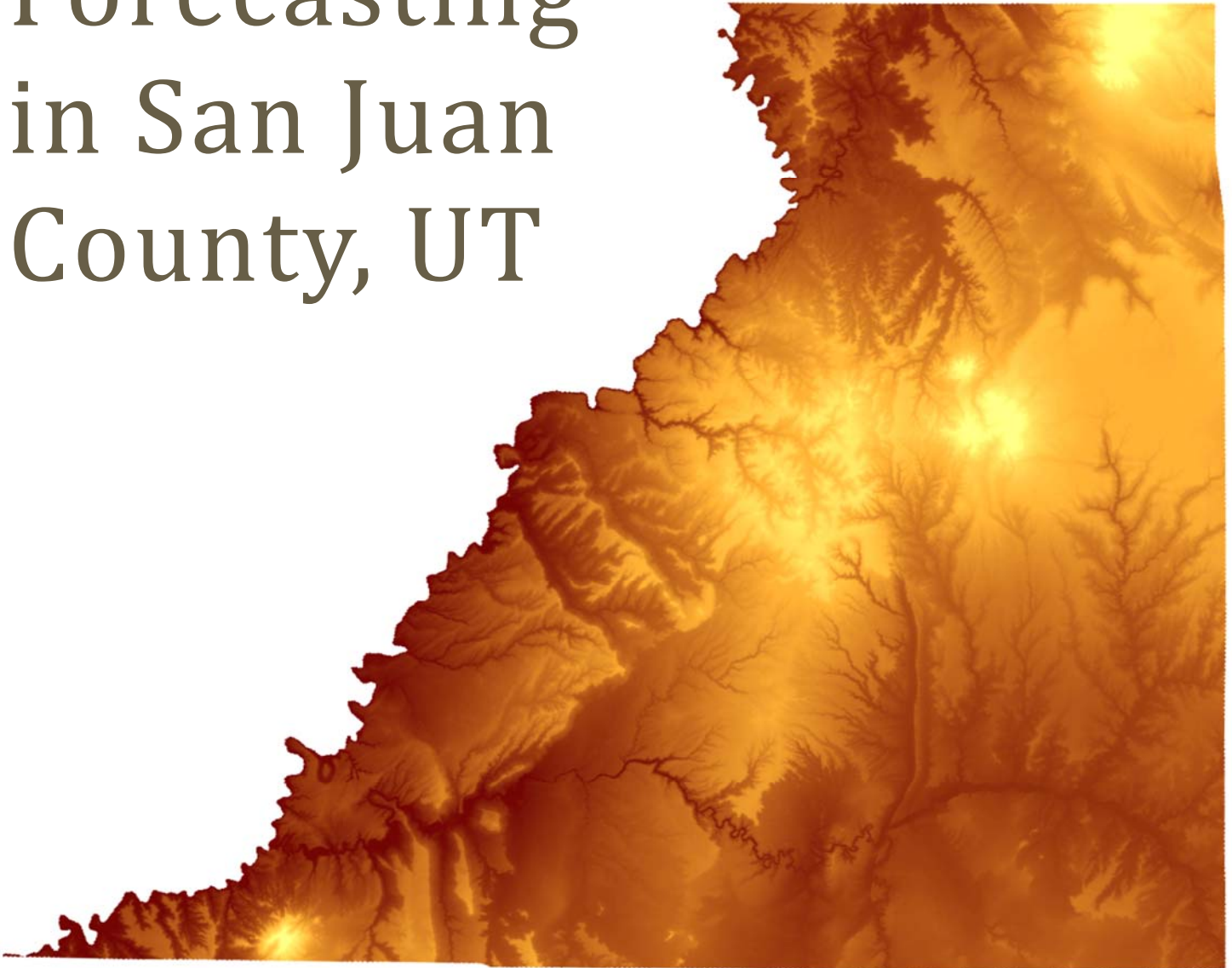

Snowfall Runoff Forecasting in San Juan County, UT



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Introduction

Objective

Lloyd's Lake and Recapture Reservoir are reservoirs in central San Juan County, UT and are fed by mountain streams from the Abajo Mountains (locally known as the Blue Mountains). These reservoirs support agriculture, recreation and other secondary uses for the communities of Monticello and Blanding. Like much of the Intermountain West, snow water is a crucial part of the annual water budget of this region. In an effort to assist local water managers, this report summarizes an effort to use Geographic Information Systems (GIS) to establish a snowfall runoff prediction model for this system.

Geography

San Juan County is located on the Colorado Plateau with a mean elevation of 1728 meters (5670 feet) above sea level. The region is semi-arid and the landscape is a spectrum of steep red rock canyons and windswept mesas covered with sage brush to high mountains with ponderosa pine and quaking aspen. Notable landmarks in and bordering the county include Canyonlands National Park, Monument Valley Tribal Park, the San Juan River and the Colorado River (including Lake Powell).

The population center is in the central part of the county at the base of the Abajo Mountains, with Blanding on the south and Monticello on the northeast. A number of reservoirs supply these communities with water for various uses, but the largest two (Recapture Reservoir near Blanding and Lloyd's Lake near Monticello) are the subject of this study. A map of this region is shown in Figure 1 on the following page.

On the north side, a stream gauge on South Creek is at the inlet of Lloyd's Lake. The nearest SNOTEL station (see Available Data on page 3) at Buckboard Flat is approximately 1.4 miles northwest of the watershed for South Creek.

On the south side, a stream gauge is on Recapture Creek approximately 6 miles upstream of Recapture Reservoir. A SNOTEL station at Camp Jackson is approximately 0.6 miles west of the watershed for this gauge. With the gauge so far upstream of the reservoir, there are other tributaries—most notably Johnson Creek—which contribute significant ungauged flow to the reservoir. The SNOTEL station at Camp Jackson is in the watershed for the reservoir.

Furthermore, a tunnel has been dug through the mountain to bring water from Indian Creek on the north side to the much dryer Johnson Creek watershed on the south side. The Buckboard Flat SNOTEL station is approximately 1.4 miles to the northeast of this watershed.

This leaves four watersheds of interest, two stream gauges and two SNOTEL sites in the study area. These are included on the following map.

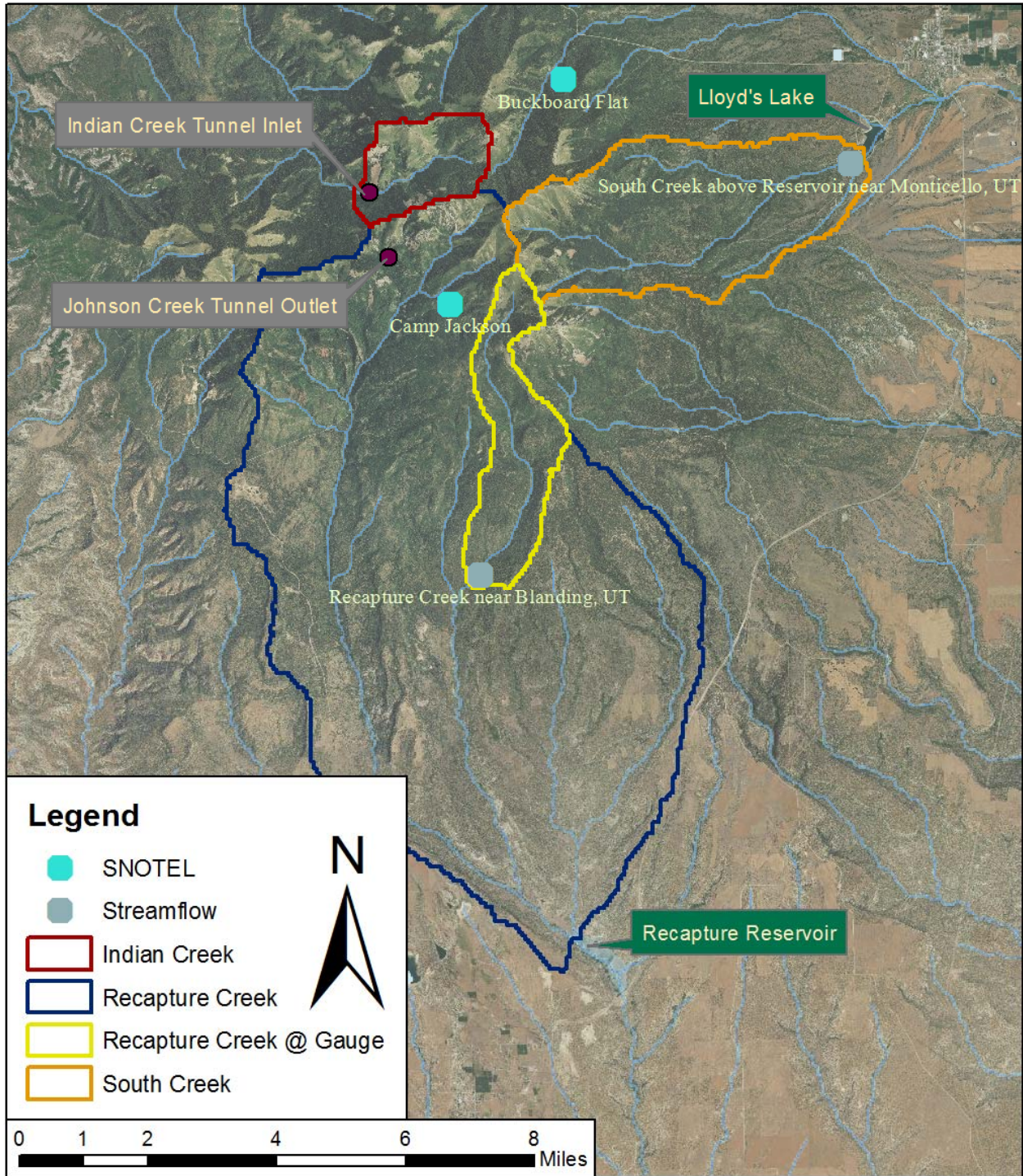


FIGURE 1. LOCATION MAP

Methodology

The model was developed entirely using historical data. It was hoped that doing so would account for variables like soil moisture and weather in an implicit way. This simpler analysis was preferred, given the nature of the project as a semester-length attempt with an emphasis on GIS rather than hydrology. The steps completed for the development of the model are described below.

Available Data

A major constraint in developing this model was the availability of data. The datasets used are described individually below.

SNOTEL (Snow Telemetry) is a system of data collection stations operated by the National Resource Conservation Service (NRCS) in the western U.S. and Alaska. It consists of a network of remote stations that collect data related to snow water (e.g. snow water equivalent (SWE), soil moisture and weather conditions) and report the data in near real-time (1). The station at Buckboard Flat has been online since May 2012 and the station at Camp Jackson has operated since October 1985. The data gathered from these sources include daily mean SWE (in inches) for the period of record.

The U.S. Geologic Survey (USGS) operates a network of stream gauges that record stream stage and flow rate on a continuous basis. The gauge on Recapture Creek has been operational since October 2007 and the gauge on South Creek has been online since October 1985. Daily mean flow rate for the period of record was collected from each of these gauges.

SNODAS (Snow Data Assimilation System) is a data product produced by the National Operational Hydrologic Remote Sensing Center (NOHRSC) of the National Weather Service. It is a “modeling and data assimilation system ...to provide the best possible estimates of snow cover and associated variables to support hydrologic modeling and analysis”. It provides 1 km resolution estimates of snow data across the U.S (1). The data collected from this system include daily (for October 1-April 30 for each water year studied) snow water equivalent estimates over the study area.

The geography on the north and south slopes of the mountain was considered different enough (on account of solar exposure) to warrant separate analysis. Data from Buckboard Flat SNOTEL and South Creek stream flow were used for calculations for Indian Creek and South Creek watersheds. Camp Jackson SNOTEL and Recapture Creek were coupled to analyze the two Recapture Creek water sheds. Pairing the data stations like this limited the temporal applicability of data in both cases: analysis on the north was limited by the Buckboard Flat SNOTEL (beginning May 2012) and analysis on the south was limited by the stream gauge on Recapture Creek (beginning October 2007).

Model Development

The desired end-user process diagram is shown in Figure 2. The goal is to allow the user to take a SNOTEL SWE reading from the SNOTEL website, enter it into an Excel sheet (represented by the black box) and receive output as a predicted runoff value for a given watershed. Inside the “black box” the SNOTEL measurement is first adjusted to correlate to the SNODAS model. That output is then adjusted to account for the spatial variation of snowfall (single point to areal average) in the watershed. This

average SWE value can then be multiplied by area to get an available volume, then by a runoff coefficient to get predicted runoff.

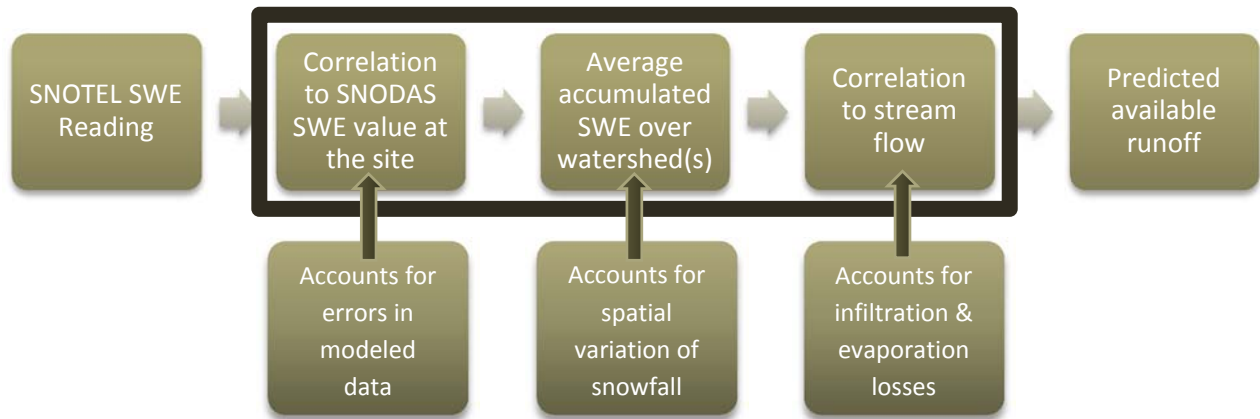


FIGURE 2. END USER PROCESS DIAGRAM

To establish the first correlation (SNODAS to SNOTEL SWE at each SNOTEL site) the SNODAS rasters were processed to retrieve the SWE value at each of the coordinates then write the result to a text file. A simple correlation was made by plotting the values against SNOTEL values. Further discussion on this correlation is given in the following section.

The analysis for spatial variation of snowwater required the daily mean SWE value in each watershed, calculated using the SNODAS rasters. As before, the output was written to a text file and then plotted against the SNODAS SWE value at the respective SNOTEL site. Regression analysis was then used to establish a correlation.

The correlation of watershed available volume to stream flow proved to be one of the most rigorous aspects of the project. The decision was made to base available volume off of accumulated snow water over the season. Using the maximum values would likely have been a simpler task, with near results, but using the accumulated snowfall controlled for any snow melt (and runoff) between snow storms, especially in the late season. This approach required taking the first raster in the file list and finding where the net difference in the succeeding raster was positive (where snow fell). This process was repeated for each raster, with the result of each being summed to produce a final cumulative snowfall raster over the entire area. Each watershed boundary was then used as a “cookie cutter” to extract the data for each watershed to its own raster. This process was repeated for each year of the study.

The stream flow data came as daily average flow rate. The flow rate was converted to total daily volume and then seasonal totals (March 1 – May 31) were plotted against total volume available calculated from the SNODAS data, as described above. This correlation was made once for each of the two watersheds with stream gauges, with the intent to apply the same correlation to the other two watersheds on their respective sides of the mountain.

It should be noted that the SNODAS data were processed using Python scripting (especially utilizing the arcpy module) and the scripts are included herein as Appendix A. SNOTEL and streamflow data, together

with correlations to SNODAS data, were processed using Excel. ArcGIS was used to verify results of the scripts, do simple processing such as watershed deliniation and present spatial data.

Data Analysis

Intially, the correlation between SNODAS and SNOTEL (as described in the previous section) was made using data from October 1 – April 30 for each water year because it was assumed that this date range would adequetly capture the snowfall accumulation season. However upon plotting the data, it was observed that late in the season the correlation became very weak. For this reason, the time frame was adjusted to October 1- March 31 anually. The correlation proved to be much stronger. Thus, the results of the model should only be considered valid for SNOTEL readings taken during this time frame. The results for the correlations at each of the SNOTEL sites are shown in Figure 3 and Figure 4. The data were correlated with a linear fit with a y-intercept of zero. Esentially, this provides a simple coefficient to correlate SNOTEL and SNODAS.

Camp Jackson SWE Correlation

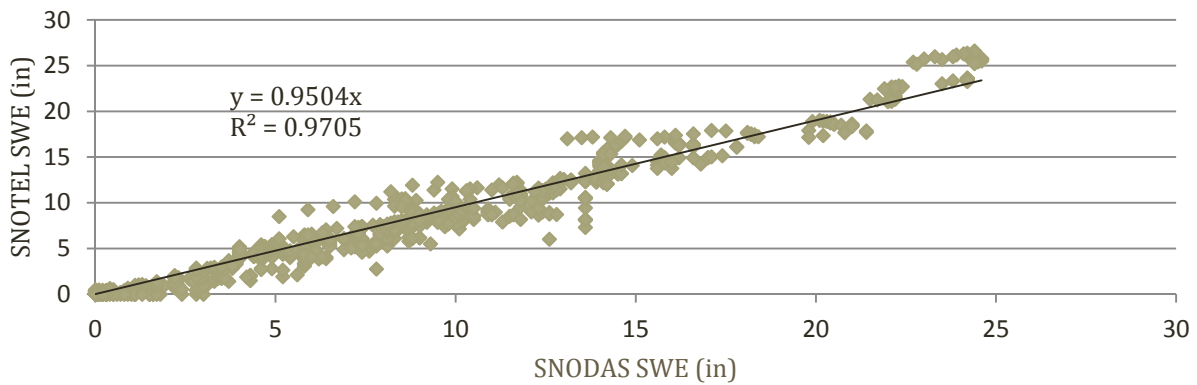


FIGURE 3. CAMP JACKSON SWE CORRELATION

Buckboard Flat SWE Correlation

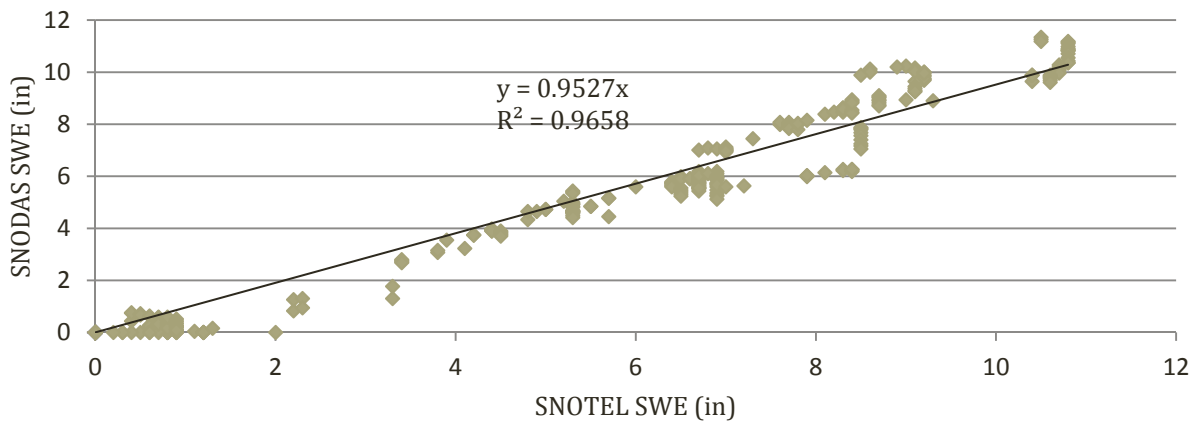


FIGURE 4. BUCKBOARD FLAT SWE CORRELATION

The correlations for spatial variation of snow water to the point measurements at the SNOTEL sites are shown in Figure 5 and Figure 6 below. For the sake of consistency, the values reported at the SNOTEL sites are actually from the SNODAS model. To keep in line with the previous correlations, the date range used for these correlations was October 1 – March 31. The regression was performed using a 2nd order polynomial, except for the South Creek watershed, which used a 3rd degree polynomial. These lines appeared to provide the best fit to the data over the given range. The correlation equations should not be considered valid outside of the range of the given data—especially since trends in polynomials can vary quickly, inconsistent with naturally observed phenomena.

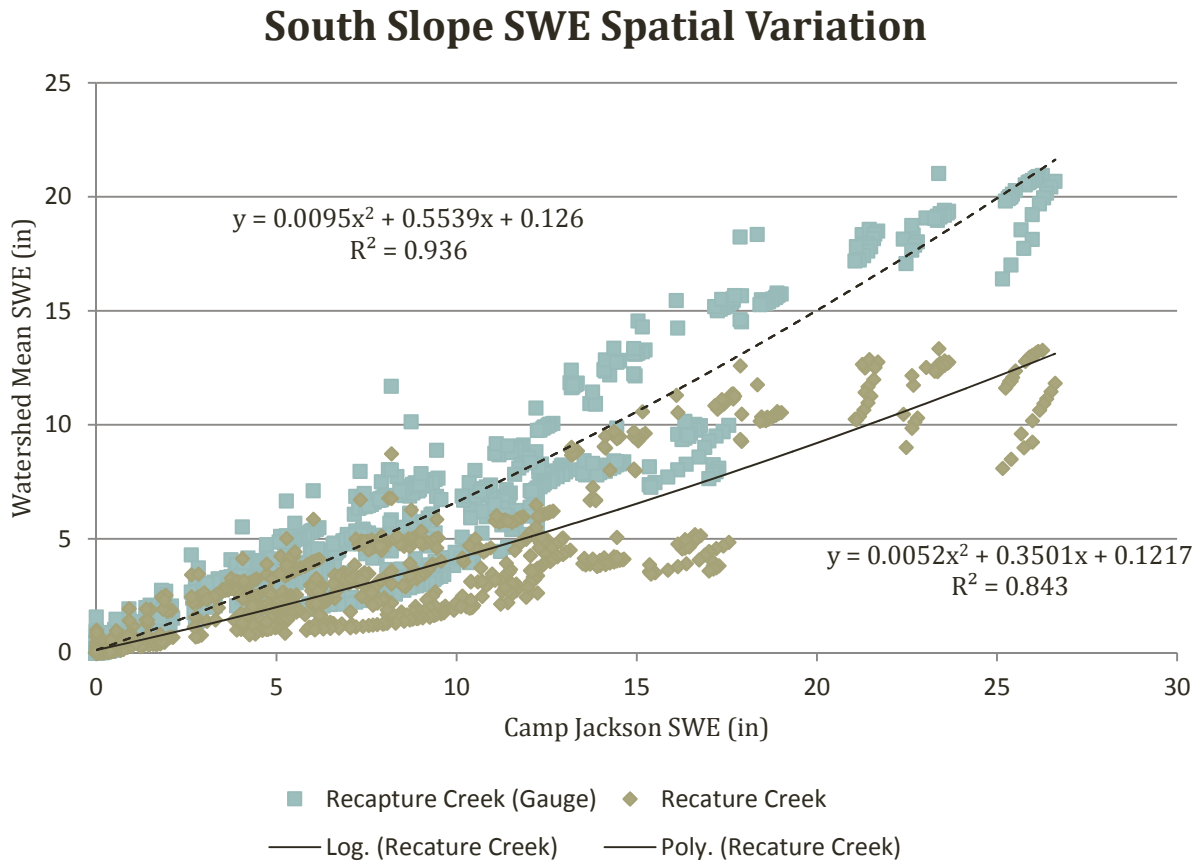


FIGURE 5. SOUTH SLOPE SWE SPATIAL VARIATION CORRELATION

North Slope SWE Spatial Variation

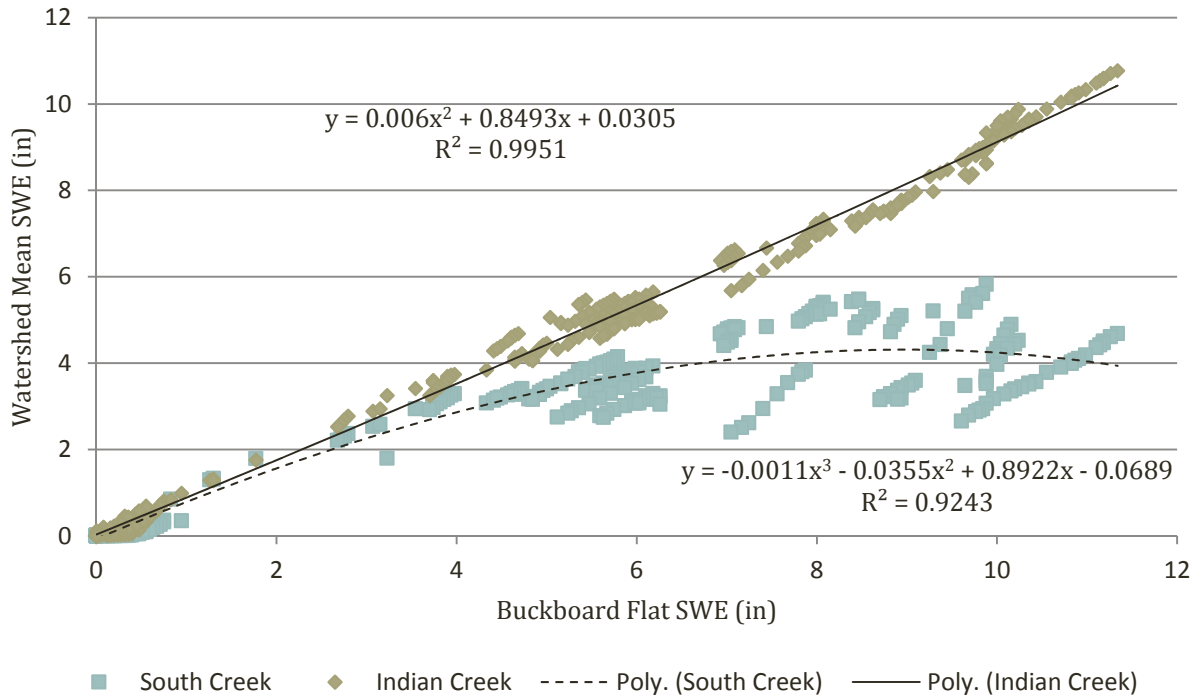


FIGURE 6. NORTH SLOPE SWE SPATIAL VARIATION CORRELATION

The results from the accumulated SWE calculations are given in Table 1. The results shown are the average SWE in each water shed in units of millimeters.

TABLE 1. SNODAS WATERSHED MEAN CUMULATIVE SWE

SNODAS Watershed Mean Cumulative SWE (mm)				
	South Creek	Recapture Creek (ga.)	Recapture Creek	Indian Creek
2008	613	239	176	505
2009	398	892	655	478
2010	642	544	399	299
2011	415	802	654	512
2012	393	631	420	304
2013	348	564	416	317
2014	304	539	333	260

A sample map showing this data for water year 2014 is shown in Figure 7.

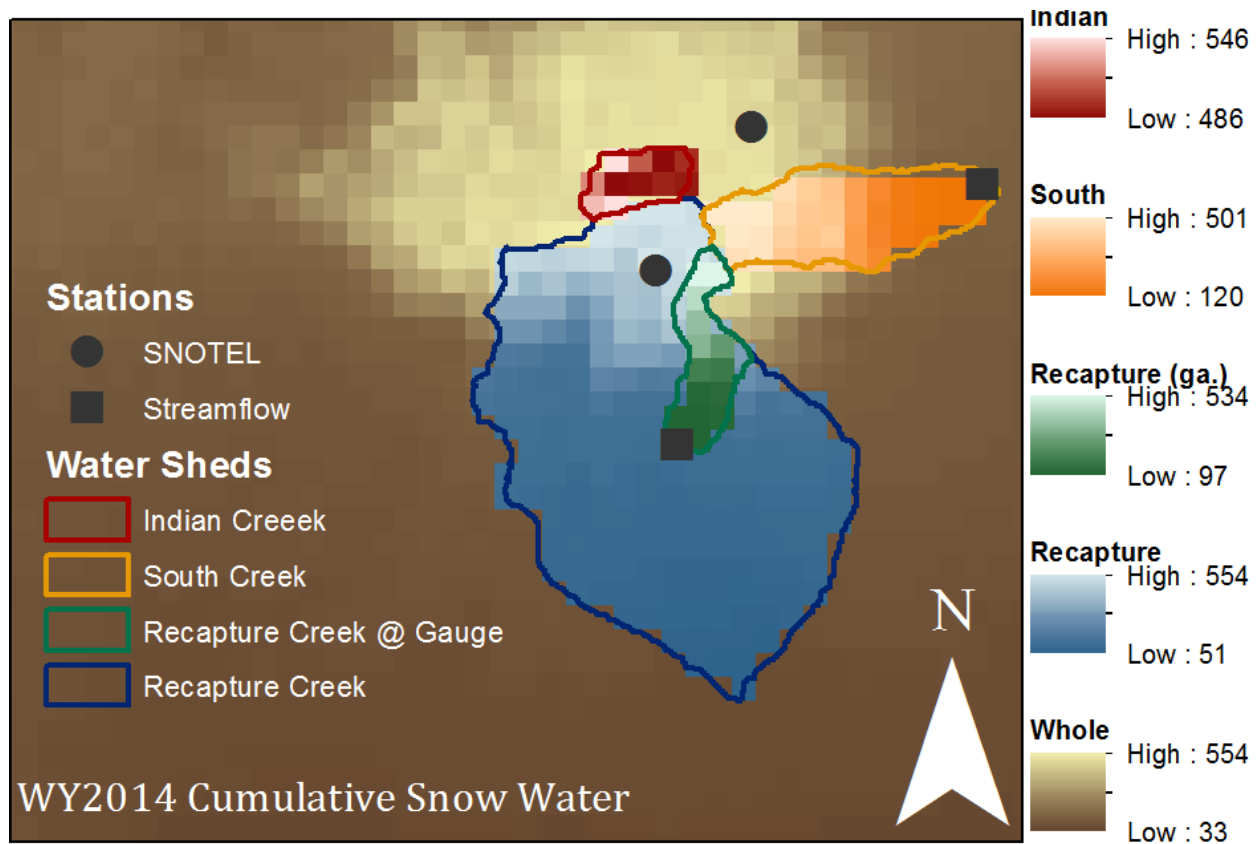


FIGURE 7. WATER YEAR 2014 CUMULATIVE SNOW WATER MAP

These depths were multiplied by the areas of their respective watersheds, then divided by the appropriate SNODAS-SNOTEL correlation coefficient (as described previously) to produce a total water volume available. A table of individual watershed areas is shown in Table 2 and the available snow water volume is given in Table 3.

TABLE 2. WATERSHED AREAS

	South Creek	Recapture Creek (ga.)	Recapture Creek	Indian Creek
Area (km ²)	142.66	26.83	11.51	6.64
Area (acres)	35252	6629	2844	1641

TABLE 3. MODELED WATERSHED AVAILABLE SWE VOLUME

Modeled Watershed Available SWE Volume (acre-ft)				
	South Creek	Recapture Creek (ga.)	Recapture Creek	Indian Creek
2008	22,700,000	1,700,000	500,000	900,000
2009	14,700,000	6,200,000	2,000,000	800,000
2010	23,700,000	3,800,000	1,200,000	500,000
2011	15,400,000	5,600,000	2,000,000	900,000
2012	14,500,000	4,400,000	1,300,000	500,000
2013	12,900,000	3,900,000	1,200,000	500,000
2014	11,300,000	3,800,000	1,000,000	400,000

The stream gauge readings for each are shown in Figure 8. The data clearly show the seasonal nature of these stream flows.

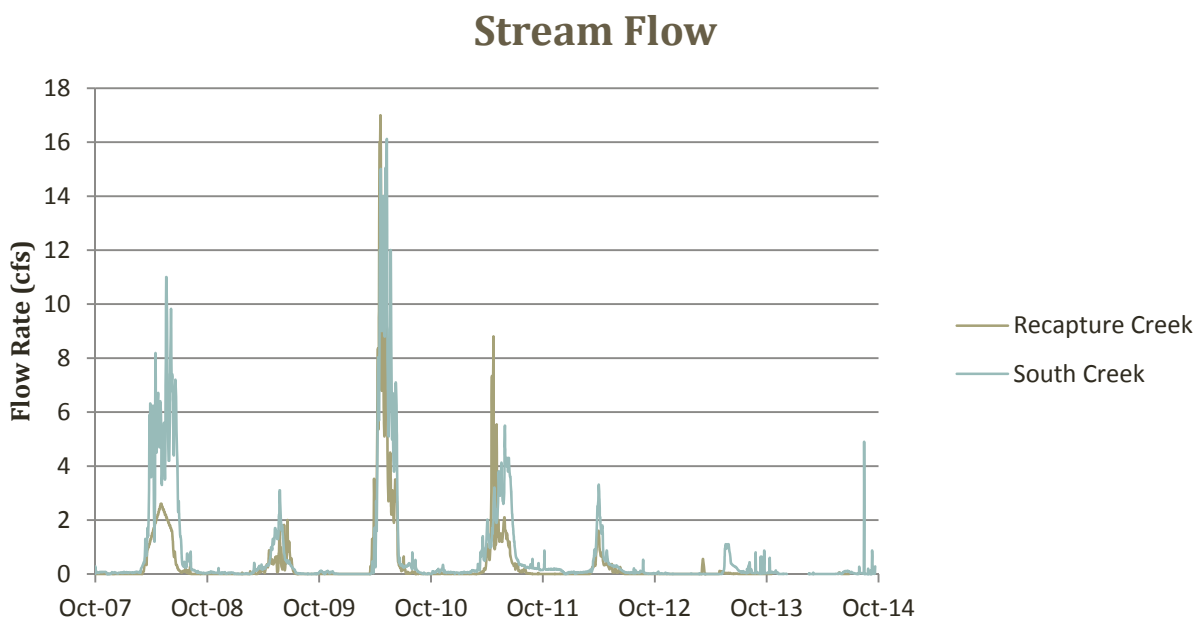


FIGURE 8. STREAM GAUGE READINGS

The volumes for the watersheds with gauges were plotted against the spring runoff volumes given from their respective gauges. The results are shown in Figure 9 and Figure 10.

Recapture Creek Runoff Correlation

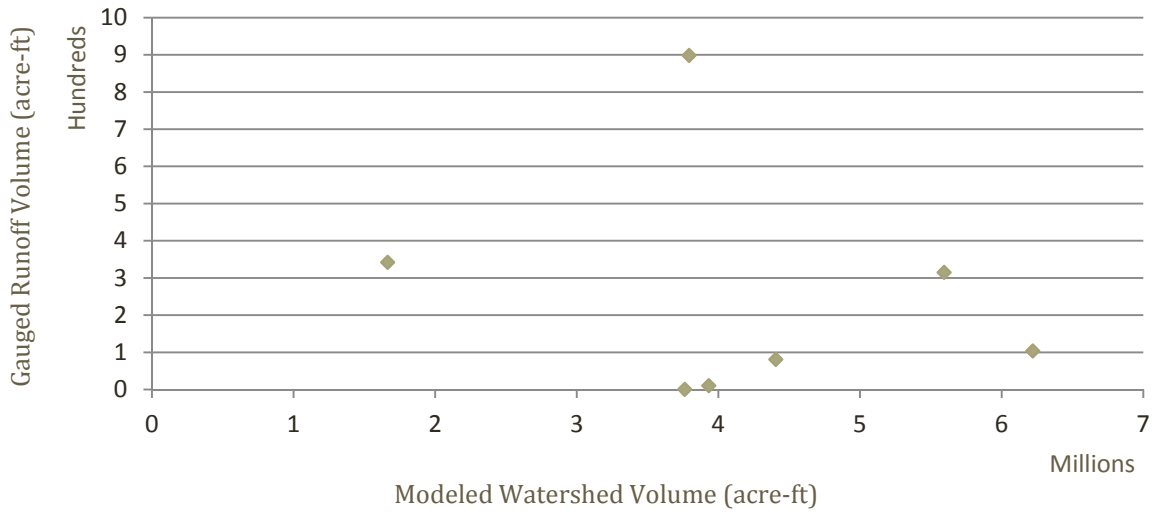


FIGURE 9. RECAPTURE CREEK RUNOFF CORRELATION

South Creek Runoff Correlation

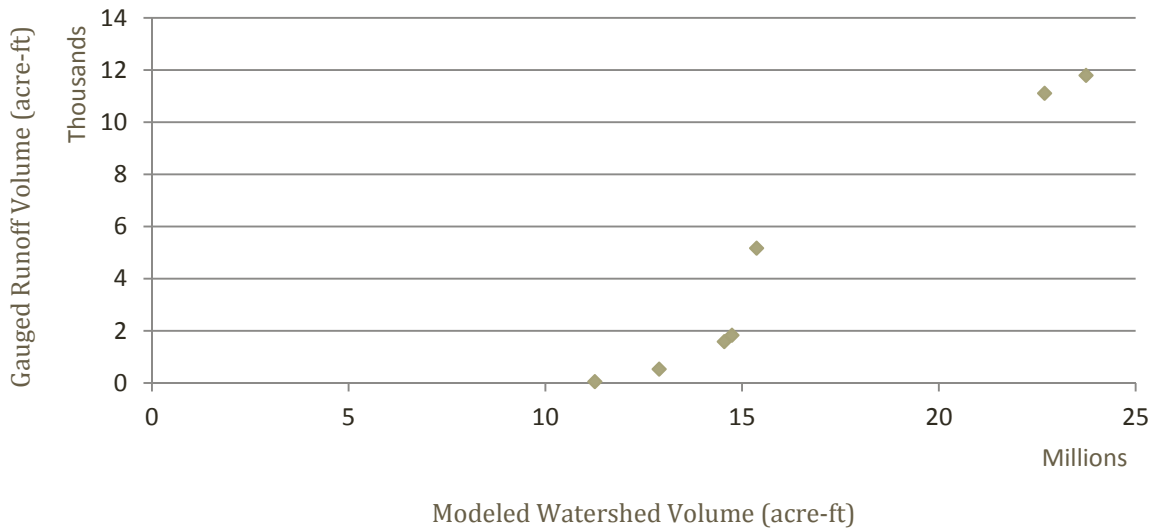


FIGURE 10. SOUTH CREEK RUNOFF CORRELATION

As can be seen from this data, the correlation is ineffective in both cases. For Recapture Creek, the spread is wide and there is no clear correlation. For South Creek, there is a strong correlation between the data points, but the y-axis intercept should theoretically be near zero, which it clearly is not. For these reasons, a correlation between watershed volume and stream flow was not attempted.

Discussion

The model could not be completed as desired as completed due to a lack of correlation between modeled watershed available volume and stream flow. However, the model provides reasonable accuracy before that step. So the model may be used to find an estimate of water volume available in the watersheds. Before the model is very useful, though, a correlation must be established to predict the runoff ratio.

The next most important parameter to consider is soil moisture. SNOTEL stations provided soil moisture readings which could readily be incorporated into the analysis. It is interesting to note a strong correlation between watershed volume and runoff on the north side (with less solar exposure) but a significantly less correlation on the south where solar exposure is much greater. Assuming soil moisture is heavily influenced by solar exposure (due to evaporation), it would be expected that lower exposure correlates to more stable soil moisture and thus less dependence of on runoff soil moisture. This is perhaps evidence of the critical role of soil moisture in runoff forecasting.

The lack of soil moisture data may also explain the issues with the correlation for South Creek shown in Figure 10. The data seem to indicate a large amount of volume is needed before any runoff is possible. This difference could be explained by infiltration losses.

After soil moisture, other parameters could then be explicitly be built into the model to increase accuracy. Likely candidates include solar exposure, temperature, pre-season precipitation and soil characteristics. The method of using cumulative snowfall, rather than another parameter such as maximum snowfall, should also be reevaluated in future iterations of this model.

Greater accuracy could also be achieved by having more data available, especially SNOTEL data at Buckboard Flat. This data will come in time, and subsequent versions of this model will be better because of it.

Conclusion

While the desired result was not achieved, some conclusions were able to be made. A strong correlation can be made between SNODAS modeled data and SNOTEL measured snow water equivalent in these regions. A more rigorous hydrologic model would allow for a correlation between watershed snow volume and stream flow. With that correlation made, this model will be a powerful tool for water managers in San Juan County to predict snow fall runoff from the Abajo Mountains.

References

1. National Water & Climate Center. 2013. *SNOTEL and Snow Survey & Water Supply Forecasting*. Portland, Oregon USA. <http://www.wcc.nrcs.usda.gov/snotel/SNOTEL-brochure.pdf>
2. National Operational Hydrologic Remote Sensing Center. 2004. *Snow Data Assimilation System (SNODAS) Data Products at NSIDC*, 1 Oct 2007-30 Apr 2014. Boulder, Colorado USA: National Snow and Ice Data Center. <http://dx.doi.org/10.7265/N5TB14TC>

Appendix A—Code Samples

Average Daily SWE in Individual Sheds

```
print 'Importing necessary modules'
import arcpy
# from arcpy import env
from arcpy.sa import *
import os
import sys
import glob
import csv
# import numpy
# import math
# import json

print 'Defining variables'
sPath=sys.path[0]
dataPath = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SNODAS\\WY2008"
scratchPath="C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SNODAS\\Scratch"
outPath = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE 6440_GISWaterResources\\SJWCD\\SNODAS\\Output"
geoPath = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE 6440_GISWaterResources\\SJWCD\\SJC_Water.gdb"

print 'Setting up environment'
arcpy.env.workspace = dataPath
arcpy.env.scratchWorkspace = scratchPath
SpaceRefRef = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SNODAS\\WY2008\\us_ssmv11034tS__T0001TTNATS2007100105HP001.dat.r
eproject.tif"
spatial_ref = arcpy.Describe(SpaceRefRef).spatialReference
arcpy.env.outputCoordinateSystem = spatial_ref
arcpy.env.overwriteOutput = True
arcpy.CheckOutExtension("Spatial")
OutRasPath = outPath

print 'Creating list of raster files'
# For method 1
path = os.path.join(dataPath, "*.tif")
RasFiles = []
for fname in glob.glob(path):
    RasFiles.append(fname)

print 'Gathering first raster in list'
RemapTab = RemapValue([[-9999,0]])
outRas = arcpy.Raster(RasFiles[0])
outRasRec = Reclassify(outRas,"Value", RemapTab)
outRasVal = Con(IsNull(outRasRec),0,outRasRec)

print 'Defining list of model SWE values'
RecVal=0
JonVal=0
```

```

# IndVal=0
# SotVal=0
ShedVal=[(RecVal,JonVal)]
# ShedVal=[(RecVal,JonVal,IndVal,SotVal)]

print 'Processing rasters'
i=0
for i in range(0, len(RasFiles)):
    print "Processing Raster: %d" %(i)

    InRas= Raster(RasFiles[i])
    InRas1Val = Reclassify(InRas,"Value", RemapTab)
    out = Con(IsNull(InRas1Val), 0, InRas1Val)

    arcpy.CalculateStatistics_management(out,"","","","OVERWRITE",os.path.join(geoPath,"RecaptureWS"))
    RecVal= arcpy.GetRasterProperties_management(out,"MEAN")

    arcpy.CalculateStatistics_management(out,"","","","OVERWRITE",os.path.join(geoPath,"JohnsonWS"))
    JonVal= arcpy.GetRasterProperties_management(out,"MEAN")

    # arcpy.CalculateStatistics_management(out,"","","","OVERWRITE",os.path.join(geoPath,"IndianWS"))
    # IndVal= arcpy.GetRasterProperties_management(out,"MEAN")
    #
    # arcpy.CalculateStatistics_management(out,"","","","OVERWRITE",os.path.join(geoPath,"SouthWS"))
    # SotVal= arcpy.GetRasterProperties_management(out,"MEAN")

    ShedVal.append((RecVal,JonVal))
    # ShedVal.append((RecVal,JonVal,IndVal,SotVal))

    i=i+1

print'Loop exited'

print'Saving list of average SWE in each watershed'
with open('ShedVal08.csv','wb') as f:
    writer =csv.writer(f)
    writer.writerows(ShedVal)

print 'Output saved. Go check it out.'
```

Cumulative Seasonal SWE and Point Readings

```

print 'Importing necessary modules'
import arcpy
# from arcpy import env
from arcpy.sa import *
import os
import sys
import glob
import csv
# import numpy
# import math
```

```

# import json

print 'Defining variables'
sPath=sys.path[0]
dataPath = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SNODAS\\WY2014"
outPath = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SNODAS\\Output"
geoPath = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SJC_Water.gdb"

print 'Setting up environment'
arcpy.env.workspace = dataPath
arcpy.env.scratchWorkspace = outPath
SpaceRefRef = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SNODAS\\WY2008\\us_ssmv11034tS__T0001TTNATS2007100105HP001
.dat.reproj.tif"
spatial_ref = arcpy.Describe(SpaceRefRef).spatialReference
arcpy.env.outputCoordinateSystem = spatial_ref
arcpy.env.overwriteOutput = True
# arcpy.env.mask = "C:\\Users\\Dane\\Documents\\Fall 2014\\CEE
6440_GISWaterResources\\SJWCD\\SJC_Water.gdb\\Mask"
arcpy.CheckOutExtension("Spatial")
OutRasPath = outPath

print 'Creating list of raster files'
# For method 1
path = os.path.join(dataPath,"*.tif")
RasFiles = []
for fname in glob.glob(path):
    RasFiles.append(fname)

print 'Gathering first raster in list'
RemapTab = RemapValue([[-9999,0]])
outRas = arcpy.Raster(RasFiles[0])
outRasRec = Reclassify(outRas,"Value", RemapTab)
outRasVal = Con(IsNull(outRasRec),0,outRasRec)

print 'Defining list of model SWE values'
CJ=arcpy.GetCellValue_management(outRasVal, "-109.483367 37.816497", "1")
BF=arcpy.GetCellValue_management(outRasVal, "-109.450012 37.866706", "1")
SnoVal=[[CJ,BF]]

print 'Processing rasters'
for i in range(1, len(RasFiles)-1):
    print "Processing Raster: %d" %(i)

    InRas1 = Raster(RasFiles[i-1])
    InRas2 = Raster(RasFiles[i])
    InRas1Val = Reclassify(InRas1,"Value", RemapTab)

```



```

InRas2Val = Reclassify(InRas2,"Value", RemapTab)

out1 = Con(IsNull(InRas1Val), 0, InRas1Val)
out2 = Con(IsNull(InRas2Val), 0, InRas2Val)

CumlOut = out2-out1
CumlPos = Con(CumlOut > 0, 1, 0)
CumlVal = CumlPos*CumlOut

# CumlVal = Reclassify(Cuml, "Value", RemapTab)
outRasVal = outRasVal + CumlVal
CJ=arcpy.GetCellValue_management(out1, "-109.483367 37.816497", "1")
BF=arcpy.GetCellValue_management(out2, "-109.450012 37.866706", "1")
SnoVal.append((CJ, BF))
i=i+1

print'Loop exited'

print'Saving list of SWE at SNOTEL sites'
with open('SnoVal14.csv','wb') as f:
    writer =csv.writer(f)
    writer.writerows(SnoVal)
    # for s in SnoVal:
    #     f.write('%5.5f, %5.5f, %5.5f\n'% (s[0],s[1]))

print 'Saving complete raster'
outRasVal.save(os.path.join(outPath,'Whole14'))

print 'Extracting rasters for each watershed'
print 'Here goes Recapture...'
RecMask=ExtractByMask(outRasVal,os.path.join(geoPath,"RecaptureWS"))
RecMask.save(os.path.join(outPath,"Recapture14"))
print 'Johnson Creek...'
JonMask=ExtractByMask(outRasVal,os.path.join(geoPath,"JohnsonWS"))
JonMask.save(os.path.join(outPath,"Johnson14"))
print 'Indian Creek...'
IndMask=ExtractByMask(outRasVal,os.path.join(geoPath,"IndianWS"))
IndMask.save(os.path.join(outPath,"Indian14"))
print 'And finally South Creek.'
SotMask=ExtractByMask(outRasVal,os.path.join(geoPath,"SouthWS"))
SotMask.save(os.path.join(outPath,"South14"))

print 'Output saved. Go check it out.'

```