD PROJECT

• Regional Hydrologic Model for the Truckee River Flood Project
• USACE Flood Control Project
• Local Sponsors Responsible for Maintaining Existing Conditions Hydrology
TRUCKEE RIVER WATERSHED - 11 BASINS
TRUCKEE RIVER WATERSHED
MODEL DEVELOPMENT PROCESS

• Create DEM for Overland Flow
• Create Index Maps
  • Land Use
  • Impervious Areas
  • Soils
• Create Mapping Tables
  • Used to link model parameters to Index Maps
• Add Streams and Detention – 1-D Flow
MODEL DEVELOPMENT

DEM Development

• Build Terrain from County DTM data 2-foot and 1-foot contours, 3-D breaklines, and spot elevations to create Detailed DEM. This covers the developed areas of Washoe County.
• Create USGS National Elevation Dataset (NED) 10-meter DEM from Terrain.
• Mosaic Detailed DEMs and NED 10-meter DEMs to cover the whole sub-watershed.
• Use Detailed DEM where available, NED everywhere else.
• Import and convert combined DEM into 30-meter computational grid in WMS
STREAMS

Delineate streams with a drainage area greater than 50 acres (1,658 Stream Miles).

Correct stream lines using:
- GIS base mapping
- Aerial photography
- GIS stormwater infrastructure data

Perform field reconnaissance to correct stream lines and measure channel sizes

Import stream lines into WMS
MODEL DEVELOPMENT

Import Streams
Streams – Trapezoidal Channels
Streams – Irregular Cross Sections
STREAM PROFILES

- Set stream elevations to DEM ground elevations.
- Smooth stream using the smoothing tool in WMS.
- Update ground DEM with new smoothed stream elevations.
FIX DIGITAL DAMS

- Run automated “Fix Digital Dams” tool to adjust cell elevations to remove artificial ponding areas.
- Compare fixed DEM to original DEM to verify changes are accurate.
- Make manual adjustments to the original DEM and rerun the “Fix Digital Dams” tool.
- Add cross-sections.
- Add in detention areas.
Detention Areas

- Spanish Springs Detention Facility
- Pioneer Meadows
- Stonebrook
Index Grids

- Land Use
- Impervious Area
- Land Use
Index Grids

- Soil Mapping
- USDA-SSURGO Data
- Supplement with Field Testing
INfiltration PARAMETERS

- Related to soil type (texture) through lookup tables
- Initial estimates based on typical textbook values
- Final values determined through field experiments and model calibration

Green – Ampt infiltration parameters for various soil classes (Rawls et al., 1983). The numbers in parentheses are one standard deviation around the parameter value given.

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Porosity</th>
<th>Effective Porosity</th>
<th>Wetting Front Suction</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>0.437 (0.374-0.500)</td>
<td>0.417 (0.354-0.480)</td>
<td>4.95 (0.97-25.36)</td>
<td>11.78</td>
</tr>
<tr>
<td>loamy sand</td>
<td>0.437 (0.363-0.506)</td>
<td>0.401 (0.329-0.473)</td>
<td>6.13 (1.35-27.94)</td>
<td>2.99</td>
</tr>
<tr>
<td>sandy loam</td>
<td>0.453 (0.351-0.555)</td>
<td>0.412 (0.283-0.541)</td>
<td>11.01 (2.67-45.47)</td>
<td>1.09</td>
</tr>
<tr>
<td>loam</td>
<td>0.463 (0.375-0.551)</td>
<td>0.434 (0.334-0.534)</td>
<td>8.89 (1.33-59.38)</td>
<td>0.34</td>
</tr>
<tr>
<td>silt loam</td>
<td>0.501 (0.420-0.582)</td>
<td>0.486 (0.394-0.578)</td>
<td>16.68 (2.92-95.39)</td>
<td>0.65</td>
</tr>
<tr>
<td>sandy clay loam</td>
<td>0.398 (0.332-0.464)</td>
<td>0.330 (0.235-0.425)</td>
<td>21.85 (4.42-108.0)</td>
<td>0.15</td>
</tr>
<tr>
<td>clay loam</td>
<td>0.464 (0.409-0.519)</td>
<td>0.309 (0.279-0.501)</td>
<td>20.88 (4.79-91.10)</td>
<td>0.1</td>
</tr>
<tr>
<td>silty clay loam</td>
<td>0.471 (0.418-0.524)</td>
<td>0.432 (0.347-0.517)</td>
<td>27.30 (5.67-131.50)</td>
<td>0.1</td>
</tr>
<tr>
<td>sandy clay</td>
<td>0.430 (0.370-0.490)</td>
<td>0.321 (0.207-0.435)</td>
<td>23.90 (4.08-140.2)</td>
<td>0.06</td>
</tr>
<tr>
<td>silty clay</td>
<td>0.479 (0.425-0.533)</td>
<td>0.423 (0.334-0.512)</td>
<td>29.22 (6.13-139.4)</td>
<td>0.05</td>
</tr>
<tr>
<td>clay</td>
<td>0.475 (0.427-0.523)</td>
<td>0.385 (0.269-0.501)</td>
<td>31.63 (6.39-156.5)</td>
<td>0.03</td>
</tr>
</tbody>
</table>
MODELING CHALLENGES
Issues with Detention Areas

Problem - Primary and spillway outlets flow to different cells

Solutions
1. Code revised to allow overland flow over low point in embankment
2. New option being added to enter an overland flow structure (weir) with a defined rating table (stage vs. discharge)
Issues with Detention Areas

- East Wash Dam – Spillway flows to West Wash Dam
Issues with Detention Areas

**Problem** – Long model run times due to small time steps. GSSHA automatically decreases time steps down to 1/1000 of a second (if needed) to maintain stability.

**Solution**
1. Fix issues with outlet structures
2. Smooth cells in detention area
3. Use cross sections to model detention area instead of 2D cells
Issues with Detention Areas

**Problem**
Detention routing does not accurately model shallow overbank flows

**Solution**
- GSSHA code revised to allow flow to spill out of channel on to overland flow cells for specific links
- Added option for a depth-varied Manning’s $n$-value for channels and overland flow
**Depth Varied Manning’s n for Overland Flow**

- Overland Flow Manning’s n values are not valid for depths greater than a few inches.
- As the flow depth increase, the Manning’s n decreases using the following equation:
  \[ n = Ae^{-B \times h} \]
  
  where:
  - A is the constant (overland manning roughness)
  - B is the exponent (0.0 for constant value, >0.0 for FLO2D curve)
  - h is the flow depth

- This will improve modeling of Channel overflow (see below) and overland flow before it reaches a channel.

**Channel Overflow and Backwater**

- These options were available, but just as a global option for all streams.
- Overflow allows water to flow out of the channel once the flow depth exceeds the channel banks.
- Backwater keeps overland flow from entering the channel when the water surface in the channel is higher than the overland flow cell.
- These options can now be turned on for individual links. We plan to use it on the mainstem of Steamboat Creek.
FIELD SOIL TESTING
Objective of Field Testing

To improve the characterization of soils with respect to surface runoff prediction (Green-Ampt Parameters)

Methods

• Measure hydraulic characteristics of soils for different surface textures at discrete points in the watershed

• Characterize soils & develop a statistical relationship to the measured hydraulic properties Pedotransfer Function (AKA: Multiple Regression)

• Use statistical analyses to scale measurements to broader soil units across the watershed
Field Methods

- Landuse Grouping (5)
  - Pasture, grassland, or range 9.5%
  - Piñon-juniper 23.4%
  - Sagebrush/grass understory 26.5%
  - Residential/Commercial 14.5%
  - Other 26.5%

- Elevation Grouping (3)
  - <4800’ 25.7%
  - 4800-6000’ 41.5%
  - >6000’ 32.7%

- Soil Grouping (6)
  - Based on ‘SimpleTex’
  - Predominant textures preserved
    - Sand, loamy sand, sandy loam, loam, and silt loam
  - Clayey soils – conglomeration
    - All textural classes with clay contents >20%
Field Methods

- Site Selection (15)
  - Accessibility
  - Range of soil textures
  - Areal coverage
- Tension Infiltrometers
  - 8 pts / transect
  - 50-cm intervals between points
- Soil Sampling
  - Core (2.5cm deep) at each infiltration point
  - Bulk density
  - Particle Size
  - Soil Organic Matter
- 118 point measurements
Infiltration Sites

- Total 15 sites, 118 experiments
  - Mt. Rose Highway (4)
  - Leadership Way (4)
  - Central Corridor (4)
  - Vista Boulevard (3)

- Texture
  - Sand (2)
  - Loamy sand (2)
  - Sandy Loam (3)
  - Loam (5)
  - Silt Loam (3)
Sampling Sites

- 111 bulk samples, approximately uniformly sampled from:
  - Sand
  - Loamy sand
  - Sandy Loam
  - Loam
  - Silt Loam
  - Clayey soils

- The soil textures above are SSURGO classifications
SNOW ACCUMULATION AND SNOWMELT
Snow Accumulation and Snowmelt

- SNOW-17
  - Snow Accumulation and Ablation Model
  - Developed as part of the National Weather Services River Forecasting System
  - Temperature-Index based method
    - Input is temperature and precipitation
  - When calibrated, outperforms the original GSSHA energy balance algorithm
- 11 SNOTEL gages in study area
Snowmelt contribution expected
- 1997 storm, all elevations
- 2005 storm, elevations below 8000 feet
- 2008 storm medium to low contribution, most elevations

<table>
<thead>
<tr>
<th>SNOTEL Gage</th>
<th>Elevation (ft)</th>
<th>1997</th>
<th>2005</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independence Creek</td>
<td>6456</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Truckee #2</td>
<td>6509</td>
<td>High</td>
<td>High</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Ward Creek</td>
<td>6655</td>
<td>High</td>
<td>High</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Tahoe City Cross</td>
<td>6797</td>
<td>High</td>
<td>High</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Independence Camp</td>
<td>7003</td>
<td>High</td>
<td>High</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Marlette Lake</td>
<td>7880</td>
<td>High</td>
<td>High</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Squaw Valley</td>
<td>8029</td>
<td>High</td>
<td>no data</td>
<td>Low/None</td>
</tr>
<tr>
<td>Big Meadow</td>
<td>8249</td>
<td>High</td>
<td>Low/None</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Independence Lake</td>
<td>8352</td>
<td>High</td>
<td>Medium/Low</td>
<td>Low/None</td>
</tr>
<tr>
<td>Mt. Rose</td>
<td>8801</td>
<td>High</td>
<td>Low/None</td>
<td>Low/None</td>
</tr>
</tbody>
</table>
- Likelihood of runoff contribution low at Mt. Rose
- Relatively no decrease in SWE during storm
- Increase in SWE = water content added to snowpack
Hydrometerological Data

• Hourly data for:
  • Barometric Pressure (in Hg)
  • Relative Humidity (%)
  • Total Sky Cover (%)
  • Wind Speed (kts)
  • Dry Bulb Temperature (oF)
  • Direct Radiation (W×h/m²)
  • Global Radiation (W×h/m²)
Hydrometeorological Data

- Sources of data include:
  - Western Regional Climate Center
  - NCDC Hourly/Sub-Hourly Observational Data Server
  - SNOTEL sites
## Snowmelt & Accumulation

### Calibration of Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Conductivity for Snowpack</td>
<td>0.036</td>
<td>m/s</td>
<td>Recommended</td>
</tr>
<tr>
<td>Reynolds # for Overland Flow</td>
<td>162.8</td>
<td>unitless</td>
<td>Recommended</td>
</tr>
<tr>
<td>Maximum Melt Factor</td>
<td>Calibrate</td>
<td>mm/°C/time step</td>
<td></td>
</tr>
<tr>
<td>Minimum Melt Factor</td>
<td>Calibrate</td>
<td>mm/°C/time step</td>
<td></td>
</tr>
<tr>
<td>Snow Cover Fraction</td>
<td>Calibrate</td>
<td>unitless</td>
<td>0.8 to 1.2</td>
</tr>
<tr>
<td>Threshold Temp between Rain and Snow</td>
<td>Calibrate</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Fraction of precipitation in the form of rain</td>
<td>Calibrate</td>
<td>unitless</td>
<td>0.0 to 1.0</td>
</tr>
<tr>
<td>Snow cover thermal gradient</td>
<td>Calibrate</td>
<td>unitless</td>
<td>0.0 to 1.0</td>
</tr>
<tr>
<td>Negative melt factor</td>
<td>Calibrate</td>
<td>mm/°C/time step</td>
<td></td>
</tr>
<tr>
<td>Empirical wind function factor</td>
<td>Calibrate</td>
<td>mm/mb/6 hours</td>
<td></td>
</tr>
<tr>
<td>Liquid water holding capacity fraction</td>
<td>Calibrate</td>
<td>unitless</td>
<td>0.0 to 0.4</td>
</tr>
</tbody>
</table>
Snowmelt & Accumulation

• Data Required
  • Date & Time
  • Barometric Pressure (in Hg)
  • Relative Humidity (%)
  • Total Sky Cover (%)
  • Wind Speed (kts)
  • Dry Bulb Temperature (°C)
  • Direct & Global Radiation (W×h/m²)
  • Precipitation
  • Temperature
  • Snow Water Equivalent

Develop HMET Files outside of GSSHA using EXCEL Macros developed by ERDC Staff
Snowmelt & Accumulation

Set up second temperature gage to determine dry adiabatic lapse rate.

Files setup for each sub-model.

<table>
<thead>
<tr>
<th>Sub-model Area</th>
<th>Gage Used to Setup HMET File</th>
<th>Second Temperature Gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 Storm Event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truckee</td>
<td>Truckee Tahoe Airport</td>
<td>Truckee #2</td>
</tr>
<tr>
<td>Little Truckee River</td>
<td>Truckee Tahoe Airport</td>
<td>Independence Camp</td>
</tr>
<tr>
<td>Truckee Canyon</td>
<td>Truckee Tahoe Airport</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>Reno West</td>
<td>Reno Tahoe Airport</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>Reno Sparks West</td>
<td>Reno Tahoe Airport</td>
<td>None</td>
</tr>
<tr>
<td>Reno Sparks East</td>
<td>Reno Tahoe Airport</td>
<td>None</td>
</tr>
<tr>
<td>Washoe Lake</td>
<td>Truckee Tahoe Airport</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>Steamboat Creek North</td>
<td>Truckee Tahoe Airport</td>
<td>Mount Rose</td>
</tr>
<tr>
<td>Steamboat Creek South</td>
<td>Truckee Tahoe Airport</td>
<td>Mount Rose</td>
</tr>
<tr>
<td>Boynton Slough</td>
<td>Reno Tahoe Airport</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>North Truckee Drain</td>
<td>Reno Tahoe Airport</td>
<td>None</td>
</tr>
</tbody>
</table>

2005 and 2008 Storm Events

<table>
<thead>
<tr>
<th>Sub-model Area</th>
<th>Gage Used to Setup HMET File</th>
<th>Second Temperature Gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truckee</td>
<td>Truckee Tahoe Airport</td>
<td>Truckee #2</td>
</tr>
<tr>
<td>Little Truckee River</td>
<td>Truckee Tahoe Airport</td>
<td>Independence Camp</td>
</tr>
<tr>
<td>Truckee Canyon</td>
<td>Truckee Tahoe Airport</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>Reno West</td>
<td>Reno Tahoe Airport</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>Reno Sparks West</td>
<td>Reno Tahoe Airport</td>
<td>Desert Springs</td>
</tr>
<tr>
<td>Reno Sparks East</td>
<td>Reno Tahoe Airport</td>
<td>Desert Springs</td>
</tr>
<tr>
<td>Washoe Lake</td>
<td>Truckee Tahoe Airport &amp; Little Valley for Relative Humidity and Temperature</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>Steamboat Creek North</td>
<td>Truckee Tahoe Airport &amp; Galena for Relative Humidity and Temperature</td>
<td>Mount Rose</td>
</tr>
<tr>
<td>Steamboat Creek South</td>
<td>Truckee Tahoe Airport &amp; Galena for Relative Humidity and Temperature</td>
<td>Mount Rose</td>
</tr>
<tr>
<td>Boynton Slough</td>
<td>Reno Tahoe Airport &amp; Galena for Relative Humidity and Temperature</td>
<td>Big Meadow</td>
</tr>
<tr>
<td>North Truckee Drain</td>
<td>Reno Tahoe Airport &amp; Desert Springs for Wind Speed &amp; Relative Humidity</td>
<td>Desert Springs</td>
</tr>
</tbody>
</table>
Calibration Snow Model Parameters

- PEST – Model-Independent Parameter ESTimation & Uncertainty Analysis
  - Developed outside of GSSHA
  - MS-DOS based
  - Uses Gauss-Marquardt-Levenberg algorithm to calculate the objective function
  - Provides best unbiased estimator, in a least-squares sense, of parameters being optimized
    - Matches to predicted & observed Snow Water Equivalent
- Input files
  - HMED, Template, Instruction, Control and Parameter
Calibration Snow Model Parameters

- Files setup for each sub-model
- Metrics used to evaluate calibration results
- Nash-Sutcliffe Efficiency. An Efficiency, \( E \), of 1.0 indicates a perfect fit, where

\[
E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}
\]

\( O_i \) = observed value at time \( i \)
\( \bar{O} \) = average of observed values
\( P_i \) = predicted value at time \( i \)

- The Root Mean Square (RMS) Error is a measure of the difference between predicted and observed values, where the individual differences are the residuals. The smaller the RMS, the better the fit, where

\[
E = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2}
\]

\( y_i \) = observed value at time \( i \)
\( \hat{y} \) = predicted value at time \( i \)
\( n \) = number of observations
Calibration Snow Model Parameters

- Reno West, Reno, Sparks, Boynton Slough & North Truckee Drain
Snow Water Equivalent (SWE) Dec. 25, 2005 (1st day of model)
Model Calibration
Modeling Land Use Change
Truckee River Flood Management Authority Regional Hydrologic Model Ongoing Training Began to Sponsor Communities in March, 2014.
QUESTIONS?