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Soil-Moisture Estimation of Root Zone through Vegetation-Index-Based Evapotranspiration-Fraction and Soil-Properties (SERVES) User's Manual Version 1.0

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PURPOSE: The purpose of this user's guide is to provide background methods and implementation guidance on the Soil-moisture Estimation of Root Zone through Vegetation-Index-Based Evapotranspiration-Fraction and Soil-Properties (SERVES) model (Pradhan 2019).

INTRODUCTION: Research and development of an effective method for obtaining effective root-zone soil moisture content from remotely sensed aerial and satellite data significantly aids in measuring and monitoring water-related stress in plants and the environment (Berg et al. 2017; Kang et al. 2009; Mananze et al. 2019). Realistic root-zone soil moisture initial condition is a primary driver for an effective simulation of surface water and groundwater interaction, through infiltration or exfiltration, and land atmospheric interaction, through evapotranspiration (ET) in a physics-based hydrological model (Pradhan 2019; Pradhan et al. 2020). Satellite-based digital soil-moisture data represent the top few centimeters (less than 10 cm[*]) of the soil column. Such shallow-depth soil moisture observations do not inform about the effective root-zone wetness.

SERVES (Pradhan 2019, 2021) was developed to improve the estimation of root-zone soil moisture distribution at a fine spatial resolution through globally available, remotely sensed digital data and soil physical properties. It is a useful method, especially in the arid and semiarid climatic regions where the topography is less dominant in the distribution of soil moisture as compared to that in humid catchments (Pradhan 2019, 2021).

The SERVES method is simple and computationally straightforward, which bypasses the complexity of ground-based auxiliary measurements, especially in an ungauged environment. The method's application and verification are shown in Pradhan (2019). Pradhan et al. (2020) shows the effect of input initial soil moisture resolution on hydrological modeling. Pradhan and Floyd (2021) applied the SERVES method to estimate prefire and postfire soil moisture in Southern California. This technical note describes how to use the SERVES model.

THEORETICAL BACKGROUND: "Actual evapotranspiration (AET) can be defined as a largely empirical function of plant-specific potential evapotranspiration (PET) and soil moisture content (SM), or a soil moisture matric potential and threshold value above which actual and potential evapotranspiration are equal. Calculation of the AET is obtained by a reduction

[*] For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52 and 345–7, respectively. *https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf*.

relationship, using functions that describe the influence of the available moisture"[†] (Bagrov 1953; Baier and Robertson 1966; Budyko and Zubenok 1978; Eagleson 1978; Minhas et al. 1974; Norero 1969; Renger et al. 1974), as

$$\frac{AET}{PET} = f(SM). \tag{1}$$

Budyko and Zubenok (1978) define the soil moisture function in Equation (1) as

$$\frac{AET}{PET} = \frac{SM}{PAM}, \tag{2}$$

where SM is the actual available soil moisture and plant-available soil moisture (PAM) is plant-available soil moisture at field capacity. In Equation (2), SM/PAM can be taken as the soil wetness index, defined as

$$\frac{SM}{PAM} = \frac{(\theta - \theta_{wp})}{(\theta_{fc} - \theta_{wp})}, \tag{3}$$

where θ is the actual soil moisture content and θ_{fc} and θ_{wp} are the field capacity moisture content and wilting point moisture content, respectively, for the soil type at the location.

From Equations (2) and (3), it follows that

$$\frac{AET}{PET} = \frac{(\theta - \theta_{wp})}{(\theta_{fc} - \theta_{wp})}, \tag{4}$$

where AET/PET is the crop coefficient, K_c (Dyck 1985). Reference ET fraction (ET_{rf}) accounts for water stress and other ET-reducing environmental stresses (Allen et al. 2005). Trezza (2002), Tasumi (2003), and Allen et al. (2007) showed that the reference ET fraction (ET_{rf}) is similar to K_c (Allen et al. 1998):

$$ET_{rf} = \frac{AET}{ET_r}, \tag{5}$$

where ET_r is the reference ET, calculated using the Food and Agriculture Organization (FAO) Penman-Monteith method and data originating from a weather station. Considering ET_{rf} to be equal to K_c (Trezza 2002; Allen et al. 2007), Pradhan (2019) related ET_{rf} to the soil moisture function defined in Equation (4) as

$$ET_{rf} = \frac{(\theta - \theta_{wp})}{(\theta_{fc} - \theta_{wp})}. \tag{6}$$

[†] Reprinted from N. R. Pradhan, *Estimating Growing-Season Root Zone Soil Moisture from Vegetation Index-Based Evapotranspiration Fraction and Soil Properties in the Northwest Mountain Region, USA*, ERDC/CHL MP-21-6 (Vicksburg, MS: US Army Engineer Research and Development Center, 2016), http://dx.doi.org/10.21079/11681/42128. Public Domain.

Considering *i* as any spatial location, spatially distributed soil moisture content from Equation (6) is derived as

$$\theta_i = ET_{rfi}(\theta_{fci} - \theta_{wpi}) + \theta_{wpi}. \quad (7)$$

Pradhan (2019) derived Equation (7) to estimate root zone soil moisture as a function of ET_{rf} and soil properties.

To further simplify the estimation of soil moisture in Equation (7), Pradhan (2019) found that in the growing season,

$$ET_{rf} = f(NDVI), \quad (8)$$

where *NDVI* is the Normalized Difference Vegetation Index.

Inversion of ET_{rf} (Pradhan 2019) was made through the globally available NDVI as

$$ET_{rf} = 1.33\ NDVI - 0.049. \quad (9)$$

MODEL DEVELOPMENT: The SERVES method is developed in the C/C++ programing language. The model architecture and code are designed in a way that is suitable for an application programming interface. In this version (version 1), of the SERVES model, the main input files are vegetation index file, soil texture file, and soil parameter linking file. The main output file is the soil moisture file. The input and output files and file formats of the SERVES model are described in the following sections.

PROJECT FILE: The SERVES model requires a project file that contains cards that pass information to SERVES for soil-moisture estimation. The name of the project file is given at run time as a command-line argument for the SERVES model. The project file consists of a single card on each line, followed by its argument. The argument is in the form of values, character strings, and file names. Table 1 presents all required project file cards followed by a brief description of each.

Table 1. Soil-moisture Estimation of Root-zone through Vegetation-index-based Evapotranspiration-fraction and Soil-properties (SERVES) model project file.

Card	Argument	Description
xllcorner	real	The raster map lower left corner longitudinal coordinate (Universal Transverse Mercator [UTM] projection in this version).
yllcorner	real	The raster map lower left corner latitudinal coordinate (UTM projection in this version).
nrows	integer	Number of rows in each raster map.
ncols	integer	Number of columns in each raster map.
cellsize	real	Grid resolution of the raster maps (m).

Table 1 (cont.). SERVES model project file.		
nodata_value	real	The “no-data” value in the raster map. It is employed when information is unavailable or when a value is not needed for a cell location. The no-data value should not match any value in a cell location. For example, no data value in an NDVI map may be −9999 as NDVI never reaches a value of −9999.
MAP_LINK	map name	File that links soil parameter values based on soil index map. It is an input file.
VEGETATION_INDEX	map name	Name of map that specifies gridded NDVI values. It is an input file.
MOISTURE	map name	Name of map that specifies gridded soil moisture content (m^3/m^3). It is an output file.

A user may define the project file name. For consistency, the project file name is in the following form: project_name.prj, where project_name is a project name (study area name, watershed name) and the prj is the file extension.

For example, the maps of vegetation index and soil moisture shown later in this study (sections VEGETATION INDEX INPUT FILE and SOIL MOISTURE OUTPUT) are from Reynolds Creek watershed. Reynolds Creek watershed is one of the study areas where the SERVES method was tested and verified (Pradhan 2019). If the project_name for this study is Reynolds_Creek, the project_name.prj will be Reynolds_Creek.prj. The contents of the Reynolds_Creek.prj, as explained in Table 1, are shown in Figure 1.

*Reynolds_Creek.prj - Notepad

File Edit Format View Help

```
xllcorner                 510435
yllcorner                 4766565
nrows                     1000
ncols                     533
cellsize                  30.0
nodata_value              -9999
MAP_LINK                   Reynolds_Creek.lik
VEGETATION_INDEX           Reynolds_Creek.nvi
MOISTURE                   Reynolds_Creek.moi
NDVI_MULTIPLYING_FACTOR    0.0001
```

Figure 1. SERVES project file layout.

PARAMETER VALUE ASSIGNMENT FILE: As discussed in the THEORETICAL BACKGROUND section, the SERVES method is based on study-area soil physical parameter values, namely soil field capacity and soil wilting point. The file that assigns soil parameter value is defined by the MAP_LINK card. A user may define this linkage file name. For consistency, the linkage file name is in the following form: project_name.lik where, project_name is a project name (study area name, watershed name) and the .lik is the file extension. The project_name for this manual is Reynolds_Creek, and the project_name.lik is Reynolds_Creek.lik. Table 2 shows the required cards in the linkage file with arguments and descriptions.

Table 2. Parameter linkage file description.

Card	Argument	Description
SOIL_PROPERTY	map name	Name of map that specifies gridded soil texture ID
SOILNUMS	integer	Total number of soil types identified

The card and argument listed in Table 2 are followed by the tabulated list of soil ID (the soil ID number must start from 1 and increase successively), soil type, and soil property values as shown in Figure 2. Figure 2 shows the content of the Reynolds_Creek.lik.

```
*Reynolds_Creek.lnk - Notepad
File  Edit  Format  View  Help
SOIL_PROPERTY    reynolds_creek.soi
SOILNUMS 8
soilid   soil type                                   soil properties: field capacity wilting point
1    silt_loam                                                           0.330 0.133
2    Sandy_loam                                                          0.290 0.060
3    Sandy_clay_loam                                                     0.260 0.140
4    Loamy_sand                                                          0.150 0.060
5    Loamy_fine_sand                                                     0.150 0.060
6    Loam                                                                0.300 0.117
7    Coarse_sandy_loam                                                   0.290 0.060
8    Clay_loam                                                           0.350 0.100
```

Figure 2. SERVES parameter linkage file example.

The soil ID defined in Figure 2 is from the soil map file defined by the SOIL_PROPERTY card. For consistency, the soil map file name is in the following form: project_name.soi. The project_name for this manual is Reynolds_Creek. Therefore, the project_name.soi is Reynolds_Creek.soi as shown in Figure 2.

project_name.soi. The file project_name.soi is the soil texture ID (integer) in ASCII file format. ASCII grid files can be created in Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS), Geographic Resources Analysis Support System GIS, or similar applications. Figure 3 shows the ASCII grid file created in ArcGIS. The header that is included in the *red box* in Figure 3 is an input in the project file mentioned in the above section PROJECT FILE and needs to be removed from this project_name.soi in SERVES model.

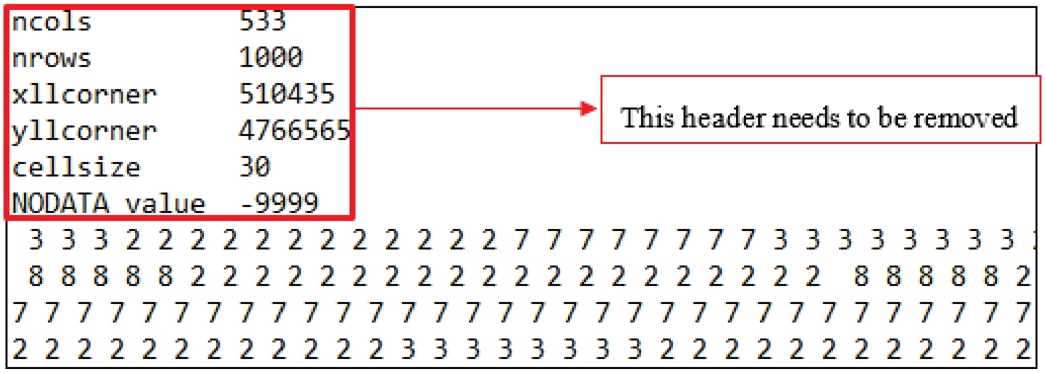


Figure 3. Example of project_name.soi file opened in notepad and cropped to show partially in this figure.

In Figure 2, the "SOILNUMS" as defined in Table 2 is 8 which means there are 8 soil types or 8 soil textural IDs. The cropped example in Figure 3 shows IDs 3, 2, 7, and 8. The cropped example does not include soil textural IDs 1, 4, 5, and 6 as mentioned in Figure 2.

SERVES soil moisture estimation formulation includes soil physical properties, field capacity, and wilting point. The details of the relationship between field capacity and wilting point can be found in the THEORETICAL BACKGROUND section. A distributed grid-based soil textural ID (i.e., a soil index map) is a map that defines soil type with ID values. This soil index map is used to assign a soil-type-based field capacity and wilting point for each grid location. There are various sources and methods for soil-texture classification. For the continental United States, the Natural Resource Conservation Service Soil Survey Geographic (SURRGO) database (*http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx*) provides the soil type at 30 m resolution. A 1,000 m resolution soil texture is available globally from FAO Harmonized World Soil Database website: *http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/.* Lahatte and Pradhan (2016) and Cotterman and Pradhan (2017) show a guideline on extracting the soil texture.

Figure 4 shows, via the ArcGIS visual interface, the soil texture distribution in Reynolds Creek watershed identified from the SURRGO database. In the actual soil moisture calculation, a soil textural ID is assigned to each cell of the domain that is depicted with 1,000 rows and 533 columns, as mentioned in Figure 3. If the soil moisture outside the watershed is not needed, the "no-data" value specified in Table 1 is assigned to the cells outside of the watershed.

Once soil textures are defined with the index values, pedotransfer functions are employed to estimate soil water properties (field capacity and wilting point). Rawls et al. (1983) is a common source for soil physical parameter value assignments based on soil texture (Table 3).

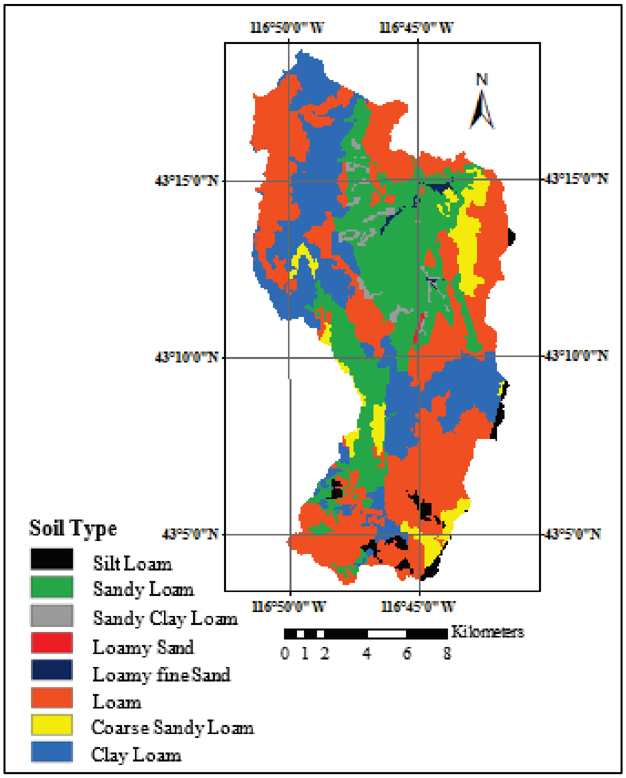


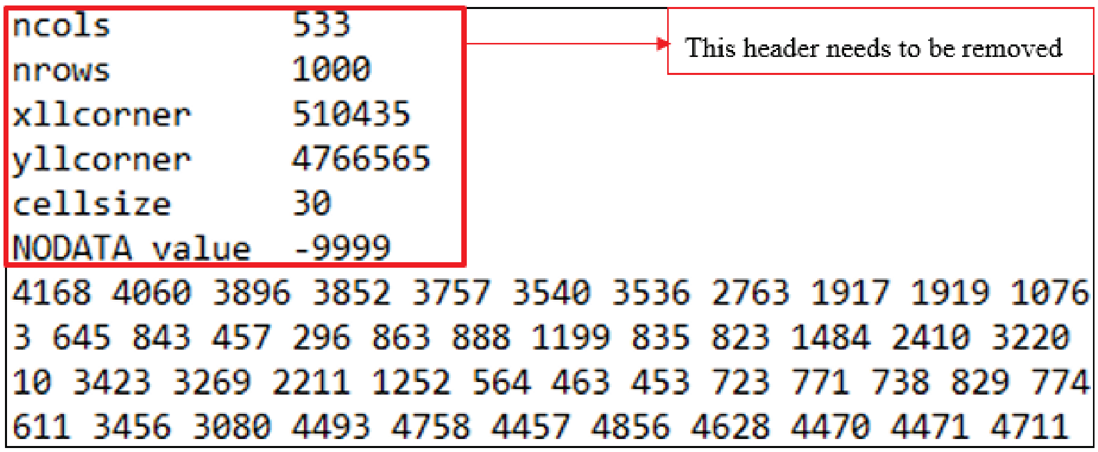
Figure 4. Reynolds Creek watershed map of soil types identified from Service Soil Survey Geographic (SURRGO) data set.

Table 3. Soil infiltration parameter values from soil textural classification (Rawls et al. 1983).

USDA Textural Classification	Field Capacity Saturation θ_{fc} (cm^3/cm^3)	Wilting Point Saturation θ_{wp} (cm^3/cm^3)
Sand	0.091	0.033
Loamy sand	0.125	0.055
Sandy loam	0.207	0.095
Loam	0.27	0.117
Silt loam	0.33	0.133
Sandy clay loam	0.255	0.148
Clay loam	0.318	0.197
Silty clay loam	0.366	0.208
Sandy clay	0.339	0.239
Silty clay	0.387	0.250
Clay	0.396	0.272

VEGETATION INDEX INPUT FILE: The file that assigns NDVI values is defined by the VEGETATION_INDEX card, which is shown in Figure 1. As discussed in the THEORETICAL BACKGROUND section, the SERVES soil moisture estimation method is based on ET_{rf}, which is related to vegetation index, NDVI. Therefore, a gridded NDVI ASCII map of the study area is required as input for the soil moisture estimation.

For consistency, the NDVI map file name is in the following form: project_name.nvi. The project_name for this manual is named Reynolds_Creek. Therefore, the project_name.nvi is Reynolds_Creek.nvi, which is shown in Figure 1. The file project_name.nvi is the NDVI values in ArcGIS/GRASS ASCII file format without the header as shown in Figure 5.




```
ncols         533
nrows         1000
xllcorner     510435
yllcorner     4766565
cellsize      30
NODATA_value  -9999
4168 4060 3896 3852 3757 3540 3536 2763 1917 1919 1076
3 645 843 457 296 863 888 1199 835 823 1484 2410 3220
10 3423 3269 2211 1252 564 463 453 723 771 738 829 774
611 3456 3080 4493 4758 4457 4856 4628 4470 4471 4711
```

Figure 5. Example of project_name.nvi file opened in notepad and cropped to show partially in this figure.

The header that is included in the *red box* in Figure 5 is already input in the project file mentioned in PROJECT FILE section above. Globally available atmospheric corrections applied 30 m resolution Landsat NDVI are available at *https://espa.cr.usgs.gov/*. Globally available atmospheric corrections applied 250 m and 1,000 m resolution Moderate Resolution Imaging Spectroradiometer NDVI is available at *https://modis.gsfc.nasa.gov/data/dataprod/mod13.php*.

The US Geological Survey, Earth Resources Observation and Science, Center Science Processing Architecture, provides 30 m Landsat Surface Reflectance, with atmospheric corrections applied, Level 2 science products that include the spectral indices, 30 m resolution NDVI, products for Landsat 4–5 Thematic Mapper, Landsat 7 Enhanced Thematic Mapper Plus, and Landsat 8 Operational Land Imager/Thermal Infrared Sensor.

Note that the NDVI maps obtained from the sources mentioned above require a scale factor multiplication of 0.0001. For example, the values of NDVI in Figure 5 need to be multiplied by 0.0001. If such a scale factor is required, an additional project card named as NDVI_MULTIPLYING_FACTOR, shown in Figure 1, needs to be added to the SERVES project file with the multiplying factor value as follows:

NDVI_MULTIPLYING_FACTOR 0.0001

The card, NDVI_MULTIPLYING_FACTOR, is not required if this scale factor is applied outside the SERVES model or if actual NDVI values are the input to the SERVES model.

Figure 6 shows, via the ArcGIS visual interface, the NDVI distribution in Reynolds Creek watershed obtained from the on-demand Landsat database (USGS 2017; USGS 2022). Like Figure 4, Figure 6 only shows the value for the cells within the watershed.

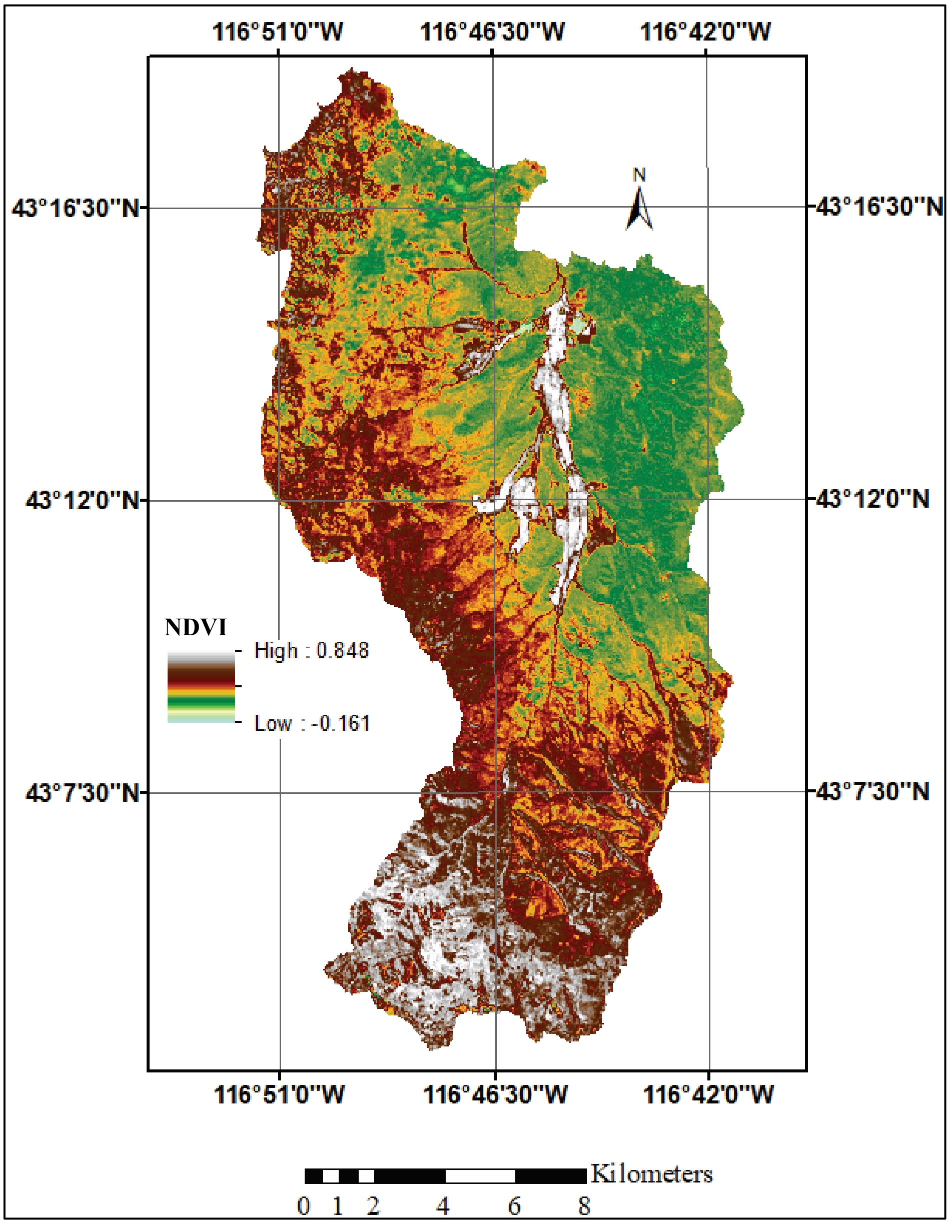


Figure 6. Reynolds Creek watershed map of Normalized Difference Vegetation Index (NDVI).

SOIL MOISTURE OUTPUT: The output file of the SERVES estimated soil moisture values is defined by the MOISTURE card, which is shown in Figure 1. For consistency, the soil moisture map file name is in the following form: project_name.moi. The project_name is the soil moisture output file and is named Reynolds_Creek for this manual. Therefore, the project_name.moi is Reynolds_Creek.moi, which is shown in Figure 1. The file Reynolds_Creek.moi is the volumetric soil moisture content (m^3/m^3) values in ArcGIS ASCII file format as shown in Figure 7. The output

ASCII files from the SERVES model has the header information included so that it can be visualized in the GIS interface.

```
ncols         533
nrows         1000
xllcorner     510435
yllcorner     4766565
cellsize      30
NODATA_value  -9999
0.248  0.241  0.223  0.235  0.244  0.247  0.230  0.232  0.270
0.271  0.254  0.244  0.288  0.318  0.333  0.330  0.318  0.304
0.303  0.297  0.303  0.305  0.311  0.299  0.295  0.278  0.270
0.197  0.193  0.199  0.192  0.232  0.340  0.340  0.340  0.340
```

Figure 7. Example of project_name.moi file opened in notepad and cropped to show partially in this figure.

Figure 8 shows the SERVES estimated soil moisture distribution in Reynolds Creek watershed.

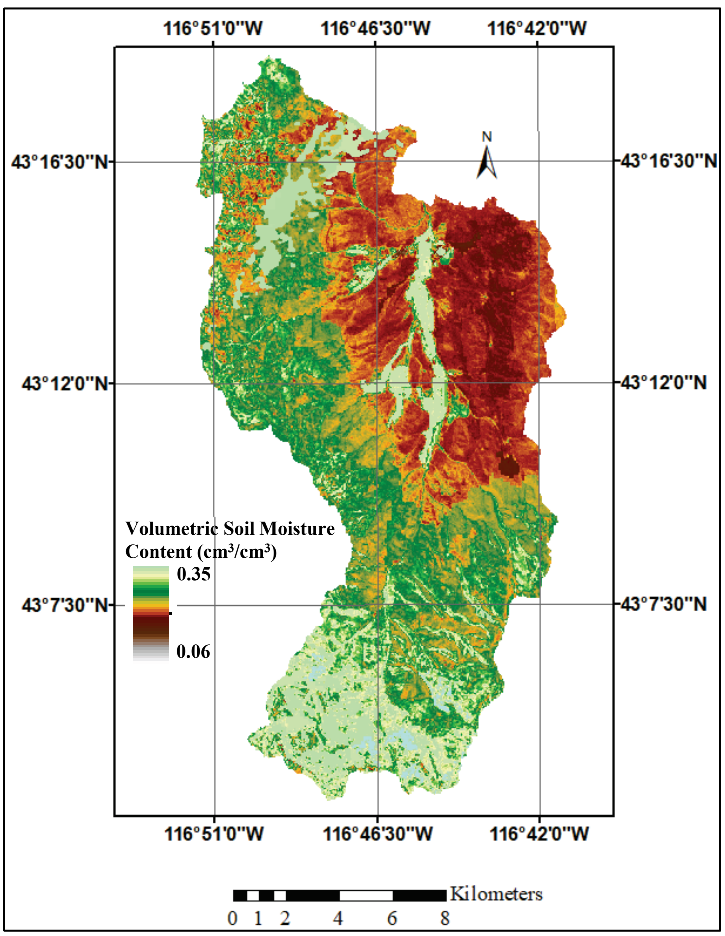


Figure 8. Reynolds Creek watershed map of estimated soil moisture for 11 September 2008.

Figure 8 shows, via the ArcGIS visual interface, the soil moisture clipped within the Reynolds Creek watershed. Like Figure 4 and Figure 6, Figure 8 only shows soil moisture content for the cells within the watershed.

RUNNING SERVES MODEL: Once the input files are in place, the following steps can be taken to run SERVES:

1. Navigate to the GitHub repository page (*https://github.com/nawa-water/SERVES*) that contains the file SERVES_V1_setup.zip. It is not required to log in to visit the page. On the repository page, locate the file SERVES_V1_setup.zip. Double-clicking on this file leads to the download page.
2. Run setup.exe in the folder SERVES_V1_setup
3. Copy the executable named SERVES.exe from where the program is set up and paste it into the folder where the input files (mentioned above) are located.

   Usually, the path where SERVES.exe is located is something like this:

   C:\Program Files (x86)\Default Company Name\Setup1
4. To run the program, open DOS command prompt and go to the location where the exe and input files exist. Type the following command (as shown in Figure 9) and press enter key: SERVES.exe filename.prj., where SERVES.exe is the SERVES model executable and filename.prj is the project file name as mentioned in section PROJECT FILE.

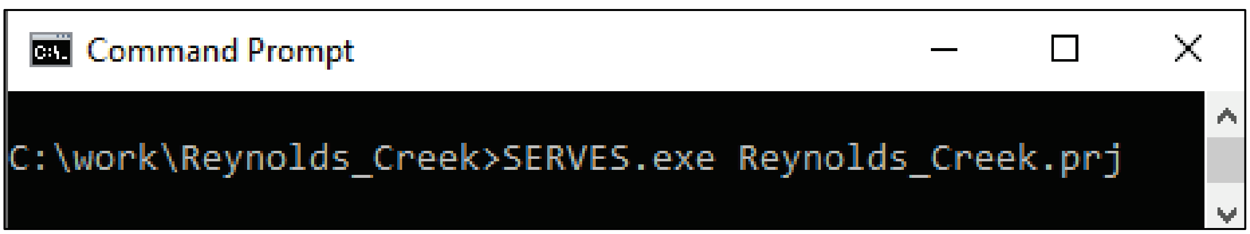


Figure 9. Running SERVES from DOS command prompt.

5. GitHub repository page (*https://github.com/nawa-water/SERVES*) also contains an example project. Double click on the project.zip file and download the zip file. To run this example project, follow the above-mentioned points and replace Reynolds_Creek.prj in the command line shown in Figure 9 with example.prj.

CONCLUSION: The SERVES software and the user's manual is freely distributed for the purpose of water resources research and application. Publications, models, and data products that make use of this software must include proper citation and acknowledgement. Any additional documents on the user guidelines of future SERVES model enhancements will be an addendum to this original SERVES user's manual.

DISCLAIMER: The software is based on Pradhan (2019, 2021) and is provided without warranty of any kind in its use.

ADDITIONAL INFORMATION: This Coastal and Hydraulics Engineering technical note (CHETN) was prepared by Nawa Raj Pradhan, Nawa.Pradhan@usace.army.mil, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory.

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