#1261

HYDROLOGIC MODELING

Proceedings of the International Conference on Water, Environment, Ecology, Socio-economics and Health Engineering (WEESHE)

October 18-21, 1999
Seoul National University
Seoul, Korea

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SNOW COVER MAPPING USING AVHRR IMAGES AND GIS FOR SNOWMELT RUNOFF PREDICTION

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ABSTRACT: A procedure is developed that links a geographic information syste (GIS) and remotely sensed data to determine the extent of snow cover in a compl mountainous watershed. Snow cover extent is used in a hydrologic model to predi snowmelt and rainfall produced runoff. A series of programs (AMLs) are used in the G ARC/INFO to reclassify AVHRR satellite data for snow cover extent, and to delinea the watershed boundary and elevation zones. Four GIS data layers (obtained fro AVHRR channels 1, 3, NDVI and derived channel 6) were used in the reclassificati scheme, which identified thresholds for the identification of snow-covered or snow-fr areas. The scheme correctly predicted the presence or absence of snow cover 72% of t time using one evaluation method, and 78% of the time using a different evaluati method. The low resolution of the AVHRR data (1-km pixel size) and the small area analysis probably reduced the accuracy of the results. Other possible inaccuracies in th method may be due to temperature variations that would cause snow to either remain melt sooner or later than expected, low or ice clouds mistaken for snow cover, sno cover under clouds mistaken for clouds, or errors in the climate data. The use of subpix analysis, further validation of the spectral differences between snow, cloud and land AVHRR data using higher resolution satellite images, or ground truthing could refine th procedure.

1. Introduction

Snowmelt runoff prediction generally requires that the snow covered area be know through time. Snow covered area can be determined using remotely sensed data, a which can then be analyzed using geographic information systems (GIS).

Hydrologic modeling frequently includes a snowmelt runoff component. A rece erosion-sedimentation study at the Fort Carson Military Reservation in Colora incorporated a hydrologic modeling component that included snowmelt runoff. Th paper presents the portion of the hydrologic model parameterization involving sno cover extent determination using satellite imagery, geographic information systems (GI map algebra, and graphical analysis.

Located southeast of Colorado Springs, Colorado, in the Front Range of t Rocky Mountains, the Fort Carson Military Reservation (FCMR) is used for hea mechanized training. The environmental management division at Fort Carson, t Directorate of Environmental Compliance and Management (DECAM), has recent identified soil erosion and gullying as problems resulting in land degradation on the ba and sedimentation downstream. To address this problem and achieve their goal of lon term sustainable land use, Fort Carson has undertaken a sedimentation study and erosi control program. Their first step has been to stop the advance of the larger gullies a trap the sediment. This was accomplished over the last several years by constructi earthen dams and sedimentation ponds across the gullies. Approximately 300 su erosion control structures have been constructed to date.

To further control the problem, DECAM has requested that the U.S. Department of Agriculture, Agricultural Research Service, Southwest Watershed Research Center (ARS/SWRC) conduct a study of erosional processes and sediment yield at Fort Carson for the purpose of long-term control and sustainable land use. That study included the selection of several small watersheds for erosion modeling, and characterization of the sediments in one of the larger channels on the base, Red Creek.

To complement and enhance the erosion modeling work, a hydrologic modeling component was investigated that would allow prediction of snowmelt and rainfall produced flows from the adjacent mountains onto the base. This would allow DECAM to evaluate land uses under different climate regimes for long-term sustainable land use and management. Although the hydrology at Fort Carson is rainfall-runoff dominated at its downstream locations, flows in most major streams entering the base have a significant snowmelt component, making it necessary to include snowmelt runoff in the analysis.

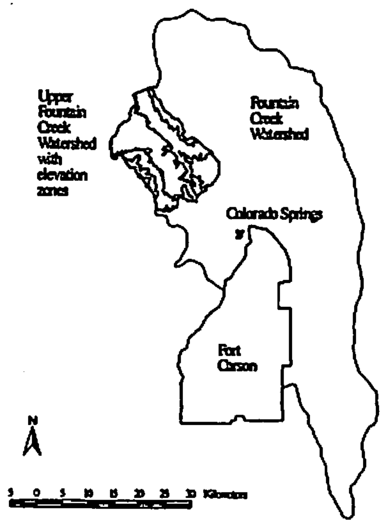

Figure 1. Watershed Location Map

Since there are few gaged watersheds at Fort Carson that could be used in runoff prediction and subsequent erosion analysis, a nearby watershed with adequate gages was needed to begin understanding the rainfall-runoff relationships in the region. The Upper Fountain Creek Watershed, northwest of Fort Carson, was selected for use as a gaged watershed near Fort Carson with significant snowmelt runoff and a long record of weather, sediment, and stream flow data (Figure 1).

1.1. Model Description

The hydrologic model chosen for this analysis was the Martinec-Rango Snowmelt Runoff Model (SRM) version 3.2 (Martinec et al., 1995), because of its ability to simulate both snowmelt and rainfall produced runoff, its small number of required inputs, and its perceived prediction ability. The SRM is an empirically-based, deterministic, degree-day hydrologic model used to simulate and predict daily runoff from snowmelt and rainfall in mountainous regions. The model computes the daily discharge from the basin by calculating the water produced from snowmelt and rainfall, and adjusting that amount by the calculated recession flow. The water produced from snowmelt is calculated by adjusting the degree-day factor, snow covered area and daily temperature by the snowmelt runoff coefficient. The water produced from rainfall is calculated by adjusting the daily precipitation by the rainfall runoff coefficient. To determine the daily discharge, the two amounts of water are added together, multiplied by a conversion factor, adjusted by the recession coefficient, and added to the previous dayʼs discharge. Daily variables and parameters are entered by elevation zone or for the entire basin. For this study the data was entered by elevation zones. To calculate snowmelt runoff, the SRM requires the snow covered area, and the snow depletion curve, of the watershed be determined for the time period of analysis, which was five years in this case (1989 ñ 1993).

1.2. Upper Fountain Creek Watershed Description

The Upper Fountain Creek Watershed, the watershed used for this analysis, is located approximately 15 km northwest of Colorado Springs and Fort Carson (Figure 1). It is described for the purposes of this paper as the drainage basin above the USGS gaging station number 07103700, "Fountain Creek near Colorado Springs" (N38°51'17" W104°52'39", 1860 m, 6110 ft gage datum). The watershed is 263 km^2 (101 mi^2) in area. Pikes Peak at 4,300 m (14,110 ft) is the highest point on the watershed. Vegetation cover ranges from forests and woodlands to tundra and rock outcrop. Approximately 80% of the land area is in the Pike National Forest. Land uses include forestry, roads, recreation and water supply.

2. Snow cover analysis

Snow cover extent can be determined using a geographic information system (GIS) and remotely sensed data. NOAA-11 AVHRR (Advanced Very High Resolution Radiometer) (USGS EROS Data Center, 1993) 1-km resolution satellite images were chosen for this project because of their low cost, and high temporal availability. The daily observations are calibrated, geo-referenced, and compiled by the U.S. Geological Survey's EROS (Earth Resources Observation Systems) Data Center into biweekly composites (USGS EROS Data Center, 1993). The geographic information system ARC/INFO[1] was used to analyze the AVHRR data for determination of snow covered area, and also aided in the delineation of the watershed and elevation zones.

The snow-cover extent for the watershed was determined through a series of programs written in the Arc Macro Language (AML) programming language of ARC/INFO. Known as AMLs, these programs were used to analyze the AVHRR images and reclassify them into two land cover types: snow-covered and snow-free. The AMLs were also used to calculate the amount of snow covered area in each elevation zone.

Although the composited AVHRR images produce virtually cloud-free images (USGS EROS Data Center, 1993), separation of clouds from snow has been a concern in this type of reclassification because clouds appear similarly to snow in satellite images. To ensure that the clouds were removed, this potential problem was investigated further. Various methods can be found in the literature that separate snow from clouds using AVHRR data (Simpson et al, 1998; Holroyd et al, 1989; Allen et al, 1990; Kidder and Wu, 1984; Derrien et al, 1993, and others). The method used here for reclassification

[1] Mention of a trade name is provided for convenience of the reader only and does not imply endorsement by the authors or any of the cooperating agencies and organizations.

was based on procedures described by Holroyd et al. (1989), Szeliga (1997), and alluded to in Derrien et al (1993).

These methods require the use of several AVHRR channels (or bands) and include a new channel created by subtracting channel 4 (11 *um*) from channel 3 (3.7 *um*). Subtraction of channel 4 from channel 3 is useful in the separation of snow from clouds due to the difference in the way radiance is recorded for the two channels. Snow and clouds have similar but slightly different spectral responses for channels 3 and 4 in AVHRR data. Channel 3 radiance includes both solar reflection and thermal emission components (Allen et al, 1990; Derrien et al, 1993; Holroyd, 1989) and the resulting reflectance values are low for snow and much higher for clouds due to their higher water vapor content. Channel 4 records emitted (thermal) radiation but is different from channel 3 in that cloud temperatures are colder (lower) than snow temperatures (Simpson et al, 1998). This difference in the spectral response can be used for separation of clouds from snow.

Subtracting channel 4 from 3 will remove most of the thermal component from channel 3 (Holroyd, 1989), leaving mainly reflected radiation (from snow), and producing a new image where lowest values indicate snow. The result of this subtraction in this research was identified as channel "6", and was used as a key component in the development of a new method for snow cover classification. To simplify the reclassification of snow cover, only the two highest elevation zones above timberline (above 3,475 m) on the Upper Fountain Creek Watershed were used. These elevation zones represent 6% of the total watershed area. Land cover types here are limited to snow cover, rock outcrop, paved surfaces, buildings, or grasslands (tundra).

Determination of a threshold value for each channel was required to separate snow covered pixels from snow free pixels. To perform this separation, 4 channels were used in this analysis: 1, 3, 6, and NDVI (Normalized Difference Vegetation Index, calculated from channels 1 and 2). The GIS was used to extract the mean values from each of the four channels for all 21 AVHRR scenes per year. These values were then plotted against each other in four combinations:

channel 1 vs. channel 6
channel 1 vs. NDVI
channel 6 vs. NDVI
channel 3 vs. NDVI.

To understand why these combinations are valid, an explanation of the values for each channel follows. Channel 1 measures visible reflected radiation, where snow has slightly higher values than clouds. Channel 3 measures solar reflected and thermal emitted radiation, where snow has higher values than clouds. Channel 6 is a calculated index of the difference between channels 3 and 4, where clouds have higher values than snow. NDVI measures the presence or absence of vegetation, where high values indicate healthy vegetation and low values indicate snow or bare soil (Lillesand and Kiefer, 1994).

Since each channel separates snow from other land cover or clouds, the plots provided a graphical method of analyzing the scenes throughout the year. It was assumed that the snow season scenes would be snow covered, providing a basis for identification of the thresholds for snow.

Thus, the resulting plots were analyzed for trends or clusters in the data. Upon inspection, it was determined that the snow season scenes were generally clustered together, allowing a line to be drawn separating the snow-covered vs. snow-free scenes.

This line, called the threshold value, was identified for each channel for snow cover or snow-free determination (Figure 2). The threshold values identified for snow cover were:

channel 1 >= 34
channel 6 <= 60
channel 3 <= 168
NDVI <= 0.28

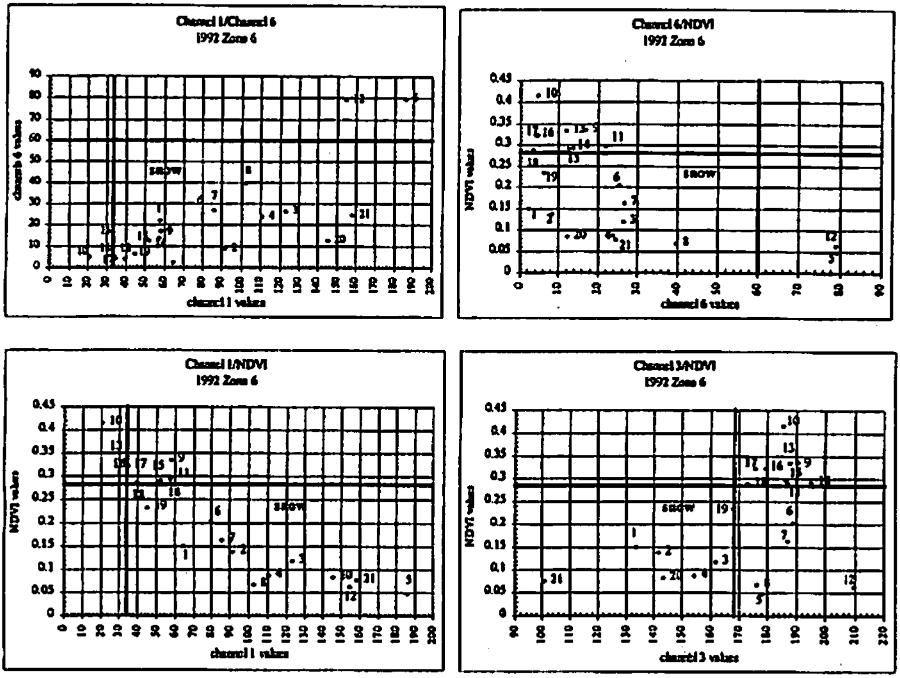

Figure 2. Sample Plots for 1992 showing each AVHRR scene and the Threshold Lines, with scenes numbered from 1 to 21 (January to December)

It should be noted that the above values are not the raw values obtained from the AVHRR satellite data. They have been normalized, converted to brightness temperatures and then converted to byte data in the EROS AVHRR composited data (USGS EROS Data Center, 1993).

It is also important to note that in order for a pixel (grid cell) to be reclassified as snow, all four of the threshold conditions must be met, i.e. all four threshold values must be used together to reclassify for snow cover. They cannot be used singly as a means of determining the presence or absence of snow in a single channel. This is due to the difficulty in discriminating between water, ice clouds, clouds and snow in any one channel (Allen et al, 1990).

Eleven primary AMLs were used to perform the complete analysis from image rectification to final calculation of snow covered area. Each AML contained a separate step for improved error checking. Several other AMLs, not listed here, moved or deleted files for file management. A brief description of each AML is included below. (Note:

these operations were performed on all 21 scenes for each of the five years of analysis.)

AML #1. Rectify the AVHRR scene that has already been clipped from the US Conterminous data, and manually registered.
AML #2. Convert the image into a grid.
AML #3. Project the grid to UTM coordinates.
AML #4. Calculate channel 6 from channels 3 and 4.
AML #5. Resample each channel (1, 2, 3, and 6) to improve area analysis.
AML #6. Calculate the NDVI from channels 1 and 2.
AML #7. Extract the statistics for channels 1, 3 and 6 for the graphical analysis and threshold value determination.
AML #8. Extract the statistics for the NDVI for the graphical analysis and threshold value determination.
AML #9. Reclassify each channel based on the threshold values from the graphical analysis for snow covered or snow free land cover.
AML #10. Test each elevation zone for presence of snow.
AML #11. Calculate the amount of snow covered area for each elevation zone with snow, and save the data to a file.

3. Validation and error analysis

The results of the classification were analyzed with two methods and each set of results was then placed into an error matrix. A summary of the results is presented in Table 1. Method number 1 used a random number generator to select 20 dates from each year.

Table 1. Error matrix, AVHRR reclassification results for 1989 – 1993

Method 1: time period of analysis: one week prior to and after 20 randomly selected dates for all 5 years (100 data points)

		percentage		total count	
AVHRR data	snow	34	10	34	10
	snow-free	18	38	18	38
72% correct prediction		snow	snow-free	snow	snow-free
		EarthInfo snow data			

Method 2: time period of analysis: 21 AVHRR scenes for 5 years (105 data points)

		percentage		total count	
AVHRR data	snow	41	8	43	8
	snow-free	14	37	15	39
78% correct prediction		snow	snow-free	snow	snow-free
		EarthInfo snow data			

These dates were compared to the closest AVHRR scene for each of the five years of analysis. Using the "snowfall" data from the climate data sets available on CD-ROM from EarthInfo, Inc[2]. (consisting of data from the National Climate Data Center and U.S. Geological Survey), as a reference, it was assumed that there was snow cover if snow fell in the week prior to or after the randomly selected day. In addition, the overall trend of snow fall was considered in determining the presence or absence of snowpack. These results were compared to the AVHRR analysis results for each scene. The total number of agreements (both snow cover or both snow-free) was tabulated along with the total number of disagreements.

Method number 2 used the twenty-one composited AVHRR scenes as the time period of analysis. For example, AHVRR scene 1 for 1989 includes the dates from January 4 through January 17 (14 days). A similar method of tabulation to Method number 1 was performed using the EarthInfo snowfall data (presence or absence of snow fall, and overall trend of snow fall) and the AVHRR analysis (presence or absence of snow cover).

When only a small amount of snowfall was recorded (i.e. 0.1 in.) during the time period of analysis, and there had been no prior significant snowfall (i.e. no existing snow cover), then that observation was not counted as snow-covered. This technique assumes that when snow falls at the climate station it fell on the entire elevation zone used for the analysis.

Although channel 6 was intended to remove most of the clouds, several summer scenes were identified by the classification scheme as having snow cover. To determine if these results were due to clouds, a comparison was conducted using the precipitation data and the results of the snow cover analysis. When analyzing the precipitation data, it was assumed that extended sequences of rainfall during the summer months have a high likelihood of cloud cover associated with a storm. For those storm events, it was then assumed that what was reclassified as snow was actually cloud cover, and those scenes were considered to be snow-free in the analysis.

The results showed that the AVHRR reclassification procedure correctly predicted the presence of snow cover 34 percent of the time using Method 1, and 41 percent of the time using Method 2. The absence of snow cover was correctly predicted 38 percent of the time using Method 1, and 37 percent of the time using Method 2, giving a total of 72 to 78 percent correct predictions. These results are consistent with previous research (Tait, 1994; Allen et al, 1990) using ground truthing or training on higher resolution satellite data such as Landsat.

4. Summary and Conclusions

Research was conducted to develop a new method of reclassifying AVHRR satellite imagery for snow cover with a GIS for use in the Martinec-Rango Snowmelt Runoff Model. Five years of AVHRR images were analyzed and reclassified using a series of GIS programs (ARC/INFO AMLs). A "new" channel, called channel 6, was calculated from channels 3 and 4 to aid in the separation of snow from clouds. Four channels were then analyzed (1, 3, 6, and NDVI) to define threshold values that differentiated between snow covered and snow-free land. Threshold values were determined graphically and then applied in the GIS to reclassify each AVHRR scene into "snow" or "snow-free" areas. The percent snow covered areas were then calculated in the GIS for each elevation zone using the results of the reclassification.

The success of the reclassification was determined by inspection of the agreement

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between the AVHRR snow cover scenes and the actual snowfall data. The results showed that the reclassification scheme correctly predicted the presence or absence of snow cover 72 — 78 percent of the time, depending on which method of analysis was used.

The advantages of this method are the ease of acquisition of the required data (AVHRR and climate data), and that no additional satellite data such as Landsat TM are required. In addition, the entire reclassification can be performed in a short period of time for the entire year using the AMLs developed during this research.

The low resolution of the AVHRR data (1-km pixel size) and the small area of analysis probably reduced the accuracy of the results. New methods under development, such as subpixel analysis, could improve these results. The method presented in this paper allows a pixel to be identified only as either snow-covered or snow-free. Subpixel analysis would allow an individual pixel to be divided into percent snow-covered and percent snow-free, greatly increasing the accuracy of this type of analysis (Rango, 1999).

Other possible inaccuracies in this method may be due to temperature variations that would cause the snow to either remain or melt sooner or later than expected, low or ice clouds mistaken for snow cover, snow cover under clouds mistaken for clouds, or errors in the climate data. Further investigation of the spectral difference between water and ice clouds would also make this method more accurate. Ground truthing would improve and refine the threshold values, as would validation with Landsat or other high-resolution satellite images.

5. Acknowledgments

Funding and support for this research was provided through the cooperative efforts of the USDA-ARS Southwest Watershed Research Center, Tucson, Arizona, The University of Arizona, Tucson, Arizona, and the US Army, Fort Carson Military Reservation, Directorate of Environmental Compliance and Management, Fort Carson, Colorado.

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