SOIL MOISTURE MAPPING OF DROUGHT IN TEXAS

FINAL REPORT

for

INTEGRATED DROUGHT INFORMATION SYSTEM (IDIS II)

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prepared by

JOHNNY SULLIVAN AND DAVID R. MAIDMENT

CENTER FOR RESEARCH IN WATER RESOURCES

THE UNIVERSITY OF TEXAS AT AUSTIN

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SUMMARY

Texas experienced in 2011 one of the worst droughts on record. To better understand and plan for its effects, this project aimed to create a map, available online and updated in real-time, showing the extent of drought in the state of Texas based on soil moisture content information. This was to be accomplished through a combination of the available water storage data provided by the USDA Soil Survey Geographic Database (SSURGO) and the continuously updated current soil moisture data made available by NLDAS, the North American Land Data Assimilation System. The SSURGO dataset is defined at a detailed county mapping scale, while the NLDAS model operates on a climate-level scale of $^1/_8$ degree polygons, necessitating consideration of the appropriate scale at which these two datasets should be joined. The combination of these two datasets resulted in a value of current moisture storage in which the percentage of moisture was defined by NLDAS, while the upper and lower bounds of the moisture levels were defined by SSURGO. It was decided, however, that current water storage is most easily understood on a percentage basis, so a soil wetness index was defined and it was upon this metric that the soil moisture map was based. The analysis began with a focus on Travis County but was then expanded to the remainder of the state of Texas. The soil parameters for each NLDAS grid point were acquired, and an ArcGIS geoprocessing model was created to calculate and display the average soil wetness index for each county across the state. Finally, a 33-year record of NLDAS soil moisture data was obtained, and the groundwork was laid to employ this long-term dataset in calculating the statistical significance of current soil moisture data.

INTRODUCTION

It is unclear at present exactly how global climate change will affect precipitation patterns on a long-term time scale. The Intergovernnmental Panel on Climate Change has agreed on general trends, however, and projects in its 2007 report that certain regions will experience wetter climates, whereas others regions, such as the American Southwest, will receive less rainfall than ever before (IPCC 2007). During the summer of 2011, Texas suffered one of the worst droughts on record (LCRA 2011). Although the extent to which this drought was caused or intensified by climate change is not known, having a system in place to better understand drought severity could prove valuable in improving preparedness for similar events in the future, whether climate change-related or otherwise.

One way to consider drought is to measure the stage and flow of important rivers and water bodies, but this is just a single part of the picture. Another aspect is the quantity of water present in the soils. This relates directly to plant health, which in turn preserves soil quality and prevents erosion. Drought could be understood better if a complete picture of soil moisture content could be constructed. Knowing how much water is present is not enough information; both the current water content and maximum available water content must be known. When combined, these two pieces of data describe the current drought status. They detail how much water is contained in the soils compared to how much could possibly exist there.

PROJECT GOAL

The objective of this project was to create a map that provides information about drought as a function of the available water content in Texas soils. It will be available online and updated in real-time. In this way it will make available critical drought information to the numerous agencies in Texas who would find this data useful. This was accomplished through the use of the continuously updated current soil water content data made available by the North American Land Data Assimilation System (NLDAS). A nationwide grid of $^1/_8$ degree quads, the NLDAS data details in the model output how much moisture soil is currently holding, and the parameters used in the model's calculations describe available water storage. This allows for the calculation of a soil wetness index: the amount of moisture present in the soils of a given region compared to how much moisture could potentially be present, represented as a percentage.

At the start of the project, the potential for calculating actual soil moisture content – such as the volume or equivalent height of moisture – was assessed. This was to be done using available water storage data provided by the Soil Survey Geographic Database (SSURGO). This dataset divides land areas into polygons with unique values describing the maximum available water storage for the given area. Thus, both datasets include the available water storage, but only NLDAS includes the current water storage as well. However, there is a discrepancy in the available water storage values as defined by SSURGO and NLDAS. The SSURGO dataset's parameters are more current and were thus viewed to be the more correct of the two. NLDAS was used to calculate a soil wetness index, and this percentage was then to be applied to the SSURGO available water storage, yielding a current water storage that is based on SSURGO's more accurate available water storage data but is updated continuously using NLDAS.

It was ultimately decided, though, that drought status is better represented as a percentage. Mapping the soil wetness index described above provides a clearer picture of the extent and severity of drought because a percentage is more intuitively significant than an amount of moisture; for a value of soil moisture in centimeters to be useful one must also know the maximum possible storage for that soil. That said, the process explored for combining the two datasets is included herein. It is presented first, followed by the final soil wetness index-based process.

SSURGO DATASET

The Soil Survey Geographic Database is administered by the Natural Resources Conservation Service (NRCS), an arm of the United States Department of Agriculture, and it makes available countrywide soil water storage capacity data at the county level. For the regular user, the data can be accessed from SSURGO's Soil Data Mart website. It is then most easily processed using the Soil Data Viewer, a tool distributed by the NRCS. This tool was developed as an ArcMap extension that facilitates the creation of soil-based thematic maps. The soil survey attribute database that supports the spatial soil data distributed by the Soil Data Mart is complex, and users can find it difficult to cull from it the specific data needed. The Soil Data Viewer was created to make this process easier; it acts as an interface between the user and the database (NRCS 2011). The soil maps, displayed as connected polygons, contain numerous types of information about the soil. The Soil Data Viewer focuses on a single variable for the map as a whole and displays that information so that the user does not need to go through the process of querying the database and then linking processed data to spatial data (NRCS 2011).

For this project, SSURGO data was initially obtained from Michael Dangermond at ESRI. He received the entire SSURGO database directly from NRCS and clipped that to Travis County. Later in the project, he also provided SSURGO data for all of Texas. This statewide data was ultimately not used, but his provision of it was particularly useful at the time because the Soil Data Viewer does not have a process in place for accessing multiple counties at once. In order to acquire SSURGO data for the entire state of Texas, a user would need to download the data for each county individually; this is inefficient and would take a vast amount of time.

The STATSGO dataset, now known as the U.S. General Soil Map, was also used in this project. It was useful once the project's analysis transitioned to the entire state of Texas because it provides the same available water storage information as the SSURGO dataset but is easier to work with. This is because it is at a much coarser scale, and thus has far fewer features over the state of Texas than the SSURGO dataset, and because the data for an entire state can be downloaded with a single query rather than requiring downloads on a county-by-county basis, as with SSURGO. As will be discussed later in this report, it was used to calculate the total available soil water storage across all of Texas.

It is important at this point to clarify the definition of available water storage, for it is not simply the total moisture content for a given soil depth, as one might expect. Soil moisture is characterized using two parameters: field capacity and wilting point. The field capacity of a soil is the amount of moisture it can hold after it has been completely saturated and then allowed to drain freely, while the wilting point is the amount of soil moisture at which plants begin to wilt and die. SSURGO defines available water storage as "the amount of water that the soil…can store that is available to plants" (SSURGO Metadata and Columns Report); in other words, it is the magnitude of the difference between the field capacity and wilting point. This means that the low point is not zero soil moisture, but rather the lowest moisture content at which plants are able to withdraw water from the soil. The plot shown in Figure 1 below is from the NRCS' Soil Quality Indicators document, and it provides a good explanation of available water storage. In the figure, available water storage is the distance between the lines representing field capacity and wilting point. There is still water in the soil below the wilting point, but it is unavailable to plants and is therefore not included in the amount of available water storage. It is certainly possible for the actual soil moisture content to be less than the wilting point – in fact, this can occur frequently during extreme droughts – but available water storage was defined from an agricultural viewpoint and thus does not take that moisture into account; if the plants are dying it matters only that there's insufficient water, not how much less there is than the limit.

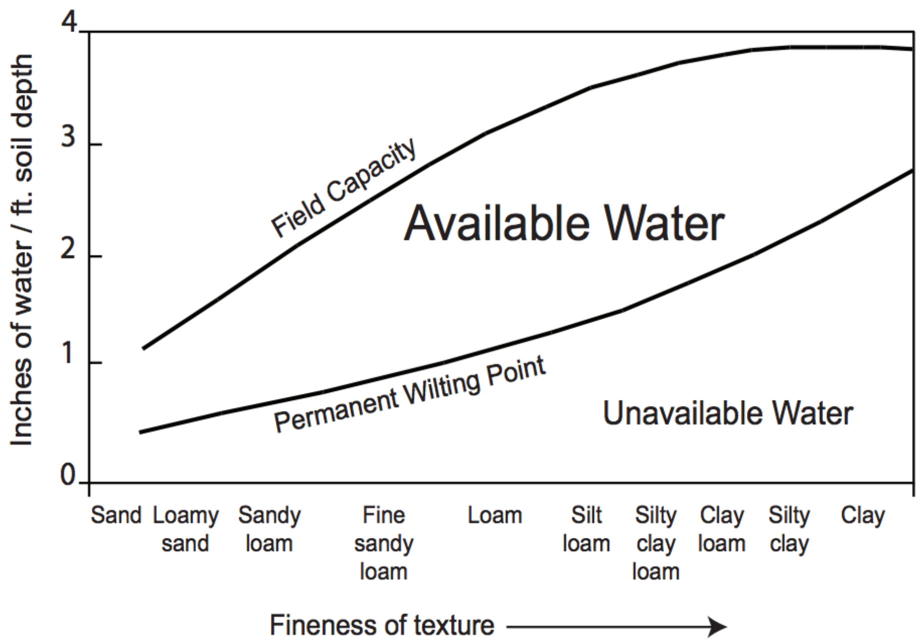


Figure 1. Explanation of the definition of available water storage from the Natural Resources Conservation Services' Soil Quality Indicators document.

NLDAS DATASET

The North American Land Data Assimilation System (NLDAS) project is a collaboration between numerous governmental and academic institutions, a full list of which is available on the NLDAS website (http://www.emc.ncep.noaa.gov/mmb/nldas). NLDAS publishes files in real-time that contain many types of land surface data, one of which is the soil moisture content, in kg/m^2, for a depth of 0-100 cm. The data is available from an ftp server that contains multiple datasets. Results from the Noah land-atmosphere model were used for this analysis.

This model includes data in hourly output increments, updated in 24-hour groups. An investigation was conducted to determine whether the soil moisture varied significantly over the course of a day. It was found that, on average, the hourly soil moisture values vary from the 12PM value by between 0.2 and 0.5%. This difference is insignificant. As such, in accessing NLDAS data the file for 12PM on the given day was always downloaded.

The NLDAS model outputs one value per variable for each $^1/_8$ degree quad. For the variable used in this analysis, current soil moisture for 0-100 cm, each quad has an attribute value in kg/m^2. When divided by the density of water, this value is converted to the equivalent depth of water contained in that quad's soils from 0-100 cm of soil depth. It is important to note here that this total amount of water does not directly correspond to the available water storage. The NLDAS model gives the volumetric soil moisture content, ranging from zero to field capacity. In order to compare the current soil moisture value from NLDAS with the SSURGO available water storage values, therefore, the NLDAS wilting point must be subtracted from the current moisture value. This then places that soil moisture value between the soil's wilting point and its field capacity, rather than between zero and field capacity as it originally was in NLDAS.

The data is downloaded as a file in the GRIB file format, a type commonly used for the storage of weather data but one that is not supported by ArcGIS. To be of use the file must first be converted to an ArcGIS-supported format before it can be opened in the mapping software. This problem was solved using Unidata's THREDDS server. The THREDDS project (Thematic Realtime Distributed Data Services) is a way by which gridded data can be accessed, and a THREDDS server has been installed on a computer on the network at the Center for Research in Water Resources. THREDDS is used to convert the NLDAS output files, which are in the GRIB format, to the NetCDF file format. When the data are downloaded, they are added to an LDM server. LDM stands for Local Data Manager, and is the file system that THREDDS is programmed to access. Data can be queried from the server using, for example, a web coverage service request, at which time the THREDDS server converts the data from its native format to numerous other formats, such as NetCDF. This facilitates the creation of an automated workflow. NLDAS data can be automatically downloaded from the ftp site, transferred to the LDM server, converted to the appropriate file format using THREDDS, and then processed using ArcGIS. All of these systems are in place. The missing piece is a set of scripts to execute each of the functions on a certain temporal basis, e.g. daily, monthly, etc.

SOIL MOISTURE ANALYSIS FOR TRAVIS COUNTY

Although the final version of this project analyzes drought as function of soil moisture for the entire state, an analysis of soil moisture was carried out for Travis County first as a kind of test case prior to before being expanded to the rest of the state. The SSURGO data for Travis County obtained from Michael Dangermond described the available water storage for the top 1 meter of soil. In order to facilitate the eventual combination of this data with NLDAS information, the SSURGO polygon data was overlaid in ArcMap with the 30 quads from the NLDAS $^{1}/_{8}$ degree dataset that intersect Travis County. The SSURGO polygons were then dissolved by available water storage value. Dissolve is an ArcGIS tool that combines any features with the same value into a single feature. This process yielded a dataset that had one polygon for each available water storage value within each $^{1}/_{8}$ degree quad. The result of this is shown in Figure 2. Areas with a storage value of 0 cm, corresponding to bright red on the map, are bodies of water. The available water storage of the first 100 cm of soil generally falls in the range of 1-20 cm, with only 25 of the 1,204 polygons in Travis County exceeding 20 cm. The map's color scale reflects this, transitioning at 2.5 cm intervals from red (less storage) to blue (more storage). The last interval accounts for the few values greater than 20 cm.

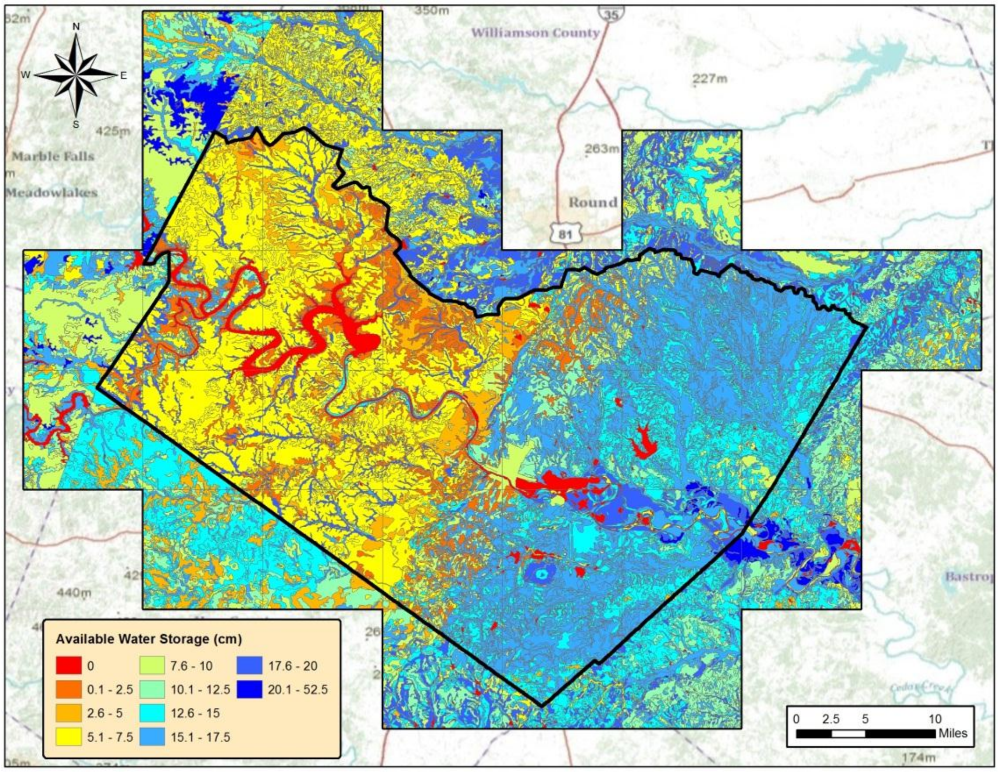


Figure 2. Map of SSURGO available water storage data for the 30 $^{1}/_{8}$ degree NLDAS quads that intersect Travis County, Texas, USA. The black line identifies the county boundary.

NLDAS data is output as one value per $^{1}/_{8}$ degree quad. There are many SSURGO soil polygons within each quad, so it was necessary to determine the best method by which to apportion the NLDAS current water storage data to the SSURGO polygons. It was resolved that the data should be apportioned on the basis of a volume ratio. The NLDAS current water storage value (in kg/m^2) was divided by the density of water (1000 kg/m^3) and multiplied by the area of the quad to produce a current water storage volume. The total available water storage volume of each soil polygon was calculated (i.e. the available water storage, in meters, multiplied by the area of that polygon, in square meters) and these values were summed, yielding the total available water storage of the quad. The current water storage volume was then divided by the available water storage volume, which produced a ratio that indicated the amount of the available water storage that was presently occupied. Multiplying each available water storage value by this ratio produces the current water storage as defined by NLDAS. As can be seen in Figure 3, a geoprocessing model was created to run this analysis automatically.

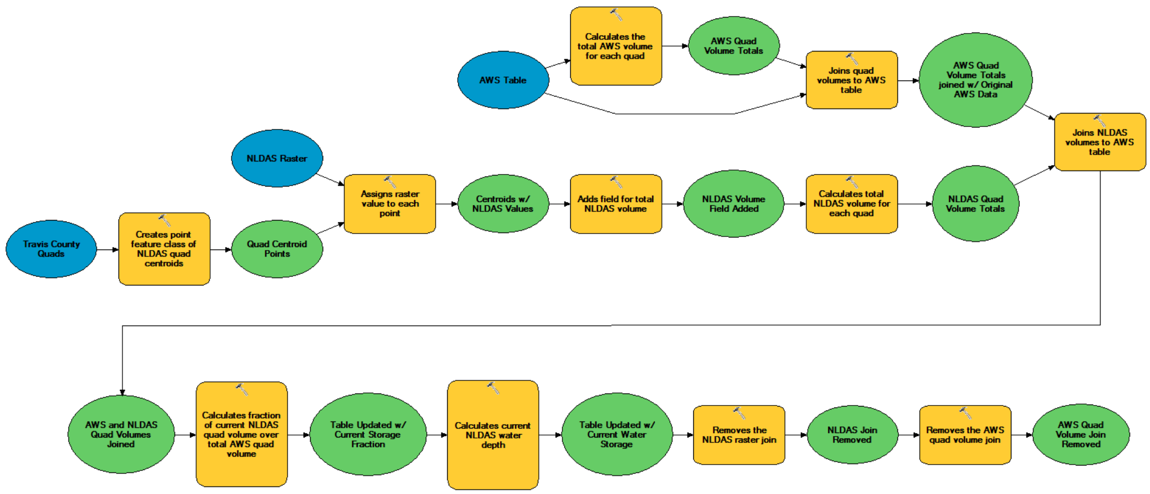


Figure 3. Initial geoprocessing model for the combination of the SSURGO and NLDAS datasets.

A significant problem was encountered at this point. In many cases, the NLDAS current water storage values were exceeding the values of available water storage from SSURGO. This is not physically possible, as available water storage is the maximum value of current water storage. Matt Rodell and David Mocko at NASA assisted in uncovering the reason behind this. It was at this point that the different available water storage definitions between SSURGO and NLDAS were discovered. As described above in the SSURGO Dataset section, SSURGO defines the available water storage as the difference between the field capacity and the wilting point. NLDAS, on the other hand, defines the same parameter as simply the field capacity - the difference between field capacity and zero soil moisture. This means that to appropriately deal with NLDAS current water storage data, the wilting point must first be subtracted so that the wilting point is then the lower limit of the data.

Even once this was taken into account, however, NLDAS current water storage values still exceeded the SSURGO available water storage capacity in certain areas. It was found that the datasets containing the soil parameters (e.g. field capacity and wilting point) on which the NLDAS model is based are approximately 20 years old, whereas the SSURGO data is more current. This is one explanation for the significant inconsistency between the SSURGO-defined soil properties and those used by NLDAS. This meant that the NLDAS current water storage, even once the wilting point was subtracted, could not be compared directly with the SSURGO available water capacity data.

Matthew Rodell of NASA suggested a solution to this compatibility problem. He proposed that the NLDAS data be employed on a relative basis, used only to obtain a sense of whether the soil is “dry” or “wet.” This assessment could then be applied to the SSURGO data to obtain a value of the actual current storage. As an example, if NLDAS ranges from 10-50 cm and SSURGO from 20-40, and the current NLDAS reading is 15, then it can be said that the soil is rather “dry” and that the current moisture content (based on the SSURGO data) is just above 20. A quantitative way to describe this is to define a soil wetness index (SWI):

$$SWI = \frac{CWS - WP}{FC - WP}$$

where CWS is the current water storage from NLDAS, WP is the wilting point, and FC is the field capacity. WP and FC are parameters from the NLDAS model, so they are defined for every $^{1}/_{8}$ degree quad across the country. This SWI calculation produces a value between 0 and 1 for each quad. The SSURGO available water capacity values within each watershed could then be multiplied by this soil wetness index in order to obtain an equivalent SSURGO current water storage.

In order to do this, though, the field capacity and wilting point parameters for the NLDAS model needed to be obtained. David Mocko explained that a STATSGO soil class is assigned to each $^1/_8$ degree quad within the NLDAS model. This soil class, numbered 1 through 19, is associated with certain values of soil parameters, including field capacity and wilting point. He provided a table with these soil parameter values, shown in Table 1. A grid is available from the NLDAS website that lists the STATSGO soil class for each quad (http://ldas.gsfc.nasa.gov/nldas/NLDASsoils.php, file named TXDM1_01.GRD). The quads that intersected Travis County were then culled from the soil texture class grid, and parameters were joined to each quad based on the soil class associated with that quad.

Table 1. STATSGO soil texture classes used in the NLDAS model.

Soil Class	Porosity	Field Capacity	Wilting Point	Description
1	0.339	0.236	0.010	Sand
2	0.421	0.383	0.028	Loamy Sand
3	0.434	0.383	0.047	Sandy Loam
4	0.476	0.360	0.084	Silt Loam
5	0.476	0.383	0.084	Silt
6	0.439	0.329	0.066	Loam
7	0.404	0.314	0.067	Sandy Clay loam
8	0.464	0.387	0.120	Silty Clay Loam
9	0.465	0.382	0.103	Clay Loam
10	0.406	0.338	0.100	Sandy Clay
11	0.468	0.404	0.126	Silty Clay
12	0.468	0.412	0.138	Clay
13	0.439	0.329	0.066	Organic Material
14	1.0	0.0	0.0	Water
15	0.20	0.17	0.006	Bedrock
16	0.421	0.283	0.028	Other (Land-Ice)
17	0.468	0.454	0.030	Playa
18	0.200	0.17	0.006	Lava
19	0.339	0.236	0.01	White Sand

With the NLDAS soil parameters acquired, it was now possible to calculate a soil wetness index for each quad. The map in Figure 4 below shows the NLDAS soil wetness index for February 11, 2012, for the 30 quads that intersect Travis County.

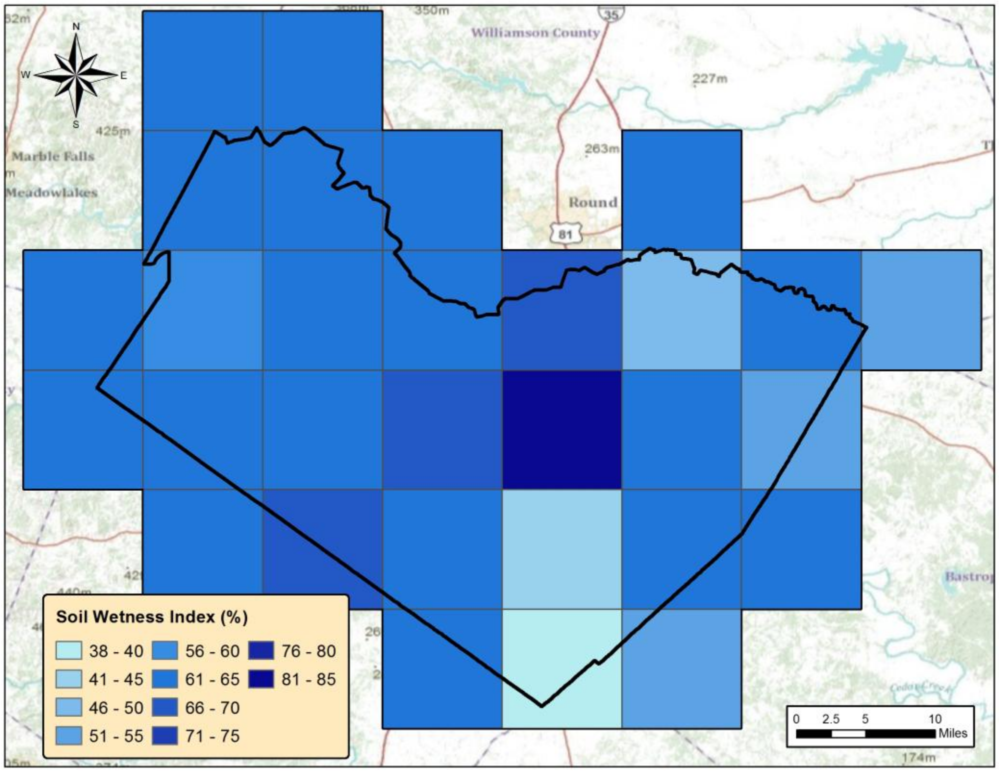


Figure 4. NLDAS-defined Soil Wetness Index (%) on February 11, 2012 for the 30 quads intersecting Travis County.

Another problem encountered was the fact that in many places around the border of Travis County, the SSURGO dataset displays significantly different values for available water storage within the county compared to the point directly across the border in the adjacent county. Many instances of these discrepancies can be seen in Figure 2, such as the change from yellow to blue along the southwest border and, even more significantly, orange to dark blue in the middle of the northern border. Such distinct changes are incongruous with the reality of the landscape; the lines separating counties are a result of differences in the soil mapping process, and ideally there should not be such noticeable changes at the county boundaries. Soil scientists in one county would map the soils within that county's borders while different soil scientists in an adjacent county would do the same, but the results from the two counties would not necessarily be reconciled so that their mapping agreed at the border where the two met. Unfortunately, this is difficult to correct because it would require a process to reconcile discrepancies in the soil mapping across the entire state.

These differences in available water storage values were significant because they demonstrated that accurately mapping drought at the scale of the SSURGO polygons was difficult. Since the SSURGO data would need to be combined with the NLDAS data, instead of translating the larger-scale NLDAS model data down to SSURGO's geospatial scale, the SSURGO data was scaled up. The USGS 12-digit HUC watershed boundaries were chosen for this synthesis. They exist at a suitable scale, much smaller resolution than the soil polygons but still finer than the model output. The average area of the HUC12 watersheds over the study area was 107.6 km^2, while NLDAS' $^1/_8$ degree quads had an average area of 166.5 km^2, resulting in a 65% downscale. The average available water storage value of the SSURGO polygons within each HUC12 watershed was computed, and the result is shown in Figure 5. As should be expected, the colors follow a similar pattern to Figure 2. Available water storage is less in the western part of the county where the arid Texas Hill Country is located and increases towards the eastern portion as the landscape changes.

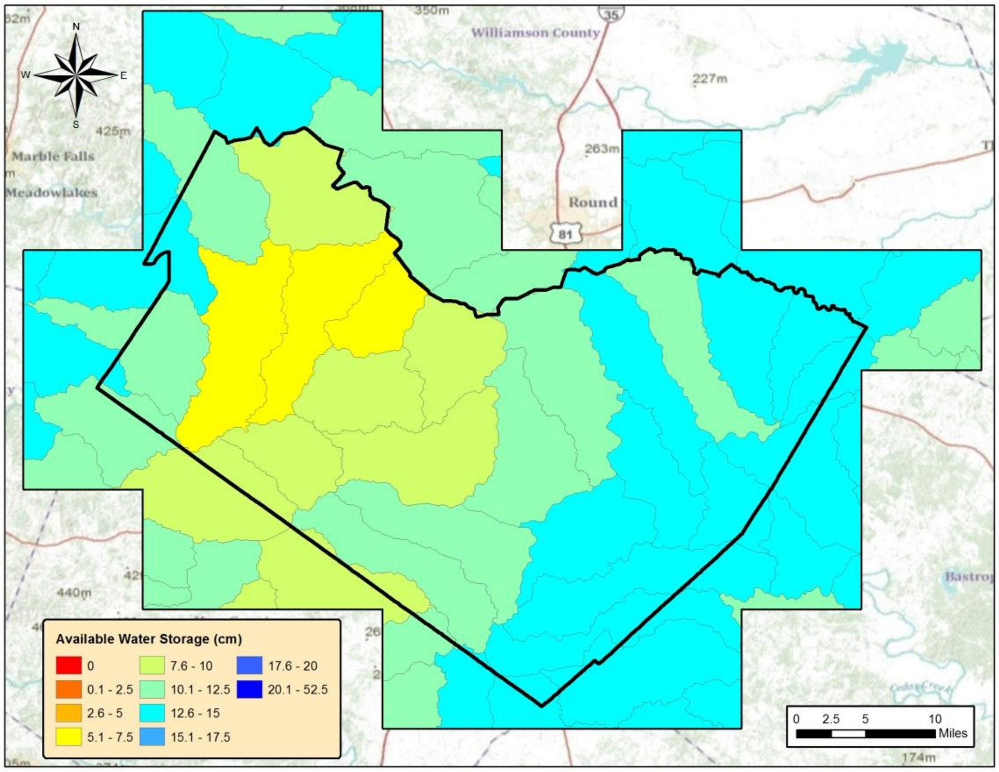


Figure 5. Map of average values of SSURGO available water capacity for each USGS HUC12 watershed boundary.

The geoprocessing model described above, which apportions the NLDAS current water storage to each SSURGO available water storage polygon based on the volume ratio, was now updated to incorporate calculation of the soil wetness index and multiplication of this ratio by the SSURGO available water storage, as well as mapping at the HUC12 scale. The model now yielded current water storage defined by a combination of SSURGO and NLDAS data. Figure 6 displays the soil wetness index on February 11, 2012 for each of the HUC12 watersheds intersecting Travis County.

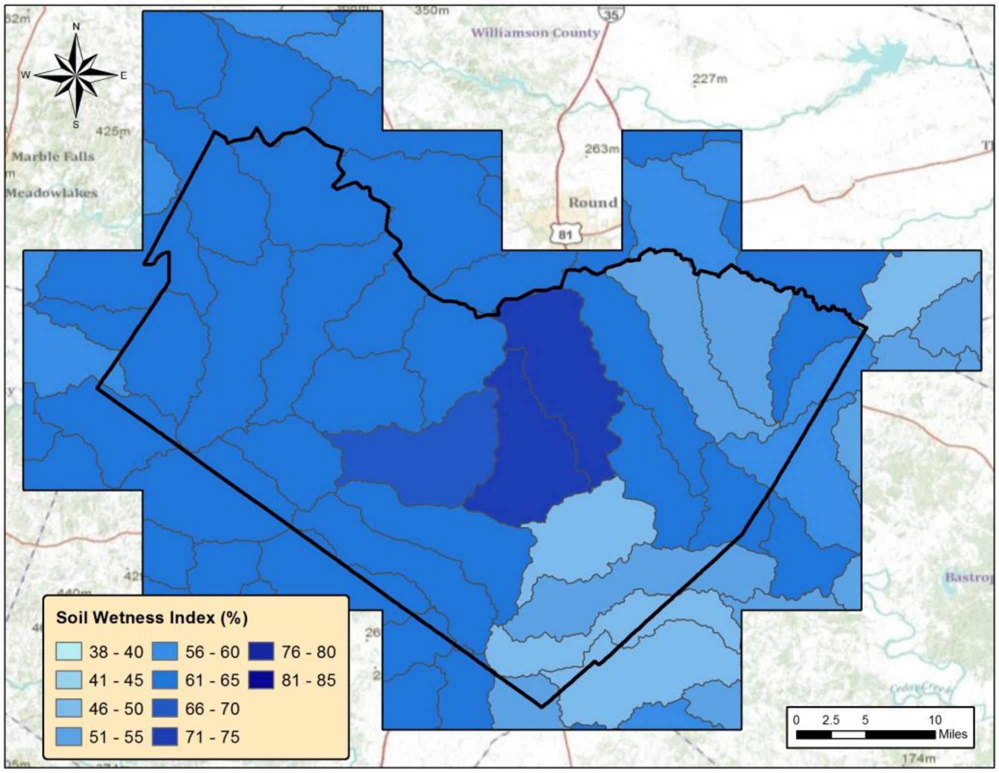


Figure 6. NLDAS-defined Soil Wetness Index (%) on February 11, 2012 for the USGS HUC12 watersheds that overlay the area defined by the 30 quads that intersect Travis County.

The SSURGO and NLDAS data had now both been scaled appropriately to the HUC12 watersheds, SSURGO as available water storage (in cm) and NLDAS as a soil wetness index. The multiplication of the available water storage by the soil wetness index yielded the current water storage (in cm), producing the map shown in Figure 7.

The soil moisture analysis for Travis County was now complete, and work began to apply this procedure at the state level. It was at this point that two important decisions were made regarding soil moisture mapping. Instead of mapping both the soil wetness index (a percentage) and the current water storage (a moisture depth in cm), it was decided that only soil wetness index would be mapped moving forward. A percentage immediately makes clear the severity of the drought, whereas a moisture depth is only useful if one also knows the maximum value possible for that soil. Secondly, although mapping at the scale of the USGS HUC12 watersheds was appropriate for Travis County, this scale was determined to be too fine for a statewide map. Instead, the soil moisture map for all of Texas would be displayed on a county basis. This scale is more appropriate in terms of the size of the area, it is the most useful for state planning agencies, and it is also a scale easily recognized and understood by the public, unlike the HUC12 watersheds.

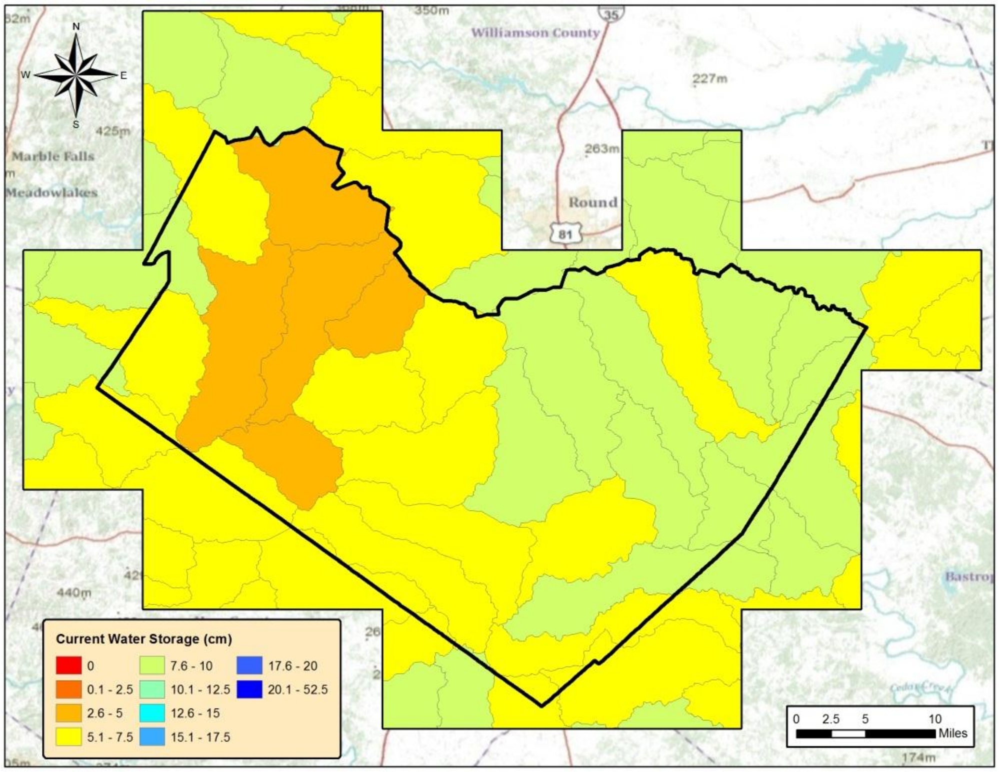


Figure 7. Current water storage (in cm) on February 11, 2012 for each USGS HUC12 watershed overlaying Travis County and surrounding area.

EXPANSION OF ANALYSIS TO STATE LEVEL

In order for the soil moisture analysis to be broadened to cover the state of Texas as a whole, the NLDAS soil moisture parameters (e.g. field capacity and wilting point) must be obtained for every NLDAS grid point across the state. Prior to starting this process, though, the team at the Center for Research in Water Resources became interested in determining the total available water storage of Texas soils. This would help elucidate the role of soil moisture in the state's overall water balance, including rivers, lakes, reservoirs, and the like.

The total available water storage amounts within the top 1 m and 1.5 m of soil were found to be approximately 78 and 110 cubic kilometers, respectively. This was calculated using STATSGO data (the U.S. general soil map) for Texas. It provides the same type of data that SSURGO offers, but at a coarser resolution; SSURGO data has approximately 1,200 soil polygons in Travis County, for instance, whereas STATSGO has 30. It was used instead of SSURGO because CRWR did not have access to SSURGO data for the entire state at that time. Statewide SSURGO data was eventually obtained. Although the decision had already been made to focus on mapping only the soil wetness index, the SSURGO data was acquired in case there was interest at some point in again calculating the current water storage by combining the NLDAS-defined soil wetness index with the SSURGO-defined available water storage data.

The statewide SSURGO data was obtained from Michael Dangermond at ESRI. The data is publicly available, but it can only be downloaded one county at a time. Thus this is not a practical method for acquiring data for every county across the state. From the backup SSURGO database he received directly from the NRCS, Mr. Dangermond was able to provide data at 25, 50, 100, and 150 cm depths. Once this data was examined, however, abrupt variations in available water storage values were found to exist. As with Travis County, these inconsistencies are likely due to a lack of inter-county verification of soil mapping and are not an accurate depiction of reality. The STATSGO map, on the other hand, is more representative of actual conditions, depicting a more continuous picture of available soil moisture content. The differences between these two datasets can be seen in Figure 8, with part (a) showing the SSURGO data and part (b) the STATSGO data.

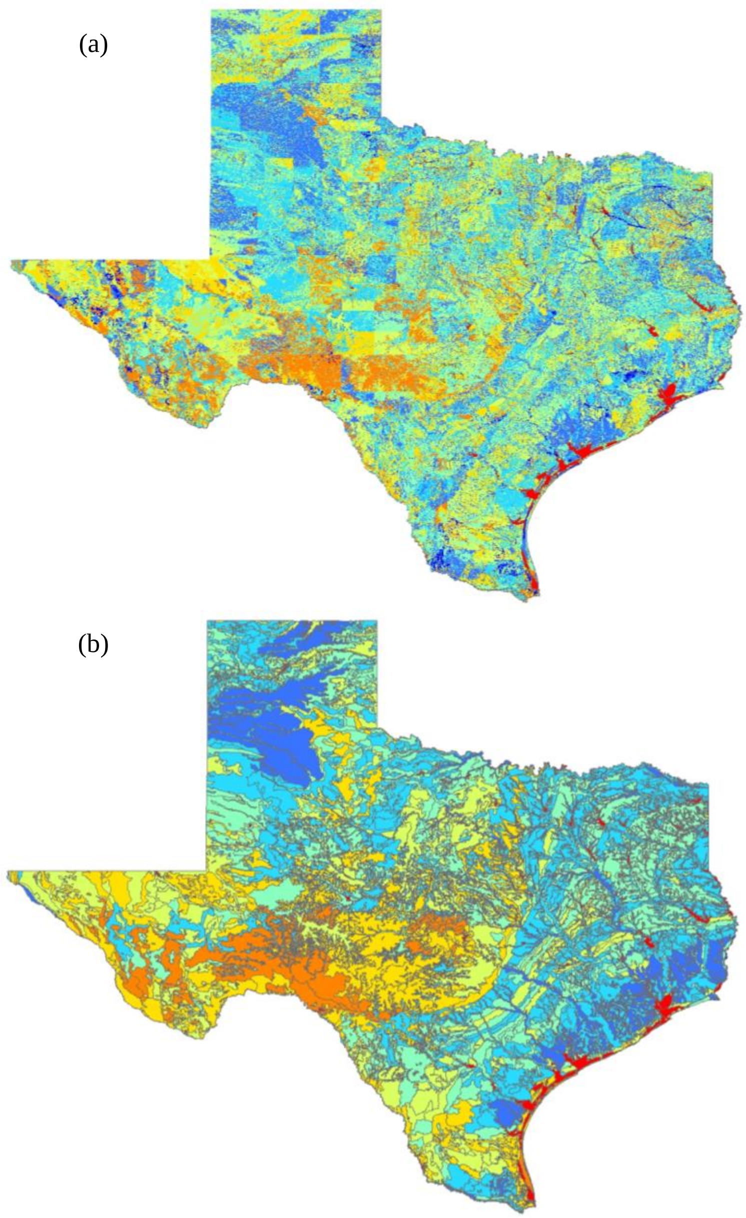
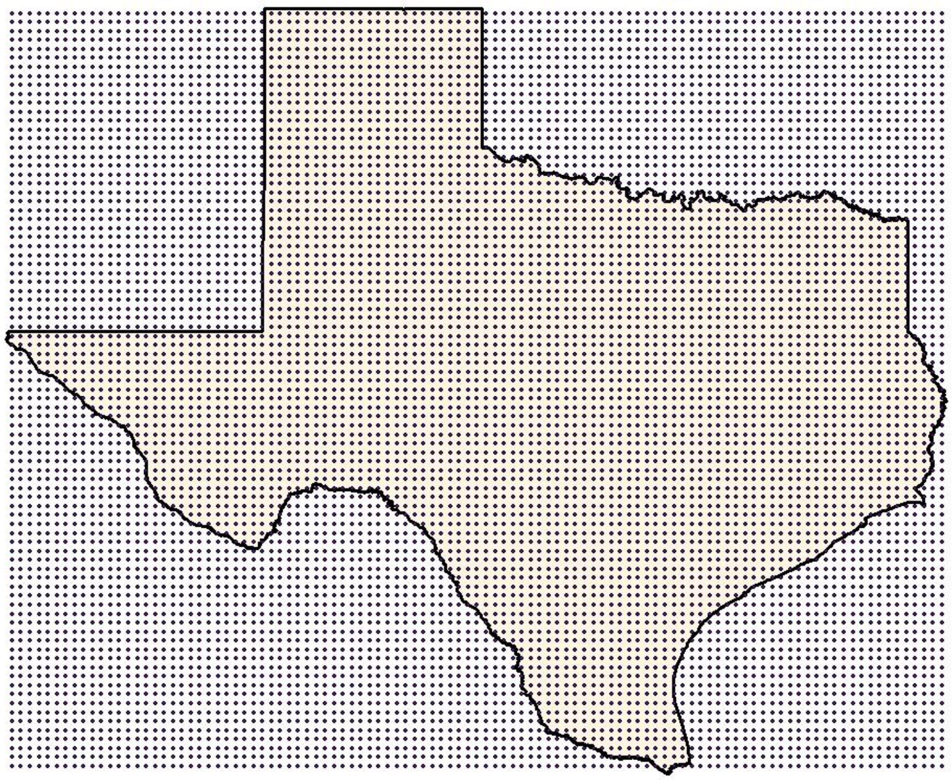


Figure 8. Comparison of SSURGO (a) and STATSGO (b) data for Texas.

It was now necessary to obtain the NLDAS soil moisture parameters across Texas. To start, the file “NLDASmask_UMDunified.asc” was downloaded from the NLDAS website. This file has the row, column, latitude, and longitude of every NLDAS grid point across the country, with the grid points being the centroids of the $^1/_8$ degree quads to which data is output. The geographic extent of Texas is from 93^{o}31’W to 106^{o}39’W and from 25^{o}50’N to 36^{o}30’N. The file was imported into Microsoft Excel, and all points that were outside those ranges were deleted. The file now contained grid points forming a rectangular area, the limits of which were the geographic extents of Texas. Figure 9 displays this area, with the NLDAS grid point and geographic coordinates of the corners.

(92, 148)
(36.438, -106.563)

(92, 252)
(36.438, -93.563)



(8, 148)
(25.938, -106.563)

(8, 252)
(25.938, -93.563)

Figure 9. Map of Texas overlaid by the NLDAS grid points that intersect the state, with the grid and *geographic* coordinates of the extents.

To ascertain the soil parameters of these grid points, the "TXDM1_01.GRD" file (downloaded from the NLDAS website and mentioned earlier in this report) was opened once again and culled to the grid extents of Texas determined above. The data was then converted from a grid into a series of three columns: (1) NLDAS row value, (2) NLDAS column value, and (3) STATSGO soil class. Three additional columns were then added: porosity, field capacity, and wilting point. The "vlookup" function in Microsoft Excel was used to obtain those three parameters for each grid point by referencing the values from the STATSGO soil class table (Table 1) based on the soil class associated with each point. Table 2 displays a small portion of this final parameter table for clarification purposes.

This data was now imported into ArcGIS using the "Display X-Y Coordinates" functionality. Since the grid is rectangular and includes areas outside of Texas, the "Select by Location" function was used to select only those NLDAS grid points that lay within Texas (a polygon feature class of the state of Texas was used for this process). This selection was then exported to a new point feature class, and the result can be seen in Figure 10. This completed the process of obtaining the NLDAS soil parameters across Texas.

Table 2. Example section of the table containing the soil parameters for every NLDAS grid point across Texas. There are a total of 8,925 grid points, but a small portion is displayed here for clarification of the data obtained for the analysis process.

Latitude	Longitude	Row	Column	Soil Class	Porosity	Field Capacity	Wilting Point
26.1875	-99.8125	10	202	6	0.439	0.329	0.066
26.1875	-99.6875	10	203	6	0.439	0.329	0.066
26.1875	-99.5625	10	204	6	0.439	0.329	0.066
26.1875	-99.4375	10	205	6	0.439	0.329	0.066
26.1875	-99.3125	10	206	12	0.468	0.412	0.138
26.1875	-99.1875	10	207	12	0.468	0.412	0.138
26.1875	-99.0625	10	208	12	0.468	0.412	0.138
26.1875	-98.9375	10	209	12	0.468	0.412	0.138
26.1875	-98.8125	10	210	12	0.468	0.412	0.138
26.1875	-98.6875	10	211	4	0.476	0.360	0.084
26.1875	-98.5625	10	212	4	0.476	0.360	0.084
26.1875	-98.4375	10	213	11	0.468	0.404	0.126
26.1875	-98.3125	10	214	7	0.404	0.314	0.067
26.1875	-98.1875	10	215	7	0.404	0.314	0.067

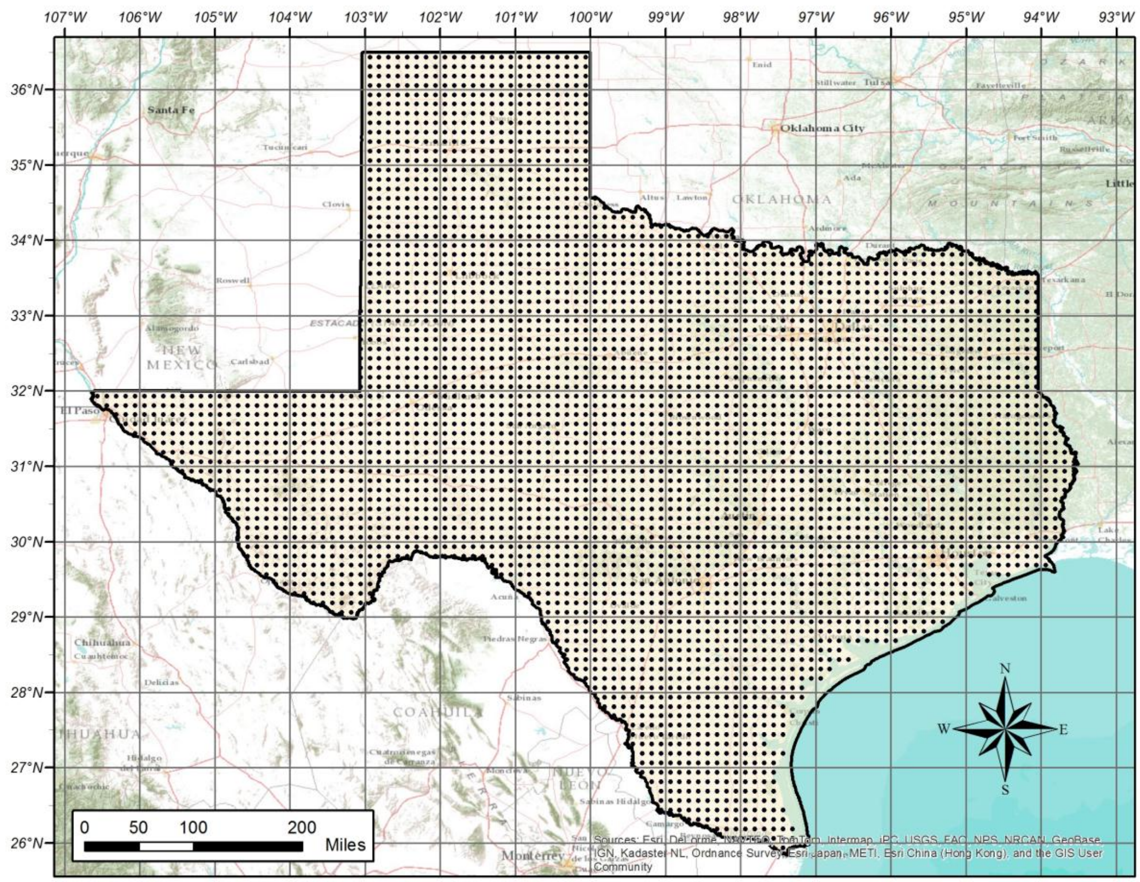


Figure 10. Map of the NLDAS grid points that intersect Texas.

The pieces were now in place to calculate the soil wetness index across Texas, and the geoprocessing model was updated to reflect these changes. One part of this update was to join the NLDAS raster (converted from a NetCDF to a raster using ArcGIS' "Make NetCDF Raster Layer" tool) to the NLDAS soil parameter point features. When it was run, though, some of the point features would receive raster values of '9999,' indicating no data. It was found that the extent of the NLDAS output raster was actually smaller than the soil parameters point feature class; the feature class contained points over the ocean, but the raster does not extend out across Texas' southeastern shore. To fix this, a new point feature class of soil parameters was created by selecting the grid points that did not have raster values of '9999' and exporting that selection. With that done, a map of soil wetness index across Texas was produced using data from August 23, 2011, during the height of the Summer 2011 drought. Going forward, the soil wetness index would be aggregated on a county basis, but this first map, shown in Figure 11, instead simply output to the NLDAS $^{1}/_{8}$ degree quads.

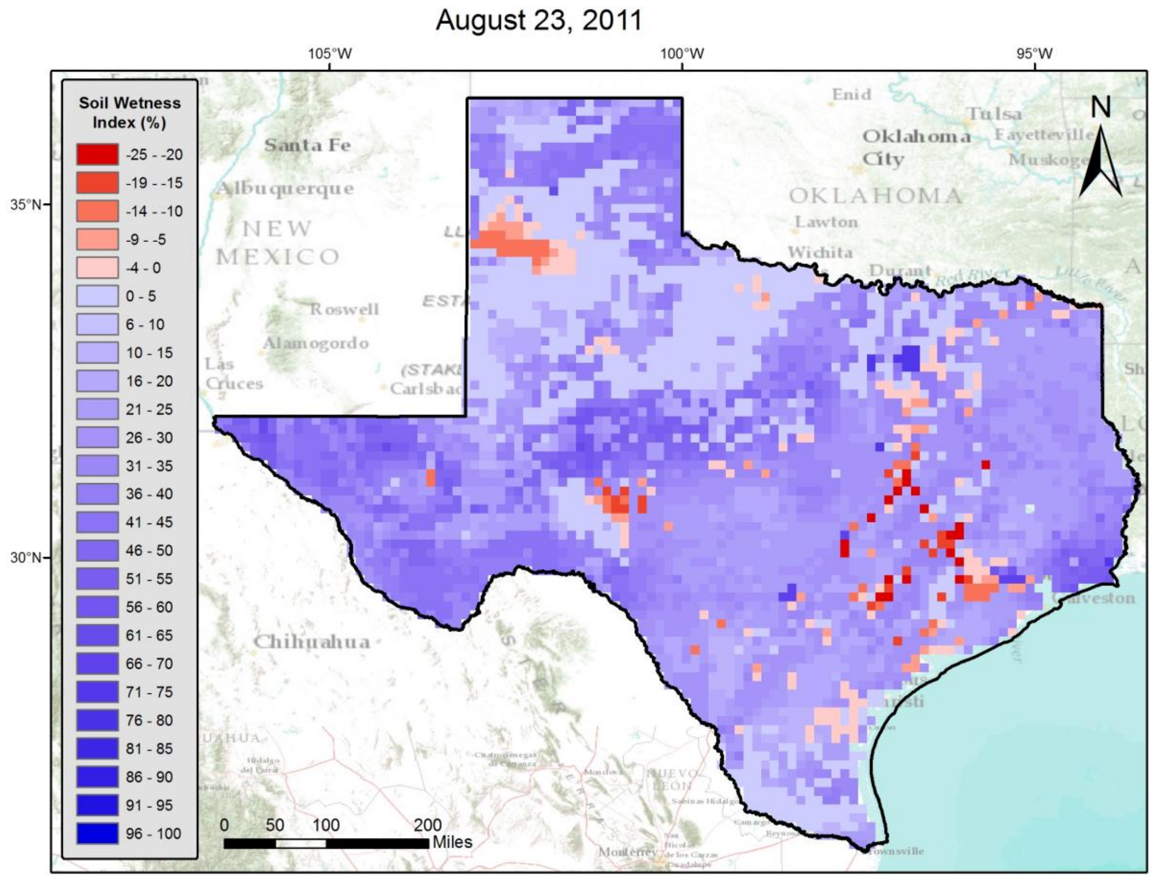


Figure 11. Map of Texas soil wetness index for August 23, 2011.

The red areas on the map in Figure 11 indicate $^{1}/_{8}$ degree quads in which the current water storage is less than the wilting point, resulting in a negative soil wetness index value. This is common during extreme drought. It was decided, however, that displaying negative soil wetness index values was not wise; negative moisture values would be difficult to explain to interested parties. Removing the use of the wilting point and field capacity parameters would have solved this problem, but this was not desirable because wilting point is a critical piece of information for a drought map that will be used by state agencies. As wilting point is defined as the amount of soil moisture content at which plants begin to die, and since many state agencies will be interested in how the drought is affecting agriculture, this is an important parameter of which to be aware. It is the point at which the actual effects of the drought become apparent.

It was decided that instead of displaying negative percentages when the soil moisture content falls below the wilting point, the SWI map should instead display zero, regardless of the magnitude of the negative value. The geoprocessing model was updated to reflect this. Additionally, the counties feature class was dissolved by the county number so that each county was a single polygon. It was also altered so that the soil wetness index was mapped onto the counties rather than to the $^{1}/_{8}$ degree quads. It is useful at this point to explain the complete soil wetness index mapping process employed by the ArcGIS geoprocessing model, seen in Figure 12.

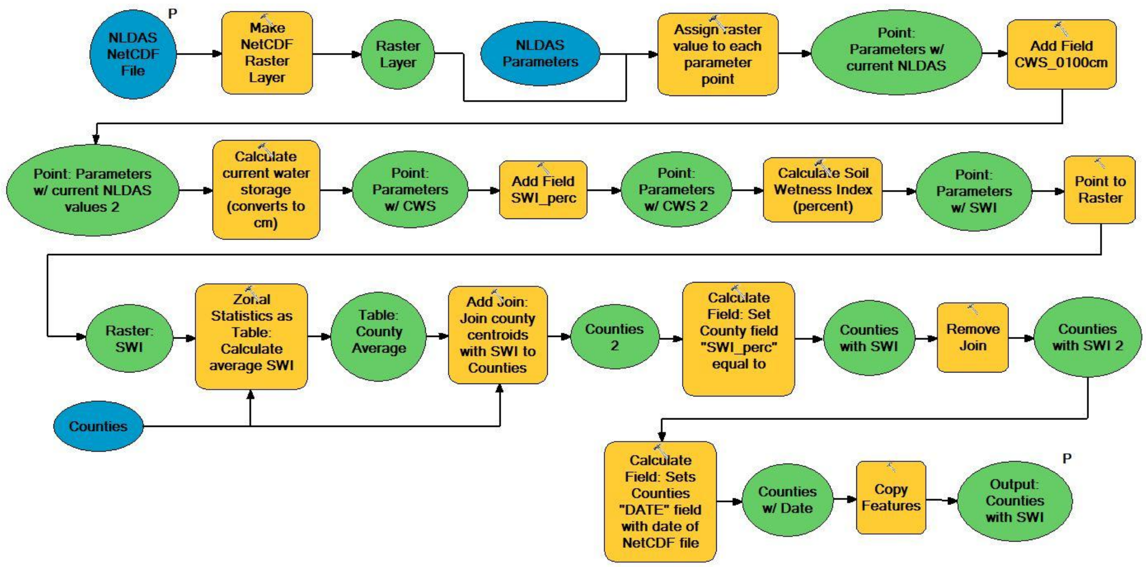


Figure 12. The geoprocessing model developed to map the NLDAS soil wetness index onto Texas counties.

The model takes as input an NLDAS NetCDF file (converted from the GRIB file format using the THREDDS-based process detailed above) and uses the "Make NetCDF Raster Layer" tool to convert that to a raster layer. A raster value is then assigned to each NLDAS soil parameter point using the "Extract Values to Points" tool. A field for current water storage is added to the point feature class, and the current water storage is calculated by dividing the raster values by 1000 kg/m^3 to convert them to centimeters. A second field is then added, this one for the soil wetness index. That is calculated using the equation shown earlier in this report, making use of the field capacity and wilting point, which are fields in the point feature class. That feature is then converted to a raster and the "Zonal Statistics as Table" tool, in combination with a feature class of Texas county boundaries, is used to calculate the average soil wetness index over each county. That table is joined to the counties feature class based on county number, and the "Calculate Field" tool is used to set the county soil wetness index equal to the average soil wetness index value. The join is then removed. The "Date" field in the counties feature class is updated with the date of the input NLDAS file. Finally, the counties feature class is copied to a new feature class for the specific analysis date.

With the geoprocessing model finalized, the soil wetness index could be mapped across the state. A number of examples of these final results are shown below. Figure 13 includes the raw NLDAS raster data from September 28, 2012 in part (a) and then displays the soil wetness index calculated from that NLDAS data and mapped onto each county in part (b). Figure 14 illustrates the progression of the drought of 2011, showing eight soil wetness index maps for the first of each month from July of 2011 to February of 2012. The improvement in soil moisture, and thus in the state's drought status, is clearly portrayed by the soil wetness index, with some areas that were at soil wetness index values of 10-20% during the drought reaching values of 80-90% by February of 2012. Finally, Figure 15 shows a plot the average soil wetness index across the state on the first of each month from January of 2011 to June of 2012. The decrease in this average value during the summer months of 2011 is due to the drought.

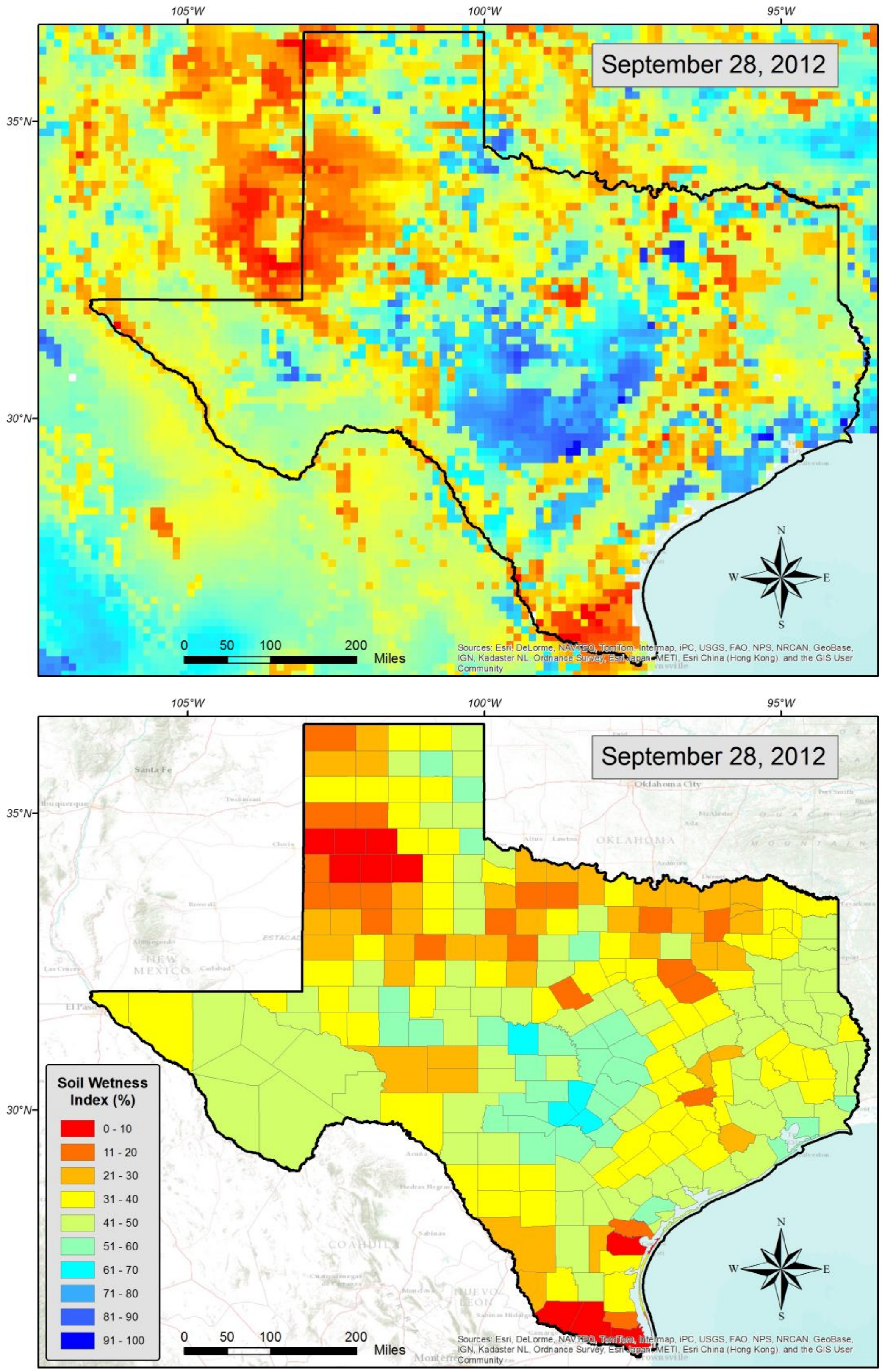
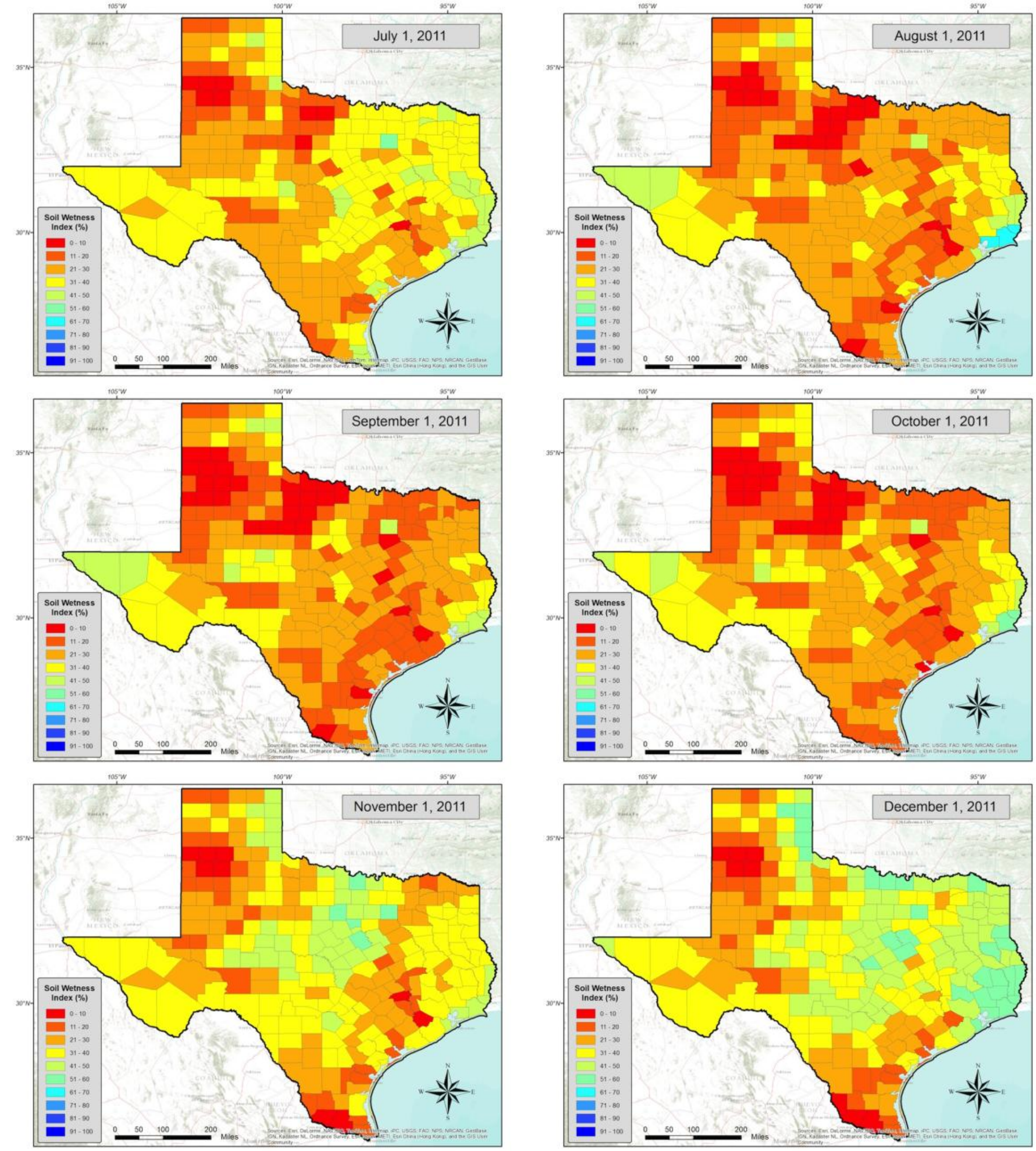


Figure 13. Data for September 28, 2012 displayed as (a) the NLDAS raster output in kg/m2

and as (b) the soil wetness index for each county.



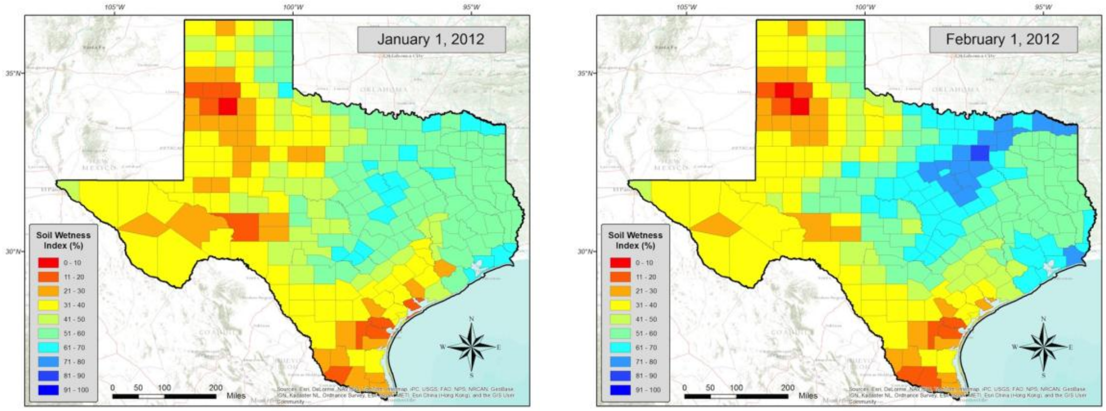


Figure 14. Maps of the soil wetness index for the first of each month from July of 2011 to February of 2012; shows the progression of drought across the state.

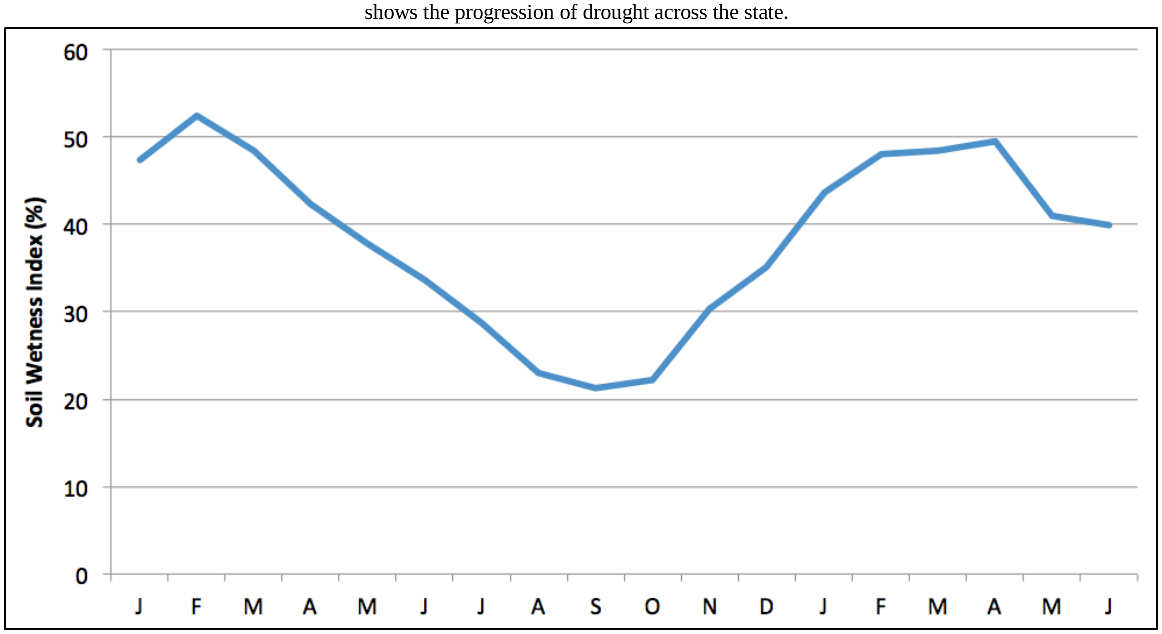


Figure 15. Plot of state average soil wetness index on the first of each month from January 2011 to June 2012.

NASA GRACE PROJECT

Dr. Byron D. Tapley of the University of Texas at Austin is working on a project that uses the GRACE satellites, which take measurements of Earth's gravity field, to measure the total mass flux of water across certain regions over time. A reduction in the gravity field indicates that the area of study has lost mass. In this way the change in the gravity field can be used to calculate the mass flux of water in the region. CRWR obtained the plot shown in Figure 16, which displays the total moisture surplus or deficit over the state of Texas from 2002 to 2012. The 2011 drought is clearly evident in the plot. Indeed, it was determined from this data that during that drought the state of Texas lost approximately 100 cubic kilometers of water storage, a volume equivalent to 70 times the volume of Lake Travis. A similar plot was made that looks at total reservoir storage in Texas for the same time period. Shown in Figure 17, it matches up very well with the trend of Figure 16.

Given the usefulness of these plots in understanding the effects of the 2011 drought on the state water balance, the team at CRWR sought to create a similar plot for soil moisture over the same time period. The first step entailed the conversion of the ArcGIS geoprocessing model described above to a script so that it could be automatically run for multiple time steps. This was accomplished by exporting it from ArcGIS to the Python scripting language, an option included in ArcGIS' Moldelbuilder. The output of the model is the average soil wetness index on the given date of analysis. In order to create a time-series plot of actual soil moisture, the soil wetness index must be multiplied by available water storage, resulting in the current water storage. This is what was done for Travis County before the project decided to focus exclusively on the soil wetness index.

As such, three additional steps were appended to the end of the Python script. First, each county's soil wetness index was multiplied by the average available water storage for that county. This storage value was calculated by intersecting the STATSGO data for 0-100 cm with the counties feature class and then averaging the STATSGO values over each county. Second, this current water storage value was multiplied by the area of the county, yielding the current water storage volume for the county. Lastly, the county volumes were summed across the state to calculate the total soil moisture storage for that time step.

To carry out this analysis, data was downloaded from the NLDAS ftp server for the 1st and 15th day of each month from January of 2002 through July of 2012. These files were loaded onto the THREDDS server and aggregated into a single NetCDF file, which was then downloaded and used as the input to the Python script. For each time step, the "dimensionValues" option within the "Make NetCDF Raster Layer" tool was updated to reflect the current date. The model then ran, calculating the soil wetness index for each county and carrying out the three additional steps described above. When complete, it produced the amount of current soil water storage that existed in the top 1 m of soils across the state for each time step. A plot of that output can be seen in Figure 18 below. The data for all three figures is in cubic kilometers, and they are lined up to allow for easy comparison.

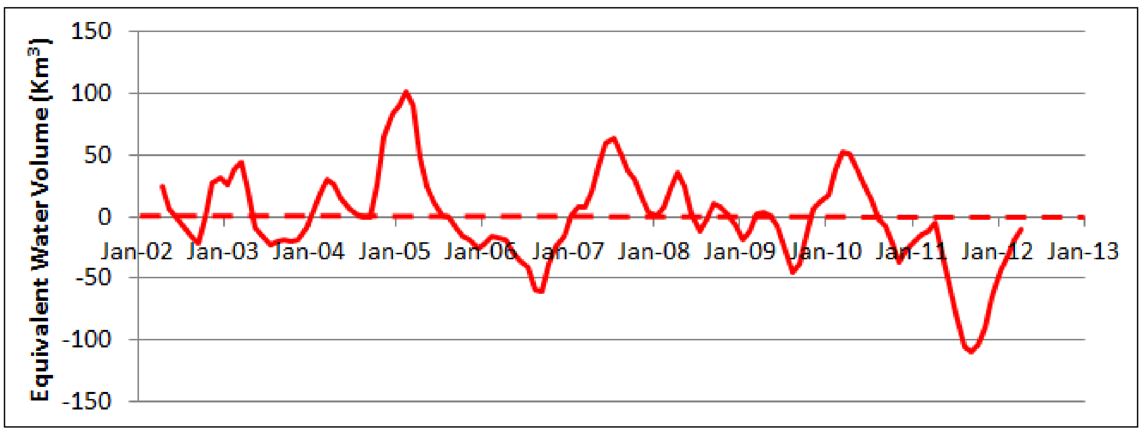


Figure 16. Water volume gains and losses calculated from GRACE gravity anomaly data for 2002 to 2012.

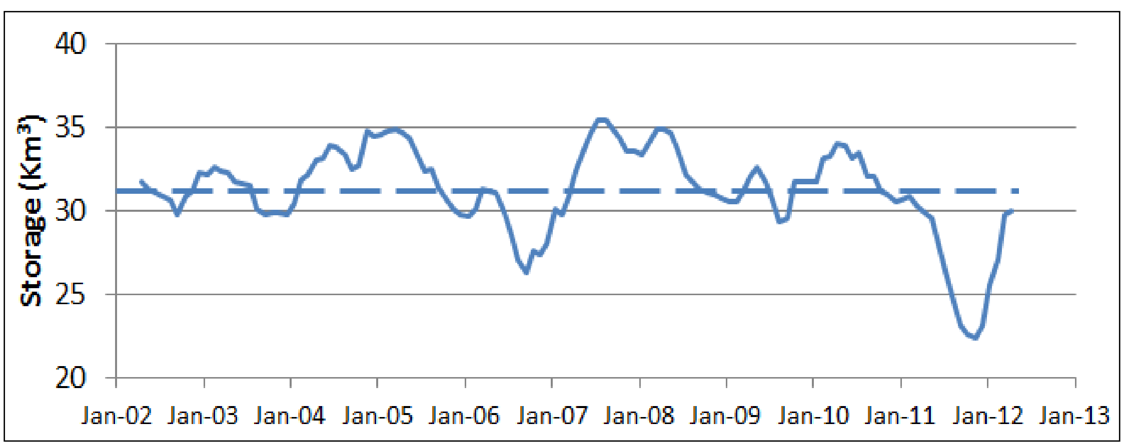


Figure 17. Changes in the water storage of Texas lakes and reservoirs from 2002 through 2012.

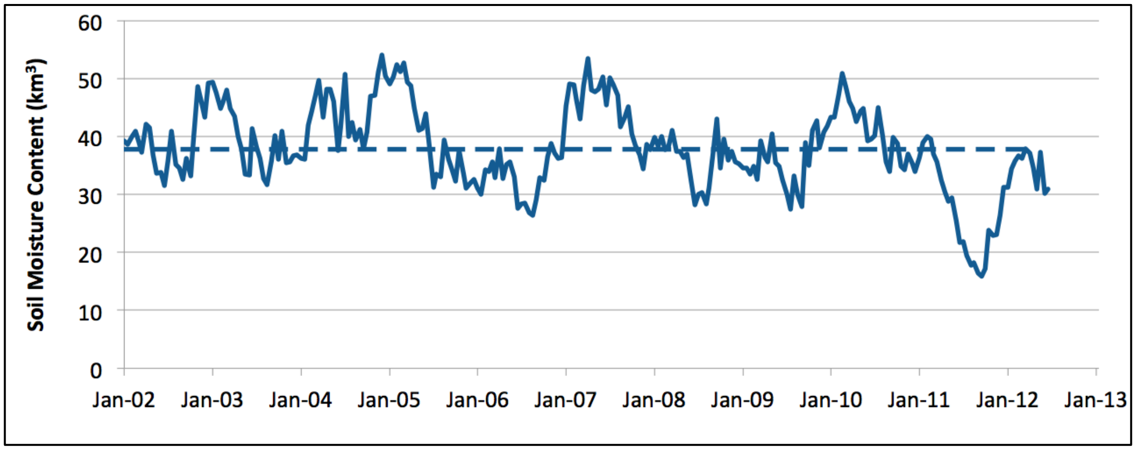


Figure 18. Plot of total soil moisture volume in cubic kilometers in the top 1 m of Texas soils. Data was plotted for the 1st and 15th of each month from January 2002 to June 2012. The dotted line represents the mean soil moisture volume over that time period.

It can be seen in comparing figures 16, 17, and 18 that the GRACE data accurately reflects the actual changes in water storage over time across Texas. The plot of soil moisture volume has a great deal of fluctuation, of course, but this is due in large part to the time steps that were plotted. The plot would be smoother if the monthly average were plotted instead of the values for the 1st and 15th of each month. Nevertheless, it is clear that the changes in soil moisture volume parallel the changes in overall storage (Figure 16) and the changes in the water storage of Texas' lakes and reservoirs (Figure 17). The Center for Research in Water Resources is continuing to examine the GRACE data and assessing how it can best be applied to analyzing the water balance of Texas and responding to extreme events, such as droughts.

STATISTICAL ANALYSIS OF SOIL MOISTURE DATA

The final component of the soil moisture mapping project involved a statistical analysis of historical soil moisture content data. The purpose of this analysis was to determine the significance of a given soil wetness index values within the context of the historical record. Until this point, the project succeeded in mapping current data, but there was no method by which to understand the importance of the current conditions. Without a statistical comparison, it is impossible to discern, for instance, whether a low soil wetness index value indicates drought, or if soil moisture content is simply perennially low in that region. The examination of historical data would allow for such a determination to be made. The project also evaluated the change in soil moisture over time across the state for approximately the past ten years, but that time period is not a sufficiently long enough record on which to base a statistical assessment; 30 years or more are needed in order to make any conclusions of significance.

The first step was to obtain historical soil moisture data. For this analysis, as for the rest of the project, NLDAS data for 12PM on each day were required. Although the data is available on the ftp server from 1979 through the present, the file structure makes it impossible to easily download the files for a certain hour of each day because every data file for a given month is contained within a compressed file for that month. As such, a Python script was written to download the compressed zip file for each month and extract from it the file for 12PM on each day within the month. When this was complete, CRWR possessed the NLDAS output files for each day from 1979 through the present.

Shortly after this was complete, however, NASA made available a new web service that allows the user to easily access the soil moisture content in kg/m^2 for each hour of every day from 1979 through the present for a single point. It is described as a "data rods" service because instead of showing the short-term change over time for a large area, it shows the long-term change for a single point. Figure 19 illustrates this conceptualization.

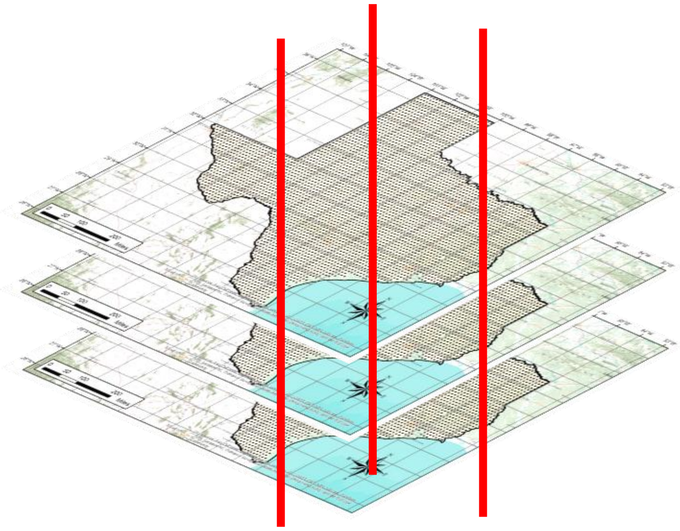


Figure 19. Illustration of the "data rods" concept. The red rods represent the time-series data available for the single points that they intersect across the state.

In this new web service, the user specifies both the start and end dates and the point location, either as geographic coordinates or as NLDAS grid point coordinates. Example URLs are shown below for the period from January 2, 1979 to October 17, 2012 and at the point with geographic coordinates (30.3125, -97.8125) and NLDAS grid point coordinates (42, 217).

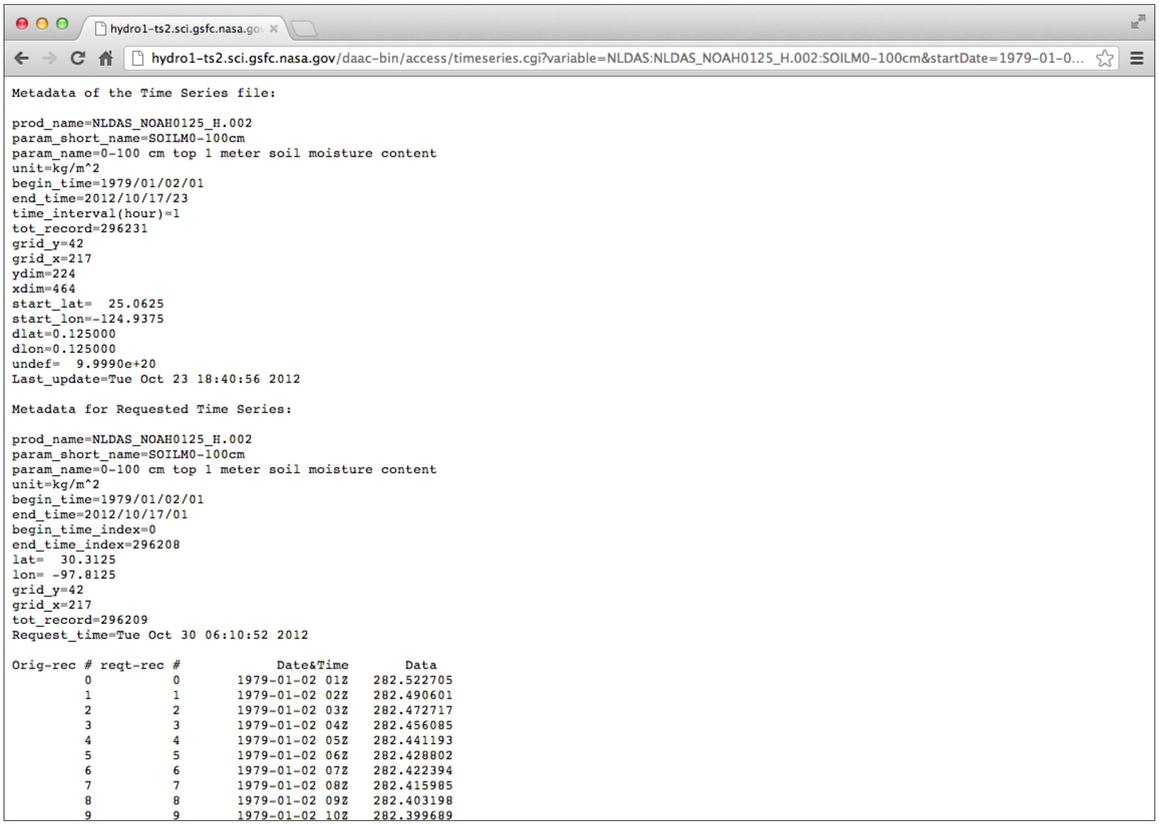
Location input as geographic coordinates:

http://hydro1-ts2.sci.gsfc.nasa.gov/daac-bin/access/timeseries.cgi?variable=NLDAS:NLDAS_NOAH0125_H.002:SOILM0-100cm&startDate=1979-01-02T01&endDate=2012-10-17T02&location=**GEOM:POINT%28-97.8%2030.3%29**

Location input as NLDAS grid point:

http://hydro1-ts2.sci.gsfc.nasa.gov/daac-bin/access/timeseries.cgi?variable=NLDAS:NLDAS_NOAH0125_H.002:SOILM0-100cm&startDate=1979-01-02T01&endDate=2012-10-17T02&location=**NLDAS:X217-Y042**

Additionally, Figure 20 shows what the website looks like when the data has been accessed properly. The metadata includes information about the parameter (top 1 m of soil moisture content), units (kg/m^2), start and end times, geographic and NLDAS grid coordinates, and the total length of the requested historical record. The soil moisture data is then displayed below this metadata with columns for an index, date, hour, and the soil moisture content. Eventually this data will be available in WaterML, a standard for the transmission of water data, but for now it must be manually processed as text from the website.


hydro1-ts2.sci.gsfc.nasa.gov/daac-bin/access/timeseries.cgi?variable=NLDAS:NLDAS_NOAH0125_H.002:SOILM0-100cm&startDate=1979-01-0...

```
Metadata of the Time Series file:

prod_name=NLDAS_NOAH0125_H.002
param_short_name=SOILM0-100cm
param_name=0-100 cm top 1 meter soil moisture content
unit=kg/m^2
begin_time=1979/01/02/01
end_time=2012/10/17/23
time_interval(hour)=1
tot_record=296231
grid_y=42
grid_x=217
ydim=224
xdim=464
start_lat=  25.0625
start_lon=-124.9375
dlat=0.125000
dlon=0.125000
undef=  9.9990e+20
Last_update=Tue Oct 23 18:40:56 2012

Metadata for Requested Time Series:

prod_name=NLDAS_NOAH0125_H.002
param_short_name=SOILM0-100cm
param_name=0-100 cm top 1 meter soil moisture content
unit=kg/m^2
begin_time=1979/01/02/01
end_time=2012/10/17/01
begin_time_index=0
end_time_index=296208
lat=  30.3125
lon= -97.8125
grid_y=42
grid_x=217
tot_record=296209
Request_time=Tue Oct 30 06:10:52 2012

Orig-rec # reqt-rec #         Date&Time        Data
        0          0       1979-01-02 01Z   282.522705
        1          1       1979-01-02 02Z   282.490601
        2          2       1979-01-02 03Z   282.472717
        3          3       1979-01-02 04Z   282.456085
        4          4       1979-01-02 05Z   282.441193
        5          5       1979-01-02 06Z   282.428802
        6          6       1979-01-02 07Z   282.422394
        7          7       1979-01-02 08Z   282.415985
        8          8       1979-01-02 09Z   282.403198
        9          9       1979-01-02 10Z   282.399689
```

Figure 20. Example of new NASA data rods soil moisture web service.

This web service is a critical development in the availability of NLDAS data, for it obviates the need to access the GRIB files that are the source of this data. Previously the user needed to download the file, which contained NLDAS output data for every NLDAS parameter and for the entire country-wide NLDAS grid, and then process it to extract the desired parameter and study area. If a user required a great number of GRIB files, this process became even more convoluted and required knowledge of writing code, as described above. Now the soil moisture data can be accessed directly. NASA will make improvements to this service in the near future, such as availability in WaterML and the ability to specify a polygon rather than just a point.

The example URLs above accessed information for a point within Travis County, shown below in Figure 21. Once the data was downloaded, the soil wetness index was calculated for each time step using the NLDAS soil parameters of that grid point, and a time-series plot was compiled for the entire data record. It is displayed in Figure 22. This plot makes evident that the 2011 drought resulted in soil wetness index values lower than at any other time in the 33-year historical record.

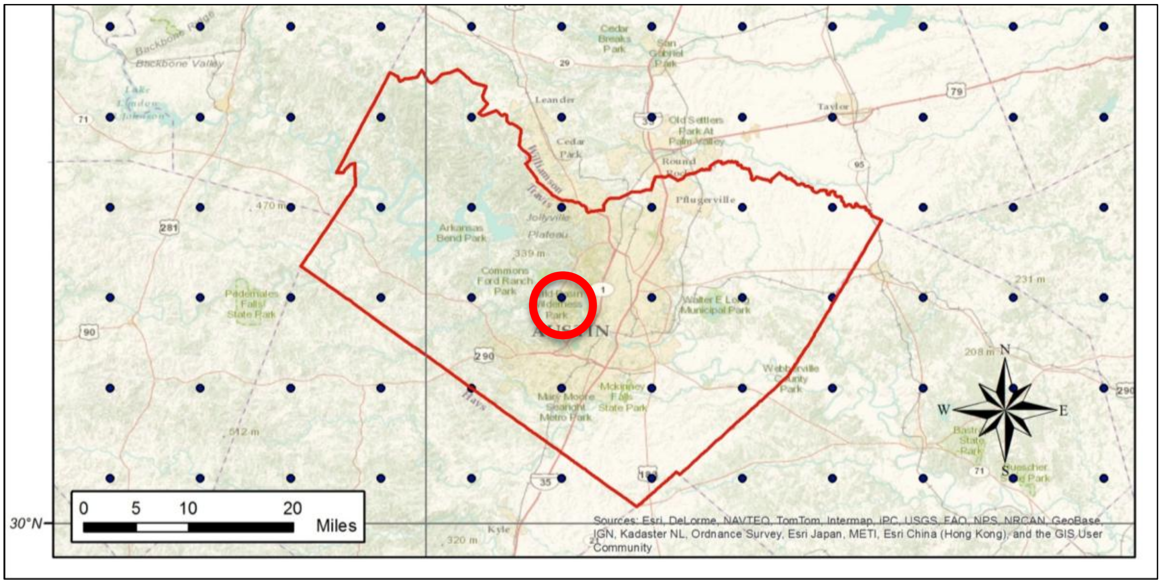


Figure 21. Location of NLDAS grid point in Travis County for which data was accessed from NASA's data rods web service.

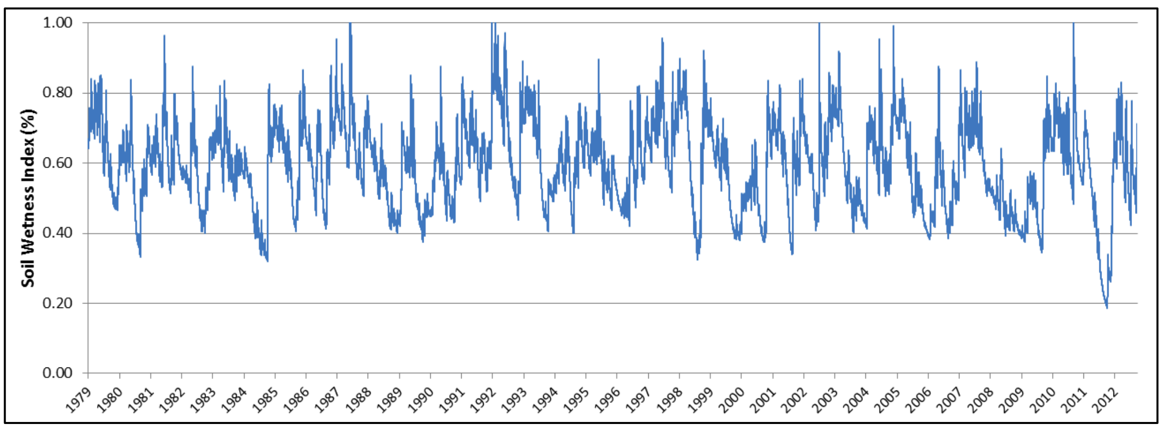


Figure 22. Time-series plot of soil wetness index (in cm) for the top 1 m of soil from 1979 through 2012 using data accessed from NASA's data rods web service.

The probability density function (pdf) and cumulative density function (cdf) were computed next, and are shown in Figures 23 and 24, respectively. Since the cdf shows the distribution of each value of soil wetness index over the historical record for the specified point within Travis County, it thus allows for current soil wetness values to be understood within a historical context. The soil wetness index on September 28, 2012 is 52.5%. To determine what percentile this falls within, one locates the value on the x-axis, draws a line directly up to the cdf curve, and then finds the corresponding value on the y-axis. In this case, 52.5% falls approximately at the 30th percentile, meaning that it exceeds 30% of the values over the 33-year dataset. The red arrows in Figure 24 illustrate this process.

In this case the soil wetness index did not match the soil moisture percentile. This means that the soil wetness index by itself is not a good metric for evaluating drought status. One could see the value of 52.5% and assume that the county is not particularly saturated but also not terribly dry either. But when the soil wetness index is combined with the statistical analysis of the historical record, it becomes clear that in reality 52.5% wetness is less moisture than has been present in the soils for 70% of the time from 1979 to present. This provides a much more complete understanding of the current moisture content.

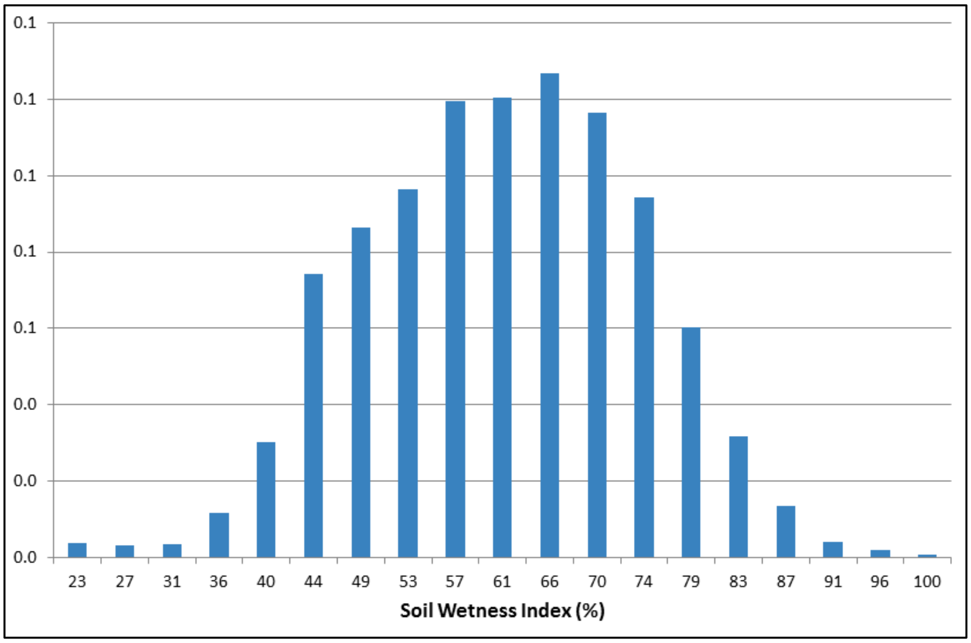


Figure 23. Probability density function for soil wetness index from 1979 through 2012 for a single point in Travis County.

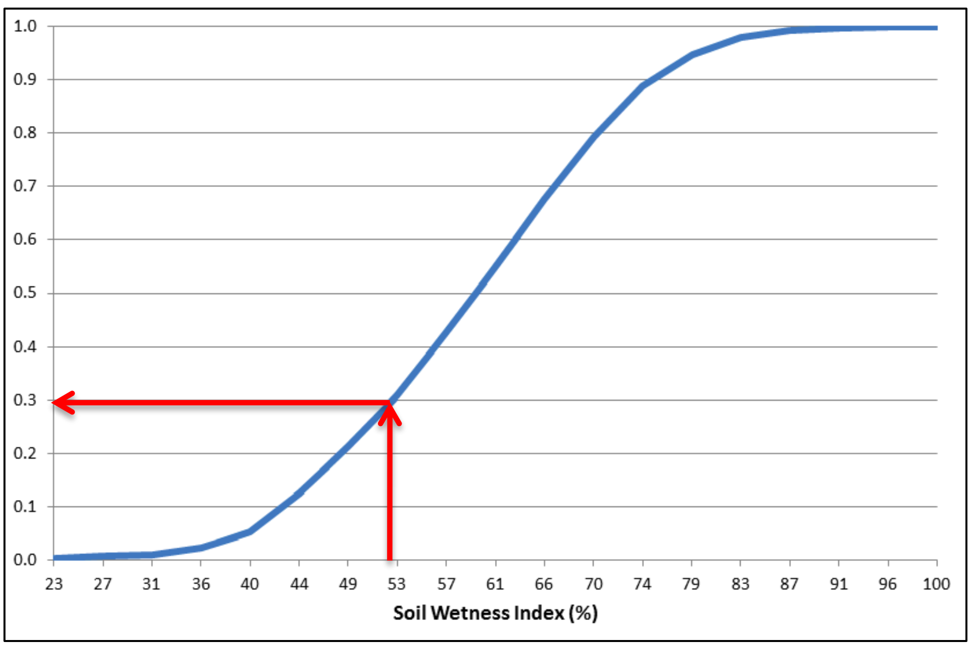


Figure 24. Cumulative density function for soil moisture content data from 1979 through 2012 for a single point in Travis County.

The statistical analysis described above has been completed only for the single point in Travis County identified in Figure 21. The team at the Center for Research in Water Resources will continue working on this aspect of the project. This will involve creating cumulative density function curves based on the average soil moisture content values for each county using the 33-year historical record. With that in place, each county's soil moisture content value will automatically have a probability percentile associated with it so that the historical significance can be understood.

CONCLUSION

A number of important discoveries were made over the course of this project. The team at CRWR learned that it can be difficult to extract and combine data from multiple soil datasets due to inconsistencies with the soil maps upon which they're based, as well as the age of the source datasets. Moreover, soil datasets don't always describe certain parameters in the same ways. The SSURGO dataset publishes available water storage. Defined as the difference between a soil's field capacity and its wilting point, it is the amount of moisture that is accessible to plants. The NLDAS model, on the other hand, includes in its output the moisture content in the top 1 meter of soil. As such, one might assume that this quantity's maximum value is the soil's available water storage, but this is not the case. Instead its maximum value is simply the total amount of water contained in that depth of soil. Because available water storage subtracts the wilting point, thereby neglecting any moisture below that level, these two parameters – available water storage and the total water content – are often not equal. This is the reason the NLDAS parameters (field capacity and wilting point) were accessed for each point across Texas and used to calculate the NLDAS-defined available water storage.

Despite these inconsistencies, it was found that the NLDAS land-surface model accurately simulates overall changes in the moisture content of soils. The actual magnitudes of the moisture contents do not always agree with what SSURGO defines as the available water storage, with the values often exceeding that definition, but the data can nevertheless be used on a relative basis. That is the theory behind defining the soil wetness index. Unfortunately, in its current format NLDAS data is prohibitively difficult for the common user to access and process, but NASA is working to improve this via new web services.

Ultimately, the project was a success. The team at CRWR learned that it's possible to use a land-surface model to produce an accurate and informative drought map based on soil moisture content. Through this development process it was also found that moisture in the top 1 meter of soils accounted for approximately 25% of the total water lost across Texas during the 2011 drought. The map was developed through the utilization of soil moisture data from the North American Land Data Assimilation System (NLDAS) and will serve as a valuable asset to planning and management within the state. The map displays the average soil wetness index – a relative measure of how much moisture is contained in the soils – for each county in Texas. A THREDDS server allows for automation of the process by which NLDAS data is acquired and converted to a usable format so that the map service, once published, will always display the most current data. A statistical analysis component was begun and will be refined in the future so that the current data can be understood in relation to historical data.

ACKNOWLEDGEMENTS

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