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Integrating Radar Rainfall Estimates with Digital Elevation Models and Land Use Data to Create an Accurate Hydrologic Model*

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Abstract

The recent development of HEC-GeoHMS by the U.S. Army Corp of Engineers Hydrologic Engineering Center (HEC) allows for the easy creation of physically based hydrologic models using ArcView®, a GIS software package. HEC-GeoHMS easily ingests digital elevation models (DEMs) and automatically creates watershed delineations based on the actual topography. The user can manually merge and split watersheds and input gage locations. Land use/land cover (LU/LC) data and soil information are available for input in GIS format from a number of governmental agencies via the web, and these data can be aggregated into basin-averaged parameters for model input.

A hydrologic model using these principles was created for a small (~ 160 mi^2) watershed near Heppner, Oregon. A watershed model delineated using DEMs and HEC-GeoHMS was exported into the HEC-HMS model. Land use/land cover and soil data were input into ArcView® and basin-average parameters were created for each subwatershed. Radar rainfall data every fifteen minutes were input into the hydrologic model for a recent storm using ModClark, a quasi-distributed runoff procedure in HEC-HMS. The results compared favorably with observed flows.

The use of accurate elevation data eliminates much of the guesswork involved with hydrologic modeling and should greatly enhance the modeling results. Combining gage-adjusted radar-rainfall estimates into the improved model will greatly enhance the ability of engineers and floodplain managers to predict watershed response to severe storm events.

Introduction

HEC-GeoHMS, an extension for ArcView® released in July 2000 by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), allows for the easy creation of the basic basin parameters of a hydrologic model based on topographic data. HEC-HMS, HEC's next generation hydrologic model, uses the data from HEC-GeoHMS and can model gridded rainfall (e.g. gage-adjusted radar-rainfall estimates) using a quasi-distributed approach called ModClark (Peters and Easton, 1996). ModClark determines rainfall excess at each radar pixel and the excess from each pixel is lagged to

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the basin outlet. The result is a hydrologic model that more accurately characterizes spatial rainfall patterns.

HEC produces user manuals for HEC-GeoHMS (Doan 2000) and for HEC-HMS (Scharffenberg 2000) that are both very comprehensive. This paper focuses on the preprocessing of the topographic data for input into HEC-GeoHMS and highlights other issues that are important for the modeling of spatial rainfall data with HEC-HMS. Finally, a recent storm in Heppner, Oregon is presented as a case study.

HEC-GeoHMS requires ArcView® and the Spatial Analyst extension. Due to heavy computation time, the authors also recommend using a fast PC with sufficient amount of memory. The case study was completed on an 800 MHz PC with a 30 GB hard drive and 256 MB of memory.

Background

Digital elevation models (DEM) are gridded topographic data that represent the elevation of a regularly spaced grid cells as the midpoint elevations of those grid cells. DEMs with 30 m horizontal resolution are available from the U.S. Geologic Survery (USGS) and were used for this analysis. HEC-GeoHMS uses DEMs to determine watershed boundaries and flow paths by analyzing the direction of steepest descent at each grid cell. In Figure 1, a hypothetical DEM (north is up) is shown with grid center elevations. Water from each grid cell will flow into one of the eight surrounding grid cells. For instance, in the northwest grid cell (elevation 59), water will flow directly to the east (elevation 56). In the grid cell immediately southeast of the original cell (elevation 58), water will either flow directly north to elevation 56, or will flow to the northeast to elevation 53. The slope to the path to the north would be (58-56)/1, or 2 elevation units per cell. The slope to the path to the northeast would be (58-53)/1.414, or 3.54 elevation units per cell. Therefore, water will flow to the northeast. In Figure 2, the grid cell with elevation 53 has a total of three upstream cells that flow into it. (Note that prior to analysis, HEC-GeoHMS creates a “hydrologically corrected” DEM, which insures that at least one of the eight neighboring cells is lower than the original cell.) An in-depth description of these processes can be found in Kull and Feldman (1998).

This analysis is completed for each cell in the DEM. At each cell, cell drainage data are determined by calculating the number of contributing upstream cells. Streams are defined when a threshold number of cells is exceeded. Cells with no upstream contributing cells form a watershed divide (see Figure 2). Watersheds are automatically defined by HEC-GeoHMS based on user-defined threshold for watershed size and at stream confluences. The user can manually add a watershed by defining an outlet on the stream network (at the location of a gaging station, for instance), and the user can merge connected watersheds. Again, these procedures are clearly delineated in the *HEC-GeoHMS User’s Manual* (Doan 2000).

The success of using DEMs for accurate estimation of stream locations and watershed boundaries is a function of the slope of the study area. Ahrens and Maidment (1999) state that the user should be “leary” of using 30 m DEMs with an average slope of less than 0.0008 (4 ft/mi or 0.8 m/km).

59	56	53	51	47	44
59	58	57	55	52	45
56	57	56	54	51	47
54	57	57	56	52	48
51	55	56	56	54	51
46	51	54	57	56	53

Figure 1: DEM with Elevation Data

0	1	3	5	7	23
0	0	0	0	0	14
1	0	0	2	3	8
3	0	0	0	2	7
5	0	0	0	0	2
11	3	1	0	0	0

Figure 2: Number of Upstream Cells

Creation of DEM for HEC-GeoHMS

DEMs are the primary input for HEC-GeoHMS for terrain analysis. However, DEMs that are available online are in Spatial Data Transfer Standard (SDTS) format and are not ready for direct ingest into HEC-GeoHMS. If one is analyzing a large watershed, all DEMs covering the target watershed will need to be merged together into a single DEM. This section will describe the steps necessary to create the single DEM for terrain analysis for use with HEC-GeoHMS:

1. Determine the names of the DEM files – Each 30 m DEM file covers a single standard 7.5 minute USGS quad sheet. To determine the names of the quad sheets that cover the target area, go to edcwww.cr.usgs.gov/Webglis/glisbin/finder_main.pl?dataset_name=MAPS_LARGE. From there, follow the directions by either clicking on an area, by entering the zip code, or by entering the name of a populated place.

2. Retrieve DEM from GIS Data Depot in STDS format – While the USGS does publish the DEM data and make the data available online, GIS Data Depot is a nicely organized website of various types of geospatial data. Their website is located at www.gisdatadepot.com/catalog/US/sublist.html. From there, follow links to *Countywide data*. Click on your county. Click on *Digital Elevation Models (DEM) - 24K*. Download the data for your area. Data will be in **.tar.gz* and you can use WinZip, or similar zipping program to uncompress the file. For instance, file 9897_30.2.1.997988.TAR.GZ extracts to 20 separate files: 1256CATD.DDF, 1256CATS.DDF, 1256CEL0.DDF, 1256DDDF.DDF, 1256DDOM.DDF, 1256DDSH.DDF, 1256DQAA.DDF, 1256DQCG.DDF, 1256DQHL.DDF, 1256DQLC.DDF, 1256DQPA.DDF, 1256IDEN.DDF, 1256IREF.DDF, 1256LDEF.DDF, 1256RSDF.DDF, 1256SPDM.DDF, 1256STAT.DDF, 1256XREF.DDF, README.7.5min, and UCOMMENT.txt.

3. Convert STDS data to DEM – To convert the data from STDS format to ArcView® ready format, download stdsedem.zip from ftp://ftp.blm.gov/pub/gis/sdts/dem/ and extract stdsedem.exe to the same folder as your DEMs. Run stdsedem.exe by double clicking on it and follow directions. Save the DEM as a unique name.

4. Merge multiple DEMs in ArcView® using Spatial Analyst – In ArcView®, with Spatial Analyst loaded, go to the *File* menu, choose *Import Data Source – USGS DEM*. Name each DEM as a unique grid file (such as `grid1`, `grid2`, and `grid3`). Once all of your DEMs are loaded into ArcView®, go the *Analysis – Map Calculator* and type `[grid1].merge({[grid2],[grid3],…,[gridn]})`, where `grid1` to `gridn` are the names of your DEMs.

5. Remove any NODATA holes in the merged DEM – There are often NODATA values in the middle of a merged DEM and this causes obvious problems for the terrain analysis in HEC-GeoHMS. If there are data gaps, use the following code to eliminate the NODATA gaps (make sure the merged DEM is active). The code was obtained in the *User's Forum* section off the ESRI website (www.esri.com):

```
theView=av.getactivedoc
theGrid=theView.getactivethemes.get(0).getgrid
filler=theGrid.focalstats(#GRID_STATYPE_MEAN,Nbrhood.make,false)
outgrid=theGrid.merge({filler})
outGthm=Gtheme.make(outgrid) TheView.addtheme(outGthm)
```

   Once the DEMs have been merged and all of the gaps filled, the DEM is ready for hydrologic analysis.

6. Retrieve DRG from GIS Data Depot (optional) – A DRG (Digital Raster Graphic) is a georeferenced digital image of a USGS quad sheet. Go to www.gisdatadepot.com/catalog/US/sublist.html and follow links to *Countywide* data. Click on your country. Click on *Digital Raster Graphics (DRG) - 24K* and download the data for your area of interest. DRGs are extremely valuable to determining locations of streams gages and landmarks.

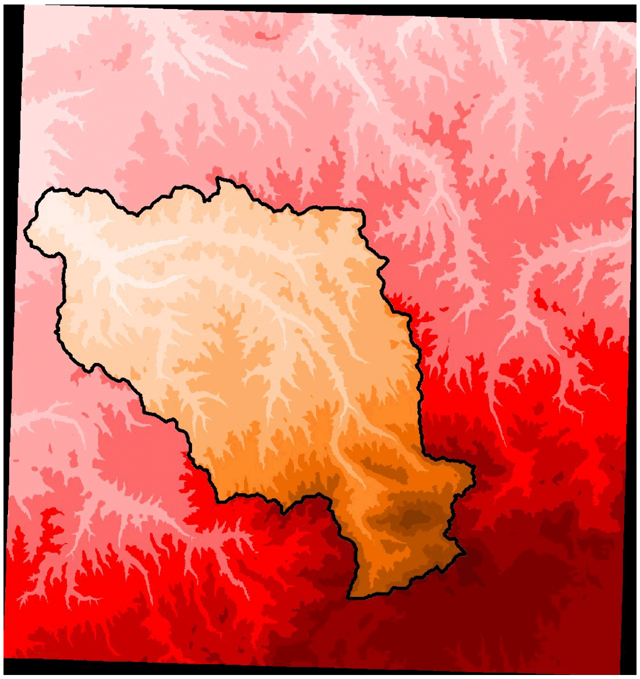

Figure 3: Merged DEM and Heppner study area outlined in black

One important note is that the DRGs and the DEMs are most likely in UTM coordinates. If you are working in decimal degrees for other GIS data, those data will need to be projected to the appropriate UTM coordinates for proper georefencing. Figure 3 shows a merged DEM and the outline of the Heppner study area.

HEC-HMS Modeling

Once the merged DEM is loaded into HEC-GeoHMS, the *User's Manual* does an excellent job of explaining the processes needed for terrain analysis. HEC-HMS currently supports gridded rainfall data in two different grids: the HRAP (Hydrologic Rainfall Analysis Project) grid, which is the grid that the National Weather Service uses for their radar output, and the SHG (Standard Hydrologic Grid). The SHG is an equal area projection, meaning that a given rainfall depth over two separate grid cells will always produce the same volume of rainfall. HEC supports a number of resolutions for the SHG, but suggests using 2000 m for hydrologic modeling. The HRAP grid varies is resolution from about 3.5 to about 4.5 km, depending on your location in the country.

HEC-GeoHMS is able to internally calculate the necessary reprojections to the SHG or the HRAP trids, but the user will need to supply an ArcInfo projection file. This file is needed to convert from DEM projection to SHG projection to intersect with radar rainfall data. An example for UTM Zone 11, NAD 27, which is the projection of the Heppner DEMs, is given below.

```
Projection  UTM
Zone        11
Datum       NAD27
Zunits      NO
Units       METERS
Spheroid    CLARKE1866
Xshift      0.0000000000
Yshift      0.0000000000
Parameters
```

HEC-GeoHMS will ask for this file prior to the creation of a grid-cell file, which allows HEC-HMS to assign the spatial rainfall data to the watershed.

In HEC-HMS, the user will need to determine the correct baseflow, unit hydrograph, loss rates, and routing coefficients to accurately model the watershed's response to a rainfall event. The HEC-HMS *User's Manual* (Scharffenberg 2000) and the *HEC-HMS Technical Reference Manual* (Feldman 2000) do an excellent job of walking the user through these steps.

Gridded rainfall data are imported into the model from a DSS (Data Storage System) file. HEC-HMS will not work operate with time steps that are smaller than the time step for the radar data. Therefore, because small watersheds generally produce fast response times (because the travel length is small), there are limitations to the size of the subwatersheds that one can model if using hourly radar data (such as is available from the National Weather Service).

Data Sources

There are a variety of data sources available for the creation of hydrologic models using HEC-HMS. Below is a short, but comprehensive list:

- Land use/land cover and soil data are available from the Enivronmental Protection Agency (www.epa.gov/OST/BASINS/gisdata.html). Click on your state and locate your watershed and click on *BASINS Core Data* to download data for your watershed.

Note that data are in decimal degrees and will need to be projected to be properly georeferenced with the DEM data. These data can be used to determine the curve number, which can be used to estimate loss rates.

- Rain gage data for California are available free of charge from the California Department of Water Resources (cdec.water.ca.gov/) and for the entire country for a fee from the National Climatic Data Center (www.ncdc.noaa.gov/). Note that data from the National Climatic Data Center are in standard time, even during the daylight hours in the summer. Other local agencies may also offer rain gage data.
- Radar rainfall data are available from the National Climatic Data Center and NEXRAIN Corporation (www.nexrain.com).
- Streamflow data are available from the USGS (waterdata.usgs.gov/nwis-w/US/). The USGS provides daily and peak streamflow data for most gages on this website, however if shorter time steps are required, one should contact the local USGS office. Data are generally on "watch time," which means that the local time does adjust to daylight savings time.
- HEC-GeoHMS and HEC-HMS are both available free of charge from the HEC website (www.hec.usace.army.mil/software/software_distrib/index.html). ArcView® and Spatial Analyst are available from ESRI (www.esri.com) for a cost of about $1200 and $2500, respectively.

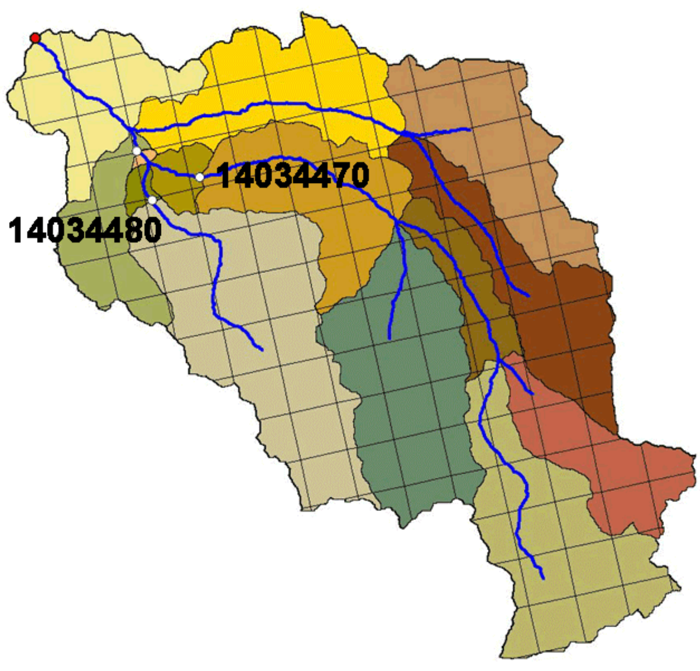

Figure 4: Heppner watershed with 2 km SHG grid and gage locations

Case Study: Heppner, Oregon

The City of Heppner, Oregon is located approximately 200 mi to the east of Porland. On average, the area receives about 18 inches of rainfall a year. In 1903, a severe storm hit the area and the small watershed (approximately 160 mi^2) reached peak flow 15 minutes after the initial rainfall. In addition, almost 300 people died in the storm and over a third of the buildings were swept away. The storm was named the most significant weather event in the state of Oregon during the 20th century (National Weather Service Oregon 2001).

Obviously, radar data were not available for the event, and thus a small storm in May 1998 was chosen for analysis. HEC-GeoHMS was used to define the watershed boundaries for the area and two outlets were manually added at locations of USGS gages (Gages 14034470 and 14034480, seen on Figure 4). Loss rates were estimated by estimating the curve number from soil data and land use/land cover data provided by the EPA. The ModClark method was utilized for basin runoff computations. Time of concentration, T_c, was calculated by estimating the time of flow along the longest flow path and assuming that some of the flow was overland sheet flow (Feldman 2000). The storage coefficient, R, was estimated by assuming that $R/(T_c + R) = 0.667$. Muskingam was used for the routing procedures and travel time was estimated by using the stream length and average slope (which are outputs of HEC-GeoHMS) and by making reasonable assumptions about the channel cross section and Manning's roughness coefficients. The Muskingam X coefficient was set to 0.25 for all reaches.

Recession baseflow was used and coefficients were used that nearly matched the observed flows at the USGS gages. These coefficients (initial runoff per watershed area and the recession coefficient) were set to the same value for all watersheds. All watershed coefficients need to calibrated and validated with multiple storms to produce an accurate model; this was more an exercise to demonstrate the capability of using topographic data with a GIS to create a hydrologic model for use with radar rainfall estimates.

Only one rain gage from the National Climatic Data Center is located within the watershed boundaries and that gage showed only 0.2 in of rainfall during the event, which ran from May 28 to June 10, 1998. However, that small amount of rain did not fall until after the peak flow was measured at each of the two gages. The radar did show some rainfall, but not enough rainfall to produce the peak flows observed at each of the two gages. The radar field was multiplied by a uniform factor at each time step to increase the total rainfall volume observed at the two gages. Adjusting the radar field by an arbitrary factor is not recommended; however, the goal of this project was to demonstrate the potential for modeling spatial rainfall data using a watershed created from HEC-GeoHMS and using the ModClark method in HEC-HMS. Therefore, it was important to make sure that the volume of rainfall was accurate.

The results at the two gages were mixed. At gage 14034480, the radar rainfall model does an excellent job on the overall timing of the storm. The modeled volume appears to be slightly high and recession limbs of the hydrographs to not show a real close match, indicating that that the storage coefficient, R, might need to be adjusted. Note that because only one subwatershed flows into Gage 14034480, there are no routing steps upstream of gage. Figure 5 shows the results for Gage 14034480.

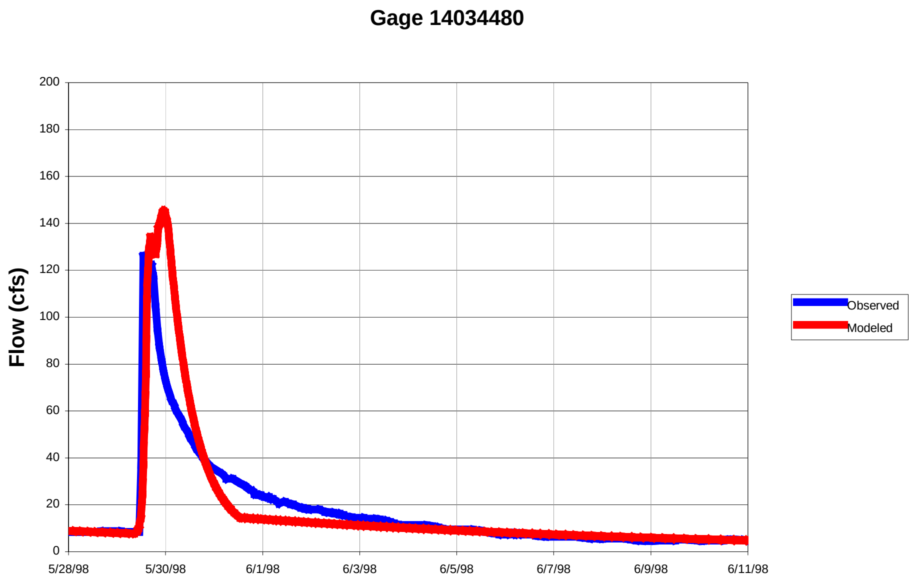

Figure 5: Modeling Comparison at 14034480

The results at Gage 14034470 were not as good. The modeled hydrograph shows a much steeper rise on the hydrograph and the timing seems to be off by almost exactly four days. Given the reported response time of the watershed, there appears be a problem with the timing of the observed gage. There are serious problems with this portion of the model and extensive calibration and validation needs to be completed. There are also two routing steps upstream of the gage, so the routing parameters will need to be calibrated. Figure 6 shows the results of the modeling effort for Gage 14034470.

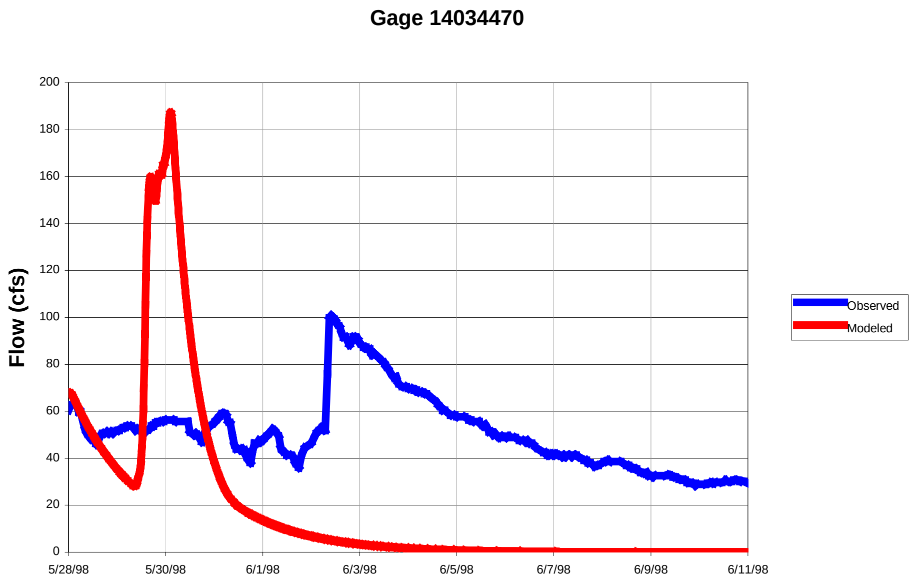

Figure 6: Modeling Comparison at 14034470

Conclusions

The use of HEC-GeoHMS and HEC-HMS allows for the creation of hydrologic models using physical data that are freely available for most watersheds in the United States. HEC-GeoHMS can create a quasi-distributed hydrologic model that, in conjunction with gridded radar rainfall estimates, will be able to accurately model complex rainfall. A case study for a recent storm in Heppner, Oregon shows how easily a model can be created, but also shows the need and importance of extensive calibration and validation to create an accurate hydrologic model.

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