Nathan Williams
The University of Texas at Austin
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Calculating the Volume of Sand in the Voca Frac Sand District in McCulloch County Texas using Submitted Drilling Reports

Introduction

The Paleozoic Hickory Sandstone exposed along the flanks of the Llano Uplift in central Texas serves as the primary groundwater aquifer in McCulloch County (Mason, 1961) and is an important source of industrial sand, especially proppants for the hydraulic fracturing industry. Proppant sand production in Texas continues to increase as developments in unconventional petroleum plays made possible by hydraulic fracturing increase throughout the state. Several new sites for the production of proppant sand are in development above the water table in poorly cemented surface exposures of the Hickory Sandstone near Voca, Texas (Kyle and McBride, 2014). The primary objectives for this project were to (1) quantify the volume of Hickory sand in the Voca Frac Sand District and (2) determine how much of the formation is above the water table. Secondary objectives included measuring the amount of sand removed from pits as of early 2007 from LiDAR data and refining existing published geologic maps of the area.

Sources of Data

Data for this project came from a variety of publically available sources and from a dataset in Excel format with depths to the bottom of the aquifer measurements obtained from Dr. Rich Kyle that appeared to be compiled from drilling reports submitted to the Texas Water Development Board (TWDB).

GeoCommunity
Digital Elevation Model – WGS84 UTM zone 14N. 10m resolution 24K DEM mosaicked from 6 quadrangle tiles. These tiles lack metadata but the readme included in the download appears to be dated November 2000.
http://data.geocomm.com/catalog/US/61085/sublist.html

USGS Earth Explorer
LiDAR – NAD83 UTM zone 14N and NAVD88 vertical datum in LAS format collected 22FEB2007. 7 tiles were converted to raster and mosaicked to create the Voca DTM.
LANDSAT - LE70280392014277EDC00 LANDSAT 7 ETM +L1T WGS84 UTM zone 14N collected 04OCT2014.
http://earthexplorer.usgs.gov/

Texas Natural Resources Information System (TNRIS)
National Agriculture Imagery Program Imagery – NAD83 UTM zone 14N. 2012 NAIM 1m NC for Mason and McCulloch counties and 2006 NAIP 2m CIR for McCulloch county.
TxDOT Roadways 2014 – Road, Railroad, and Cities shapefiles for Texas clipped to the study area. Data was reprojected from GCS to UTM zone 14N to import into the Hickory mapdatabase.
USGS Quadrangle Indices – Index of USGS 7.5' quadrangles with names.
Texas Counties – NAD83 GCS StratMap shapefile of Texas Counties clipped to the study area.
http://www.tnris.org/

Texas Water Development Board
Geologic Atlas of Texas (GAT) 1:250,000 map – A simplified geologic map of the Llano region was acquired by request from the TWDB as part of a database compiled by Allan Standen as part of a contract report for the TWDB in 2007 (also available from TNRIS).

SDRDB – NAD83 UTM zone 14N shapefile of well locations compiled from submitted driller's reports.
GWDB – NAD83 UTM zone 14N shapefile of wells maintained by the TWDB.
http://www.twdb.state.tx.us/groundwater/data/index.asp

Preparing Base Maps

After viewing the GAT map of the area and NAIP imagery, I selected a study area that contained most of the Hickory exposed on the western flank of the Llano uplift in Mason and McCulloch counties. The Voca Frac Sand District was apparent in the imagery near the southern portion of McCulloch county near the county line.

1. I created a mosaic of the six 10m DEM images and used this mosaic to create a hillshade clipped to a polygon of the study area.

2. Created a new LAS dataset in ArcCatalog to contain the LAS data from the USGS covering the Frac Sand District.

3. I added the seven LAS files to the dataset and calculated statistics. The mean point spacing was approximately 0.66 meters but only approximately 24% of the returns were classified as ground returns. The remaining 76% of returns were unclassified.

4. I attempted to create a raster from the LAS dataset using the LAS Dataset to Raster tool. For an unknown reason, the software would not complete the conversion to raster. To work around the issue, I created individual rasters of the separate LAS tiles choosing the minimum value option, then mosaicked these rasters to form the Voca DTM at 1.5 meter resolution specifying spatial reference to NAD83 UTM zone 14N and the vertical datum to NAVD88. In hind sight, I would probably chose a slightly coarser spatial resolution for this DTM considering the spacing and large number of unclassified point returns.

5. I used the Hillshade tool under spatial analyst to create a hillshade of the mining area displayed with the percent clip stretch type.

Digitizing Geologic Maps

Initial review of the GAT 1:250,000 scale map of the area compared with NAIP imagery showed unit contacts that differed by several hundred meters in some places (See Figure 1). To account for this, and improve accuracy in interpolating the Hickory surfaces, three University of Texas at Austin masters theses that contained geologic maps at 1:24,000 scale were digitized and incorporated into the GIS. Rock Units, Contacts, and Faults were stored in the "Hickory" map database. Unfortunately, the bulk of the Frac Sand District lies outside the portions of the mapped quadrangles in these theses. The contacts drawn in the 1:24,000 scale maps were carried through the remainder of the map area from topography and vegetation relationships visible on the 10m DEM and the NAIP imagery when these boundaries were obvious, and from the contacts on the GAT map when they were not. A composite of LANDSAT bands 7, 4, and 2 was also created using the Composite Bands tool which showed promise in aiding further correction of contacts but ultimately fell outside the scope of this project. The resulting rock units feature was symbolized using the symbology of the GAT map and saved as a layer file.
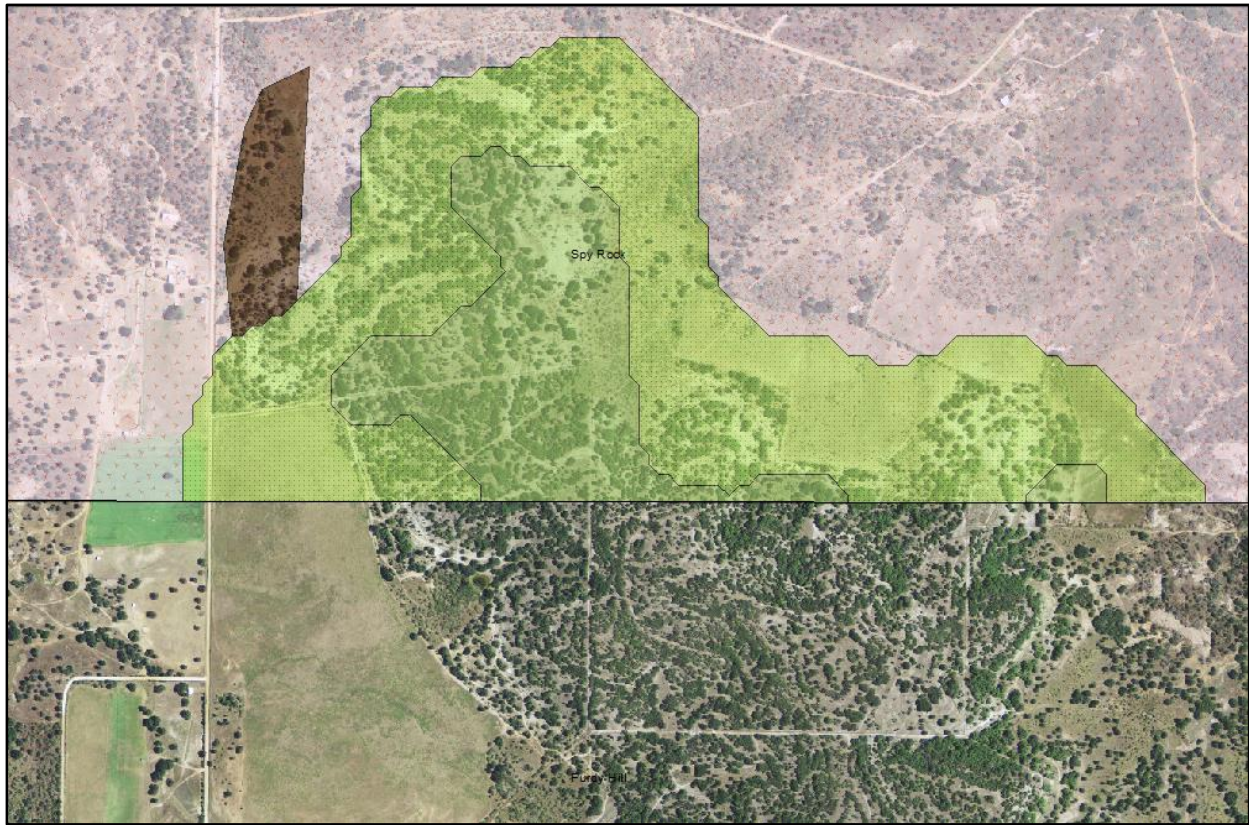
Figure 1. Cretaceous unit contacts from the GAT 1:250,000 map in green shown offset from actual contacts visible in 2012 NAIP imagery.

1. 1:24,000 geologic maps of the northern and northwestern portions of the Grit quadrangle (Le, 1993), southern portion of the Spy Rock quadrangle (Lydecker, 1988), and southern portion of the Katemcy quadrangle (Sheffield, 1995) were scanned using the map scanner in the Walter Geology Library.

2. I georeferenced and rectified these scanned images using corners of the quadrangles and major road intersections when visible on the 2012 NAIP imagery.

3. I created the Hickory geodatabase to contain digitized features and created feature datasets for Boundaries, Geology, Prop_Mines (frac sand mining areas), Structure, Transportation, and Wells. The spatial reference for the geodatabase was selected as NAD83 UTM zone 14N as that spatial reference seems to be widely used and much of the acquired data for this project was already in that format.

   a. The roads, railroads, and cities feature classes from TxDOT had to be converted to UTM Zone 14N projection using the Projections and Transformations tool in order to be imported into the geodatabase.
   b. After creating the feature classes, they were linked to appropriate domains created in the Hickory geodatabase.
   c. Contacts between rock units were digitized as lines, then following a validation of topology, converted to polygons and symbolized with the layer file contained in the Standen report.
   d. The scanned maps contained oriented strike and dip symbols with dips labeled, but no recorded measurements for strike. The strikes were digitized as lines with consideration to the "right hand rule."

e. A new field "STRIKE" was created in the strike dip feature class and populated using the python parser in the field calculator and the formula

*180+math.atan2((!Shape.firstpoint.X! - !Shape.lastpoint.X!),(!Shape.firstpoint.Y! - !Shape.lastpoint.Y!)) * (180 / math.pi)*

obtained from the ESRI geonet forum to assign an orientation with respect to north to all of the digitized lines. The attribute table for this line feature class was joined to a new point shapefile and symbolized to correctly orient these strikes on the map.
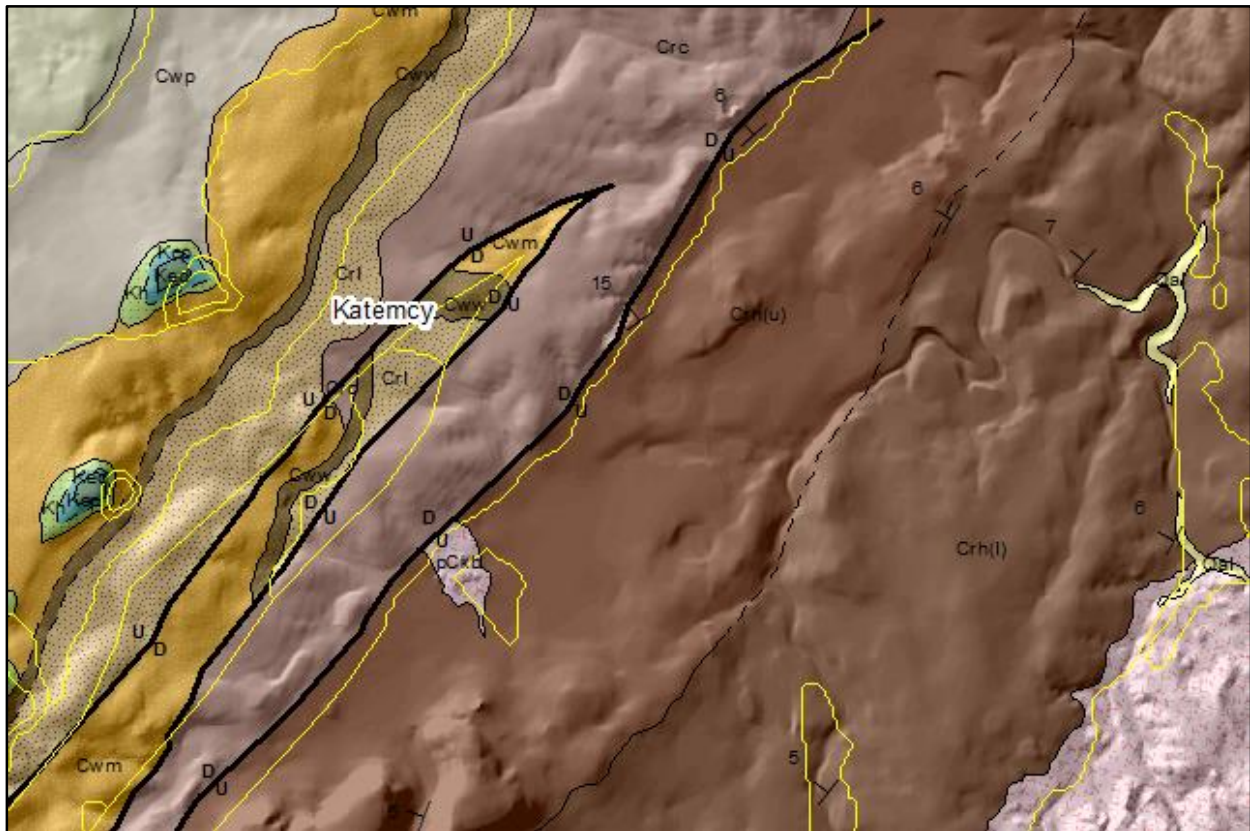

Figure 2. A portion of Katemcy quadrangle digitized geologic map drawn at 1:40,000 scale showing the improvement in contact location over the GAT map (yellow lines) with respect to topography. Strikes and dip symbols are drawn from calculated strikes as described above.

Importing Well Data and Creating Structure, Isopach, and Water Table Maps

1. The Excel file containing well locations with depths to the top and bottom of the Hickory were initially imported into ArcMap as XY data. This dataset had coordinates for wells in decimal degrees, but did not come with spatial reference metadata. After experimenting with several spatial references during import, NAD83 with a GCS projection appeared the most likely to be correct. However, after downloading and importing the GWDB well locations as a shapefile from the TWDB, there were discrepancies in the location of wells with the same well numbers between this shapefile and the imported XY data. To account for this, the data in the Excel table was joined to the attribute table of the GWDB shapefile with the assumption that the recorded spatial reference in the TWDB managed shapefile was correct.

2. After importing and joining the well shapefile with the Excel file, the Hickory was divided into sections bound by faults visible on the GAT map and digitized masters theses. The purpose of dividing the surface exposures of the Hickory was to try to differentiate between changes in apparent thickness due to faulting and changes due to variations in paleotopography. Although I divided the Hickory in the study area into three sections, the remainder of the study only focuses on the first section that contains the current frac sand mining area.

3. I had several options for creating structure and isopach maps of the Hickory from the well data. The first method would have been to use the spline tool under spatial analysis to interpolate the thickness of the Hickory, then subtract this isopach raster from the DEM using the raster calculator to obtain the base of the Hickory structure map. The second option was to calculate the elevation of the base of the Hickory at each well from the well depth and use these values in the spline interpolation. The base of the Hickory structure raster can then be subtracted from the DEM to obtain the isopach map. I determined that the second method would be best since this appears to minimize the range of values that will be used in the spline as it accounts for surface topography up front in the calculation.

   a. Converted the DEM in meters to feet using the raster calculator expression obtained from the TxDOT Survey Manual. This formula was used for all subsequent conversions of feet to meters and meters to feet.

   *"Elevation_M" * 3937 / 1200*
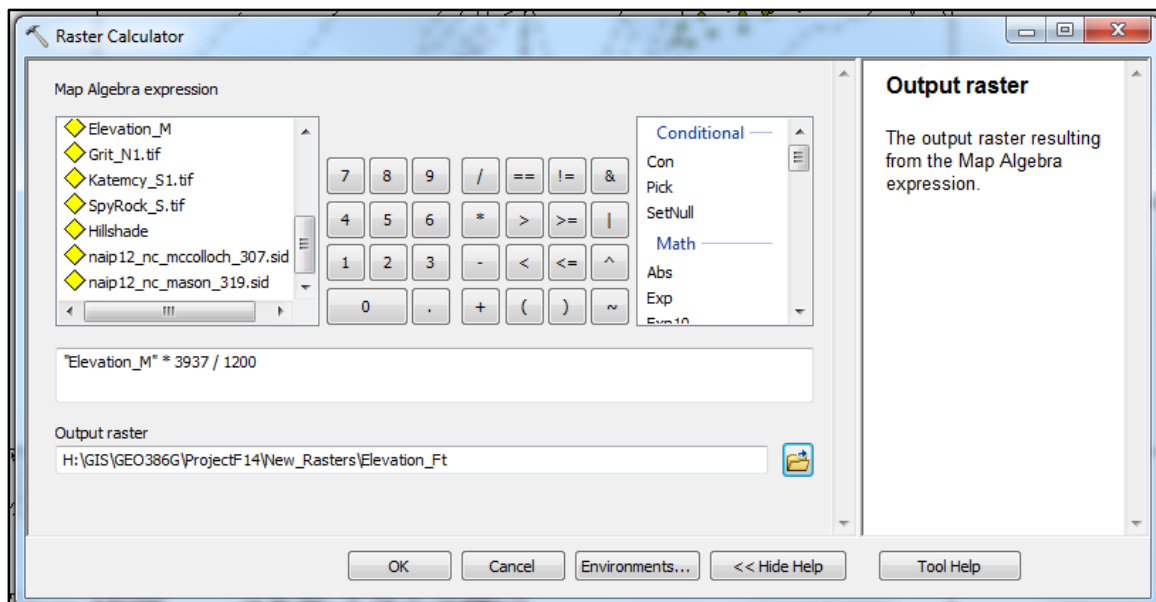
Figure 3. Raster Calculator expression to convert the DEM in meters to feet using the formula described by the TxDOT Survey Manual.

   b. Used the Extract Values to Points tool to record elevations in feet from the DEM at the location of each well in the GWDB well shapefile.
   c. Created a new short integer field in the GWDB well attribute table.
   d. Used the field calculator to calculate the elevation at the base of the Hickory by subtracting the distance to the base in feet from the elevation at the surface in feet using the formula:

   Bot_El_Ft = Elevation_Ft – Bottom_Of_Aquifer

6

e. This new field representing the elevations of the base of the Hickory was interpolated using the spline tool with a tension weight of 6 and 12 closest points and masked to the shape of Hickory section 1. These settings were determined by varying the inputs until the tool produced an acceptable output where the minimum and maximum thicknesses seemed reasonable from previous studies and the minimum and maximum values used in the spline. Although the shape of the raster surface did not vary much with changes in the input, the minimum and maximum values did. Before finding the appropriate inputs, I attempted to rescale the interpolated surface using the formula:

*[(grid - min value from grid) * (max scale value - min scale value) / (max value from grid - min value from grid)] + min scale value*

obtained from the ESRI user forum. This successfully rescaled the raster to the range of values I specified, but the thickness and elevation values at the well sites changed.

f. I subtracted the resulting raster from the DEM converted to feet to obtain the isopach map of the Hickory (Figure 4).
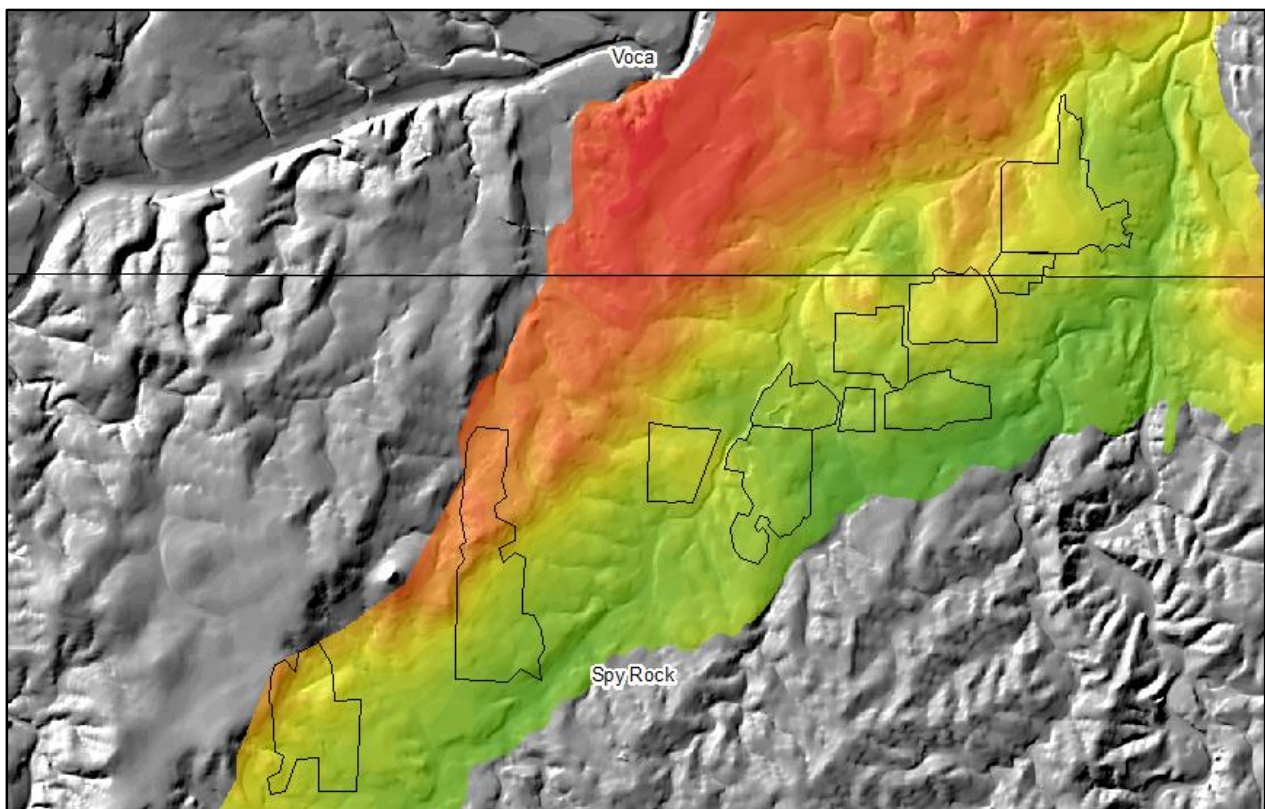
Figure 4. Isopach of a portion of the Hickory with the outline of Frac Sand Mining areas shown classified in 20ft Intervals at 1:50,000 scale. Red colors indicate the highest and green the lowest thicknesses. Values range from 6-380 feet.

4. The depth of frac sand mining in the Voca District is limited to the portion of the Hickory that lies above the water table which necessitated creating a model for the top of the water table. The TWDB manages a MS Access database for all wells in the GWDB shapefile that contains a field for depth to the water table from the land surface. After joining this database to the GWDB wells shapefile using the state well number as the key field, I sorted the data by the date of entry. There were no entries for the wells in section 1 with measurements later than

2010. To more accurately model the surface of the water table, I downloaded the Submitted Driller's Report Database (SDRDB) as a shapefile from the TWDB website. This database includes a link to online drilling reports since 2001 that contain depths to water surface measurements for certain wells at the time of drilling (Figure 5). Although the locations of the wells in this database are not validated by the TWDB, the information it contains is much more recent and includes wells in the study area from October 2014 and earlier.

    a. I downloaded the SDRDB shapefile for Texas and clipped it to the map area of interest.
    b. I created a new field in the attribute table for water level (Water_Lev).
    c. I manually input depth to water surface measurements for 51 wells drilled from October 2011 to October 2014 (included one well from October 2009 that improved coverage in the southern portion of the area of interest).

Water Level:	Static level: **62 ft. below land surface on 9/6/2014**
	Artesian flow: **No Data**
Packers:	**Rubber 105'**
Plugging Info:	Casing or Cement/Bentonite left in well: **No Data**
Type Of Pump:	**Submersible**
	Depth to pump bowl: **120 ft**
Well Tests:	**Jetted**
	Yield: **100 GPM with (No Data) ft drawdown after (No Data) hours**

Figure 5. A portion of a drilling report from the SDRDB showing the depth to water for a well in the study area of interest. Reports also contain descriptions of intervals and depths penetrated during drilling.

    d. Following the procedure described above for interpolating the isopach and structure maps, I used the Extract Values to Points tool under spatial analyst to record elevations at each of the SDRDB wells.
    e. I then created a new field in the SDRDB attribute table for Water Elevation and used the field calculator to populate the field by subtracting the depth to water from the surface elevation.
    f. Used the spline tool tension method with a weight of 6 and 12 nearest points to interpolate the surface elevation of the water table masked to Hickory section 1.
    g. Used the raster calculator to subtract the elevation of the water table from the surface elevation. Resulting values ranged from -29 to 210 feet. Positive values represent depth to water table surface. Negative values were in areas immediately surrounding streams and are the result of rapid elevation changes in those areas that were not accounted for in the interpolation because of a lack of nearby datapoints. These values were validated by comparing the original depth to water measurements from select wells (Figure 6).

8
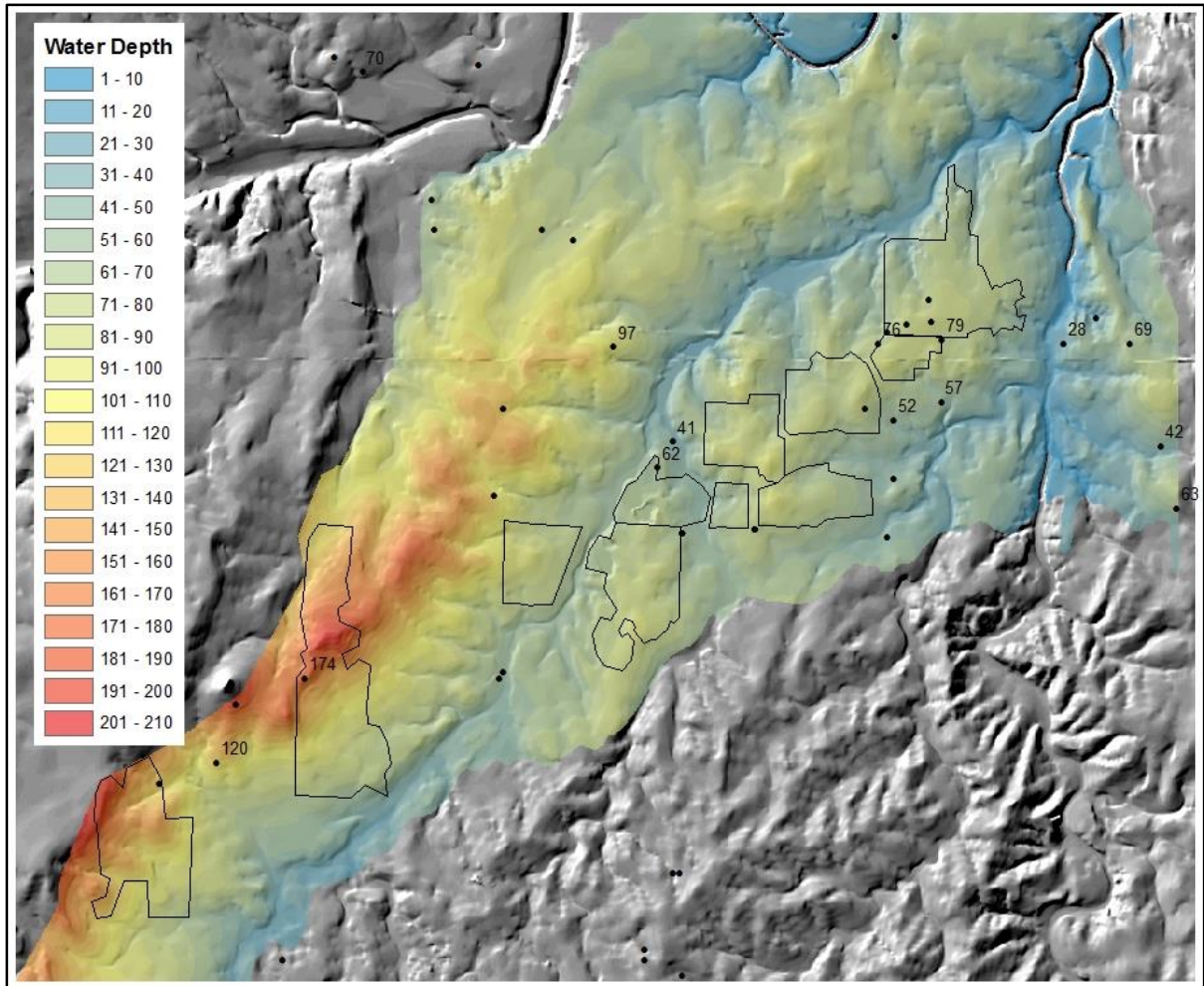
Figure 6. Water table depth from surface in feet shown with the outline of 2012 Frac Sand Mining areas. Uncolored areas in the north east portion of the image are areas calculated with negative water table depths corresponding to streams. Labels indicate depths to water measurements from drilling reports for the points used in the interpolation.

Calculating Changes in Surface Elevations from Mining as of February 2007

1. I created a new line feature class in the Hickory map database under Prop_Mines and defined the boundaries of the areas that appeared to be actively mined at the time the LiDAR data was collected in February 2007 using the Hillshade and a 2006 near color NAIP image (Pit_2006_Poly).

2. Since the DEM data is from 2000 or before, I subtracted the LiDAR derived elevations from the DEM using the raster calculator to show changes in elevation in the mining areas between when the DEM was produced and the LiDAR was collected. Positive values indicate the depth of mining and negative values indicate piles of sand (Figure 7).
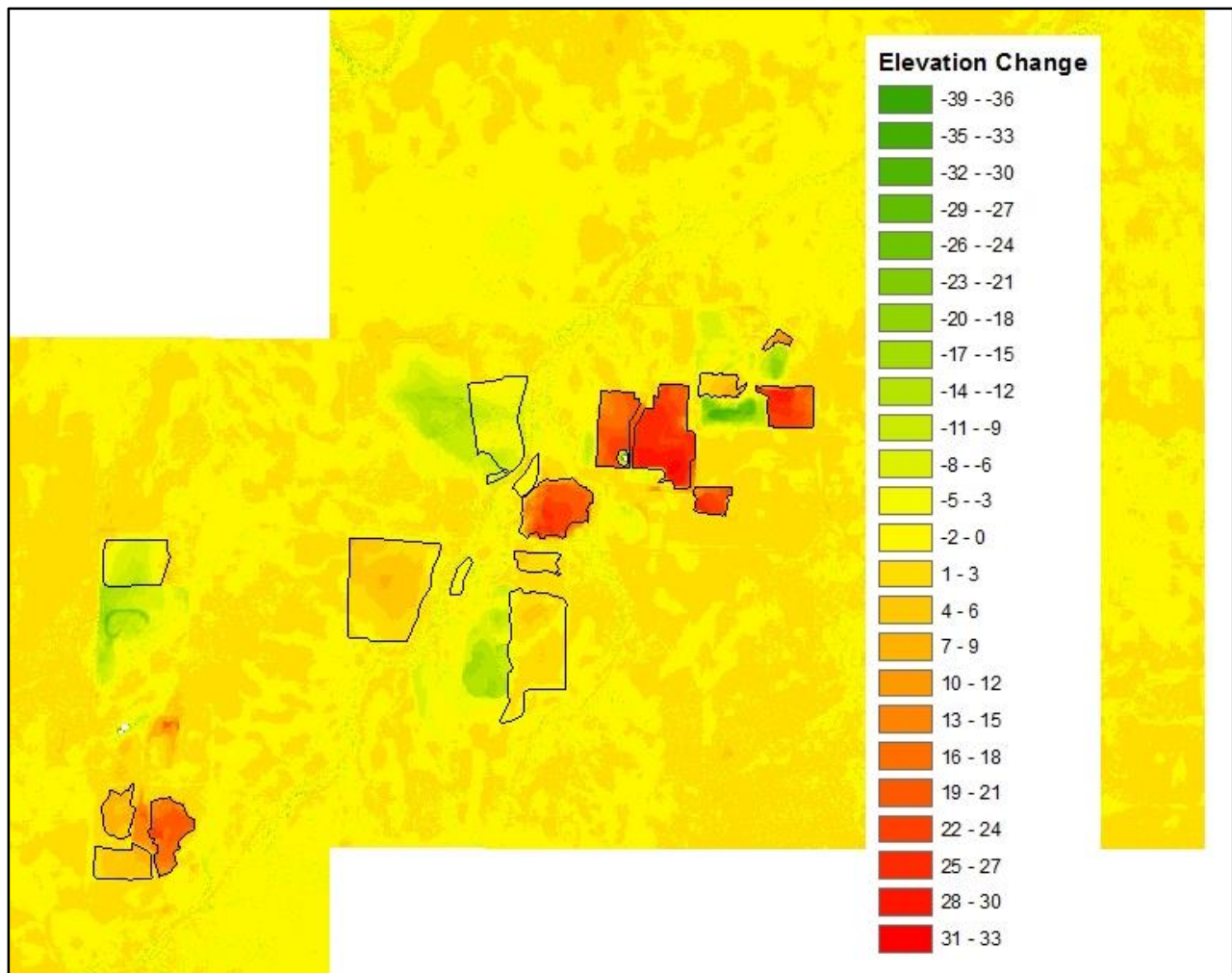
Figure 7. Elevation change in meters calculated by subtracting 2007 LiDAR elevations from 2002 DEM shown with the outline of 2007 sand mines drawn from a hillshade of the 2007 DTM. Red colors indicate decreased 2007 elevations and green colors indicate increased 2007 elevations.

3. From this change raster, it became apparent that some areas that were initially thought to be pits as defined from the hillshade did not actually have a significant elevation change. One possibility for this is that these features may represent reclaimed areas that had been filled in after mining was completed. It is also apparent that most areas even outside the mining areas have had either a positive or negative elevation change most ranging from -3 to 3 meters. I attributed this variation to processing the LiDAR data as a bare earth model and also to minor z direction errors in both the DEM and DTM datasets. I edited the Pit_2006_Poly polygon to select the 6 most obvious actively mined pits that represented the most dramatic elevation changes.

4. I converted the mined areas (Pit_2006_Poly) to rasters (Pit_06_ras) using the Feature to Raster conversion tool at 1.5m pixel size to match the DTM, then reclassified to a value of 1 using the Reclassify tool (Pit_06_reclas).

5. I used the raster calculator to multiply the Pit_06_reclas raster and the DTM_change raster to produce a raster that shows only the changes at the pit sites (Pit_06_Change).

10

6. This raster still contained a few large negative values, which are most likely the result of reflection off of a water surface during LiDAR collection. Additionally, the edges of several pits had negative values indicating that the pit polygon was initially drawn slightly too large. To account for this, I used the raster calculator to set all negative values to null using the expression:

SetNull("Pit_06_change" < 0, "Pit_06_change")

The resulting raster (Pit_06_Ch_pos) shows only areas of the pits that have a lower elevation than the interpolated pre-mining elevation (Figure 8).

Figure 8. Raster showing areas that have a lower elevation post mining. Areas in green contained negative values that resulted from errors in the LiDAR data and from an incorrect definition of the edges of the pits and were set to null by the method described above.

7. The next step was to calculate the volume of sand that had been removed from these pits. I used the Surface Volume 3d analyst tool with the reference set to above 0 to calculate the volume of sand removed from the select pits and determined the volume was 11,850,002 cubic meters. A 1999 study by Yongje Kim estimated the density of the groundwater aquifers in the region which include the Hickory at 2.7 g/cm3. Assuming this value, the amount of sand as of 2007 from the selected pits is equal to 4,388,890 metric tonnes or about 4.8 million short tons.

11,850,002 m3 / 2.7t/m3 = 4,388,890 tonnes * 2204.6/2000 = 4,837,873 short tons

Kyle and McBride estimate that the majority of frac sand produced in the area is from a 50-65 foot (15-20 meter) interval near the surface, so it is probable that the maximum elevation

change of 31 meters is incorrect. This is likely due to the selection of a bare earth model when creating the DTM. Most elevations on the map were lower by a meter or two in the DTM than in the DEM. However, the mean change in these pits of 20 meters seems reasonable.

8. The next step was to calculate the amount of sand remaining in the 2007 pits above the modern water table. Unfortunately, there were not enough wells from 2007 and earlier in the SDRDB to adequately interpolate the water table surface. Instead, I used a water table interpolation based on wells that have been drilled in the past three years as described above. Using the raster calculator, I subtracted the elevation change raster from the depth to water table surface raster. All of the 2007 pits appear to be within a few meters of the present day water table. I compared the resulting raster with 2012 NAIP imagery and symbolized negative values representing portions of the surface that are below the current water table in blue. Several of the pits have standing water in the photos that closely match what I predicted in the calculations (Figure 9).

Figure 9. 10 meter raster image at 1:16,000 showing sand remaining above the modern water table in 2007 pits. Negative values are symbolized in blue and show areas where the modern water table was calculated to be above the surface of the 2007 pit. The image on the right shows areas of standing water corresponding to the blue areas on the left.

9. Lastly I calculated the quantity of all sand remaining above the present day water table in the visible extent of 2012 mining using the technique described above.
   a. Traced boundary of mining area as of 2012 from NAIP 1m imagery.
   b. Converted the boundary polygon to raster using the feature to raster tool.
   c. Reclassified the resulting raster so all portions have a value of 1.
   d. Subtracted elevation change raster for the entire study area (shown in Figure 7) from the depth to water table raster.
   e. Multiplied the resulting sand above water table raster by the reclassified 2012 extent raster to clip all portions outside the mining areas.
   f. Set extreme values (all above 80m) caused by water returns in the LiDAR data to null using the raster calculator.
   g. I calculated the volume of sand in the 2012 extent with the Surface Volume tool and determined that there are 157,858,222 cubic meters of sand in the 5,362,337 square meters extent of the 2012 mining area remaining above the modern water table.
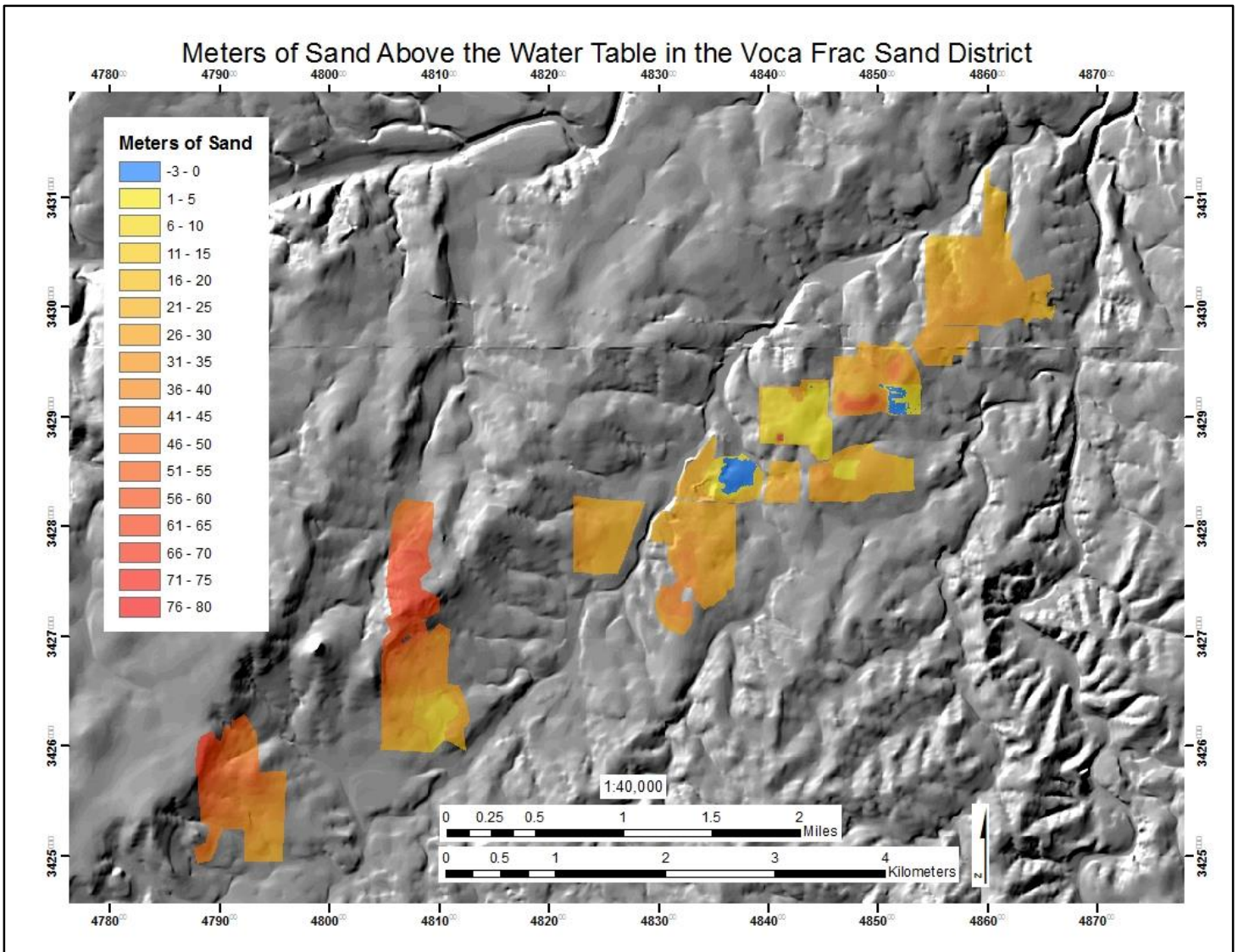
Figure 10. Outline of the 2012 extent of mining activity showing the quantity of sand above the water table at 10 meter spatial resolution and 1:40,000 scale. Blue areas represent areas where the water table is above the land surface and red areas have the largest amount of sand above the water table.

Conclusions

The limiting factor and greatest source of error in this project were publically available sources of elevation data in the study area. With additional LiDAR datasets for the area, this study could be repeated to further refine results. The lack of sufficient metadata for the 10m DEM used in this study makes it impossible to know exactly when it was created and this is obviously critical for studies involving changes in elevation over time. However, presence of water in areas estimated to be below the modern water table (Figure 9) provides at least some validation to the methods and results of this work.

The SDRDB is a valuable resource for low cost groundwater and subsurface geology studies. The distribution of the over 300,000 wells in this database and linked drilling reports provides enough detail to map subsurface features at a relatively large scale. This project could be additionally refined by using subsurface data from these reports.

Future work in the area should also focus on refining the location of geologic contacts from the GAT 1:250,000 map. This could potentially be accomplished using remotely sensed

LANDSAT and ASTER data, then validating the results in the field. The location of faults could be refined using LiDAR data where available.

The economic impact and massive potential for growth of the frac sand mining industry in Voca as fracking technology becomes even more widely implemented across Texas warrants additional large scale studies of the area. The results of these studies will potentially be beneficial to identifying other suitable areas for frac sand production in central Texas.

References

Barnes, V.E. and Bell, W.C., 1977, The Moore Hollow Group of Central Texas, University of Texas, Austin, Bureau of Economic Geology, Report of Investigations no. 88

Kyle, J.R. and McBride, E.F., 2014, Geology of the Voca Frac Sand District, western Llano Uplift, Texas, in, Conway, F.M., ed., Proceedings of the 48th Annual Forum on the Geology of Industrial Minerals, Phoenix, Arizona, April 30 - May 4, 2012. Arizona Geological Survey Special Paper #9, Chapter 2

Le, C.T., 1993, Geology of the Northern and Northwestern Parts of the Grit Quadrangle, Mason County, Texas: Masters thesis, University of Texas, Austin

Lydecker, W.F., 1988, Geology of the Southern Half of the Spy Rock Quadrangle, Mason and McCulloch Counties, Texas: Masters thesis, University of Texas, Austin

Sheffield, T.D., 1995, Geology of the Southern Half of the Katemcy Quadrangle, Mason County, Texas: Masters thesis, University of Texas, Austin

TxDOT Survey Manual, 2011, http://onlinemanuals.txdot.gov/txdotmanuals/ess/ess.pdf