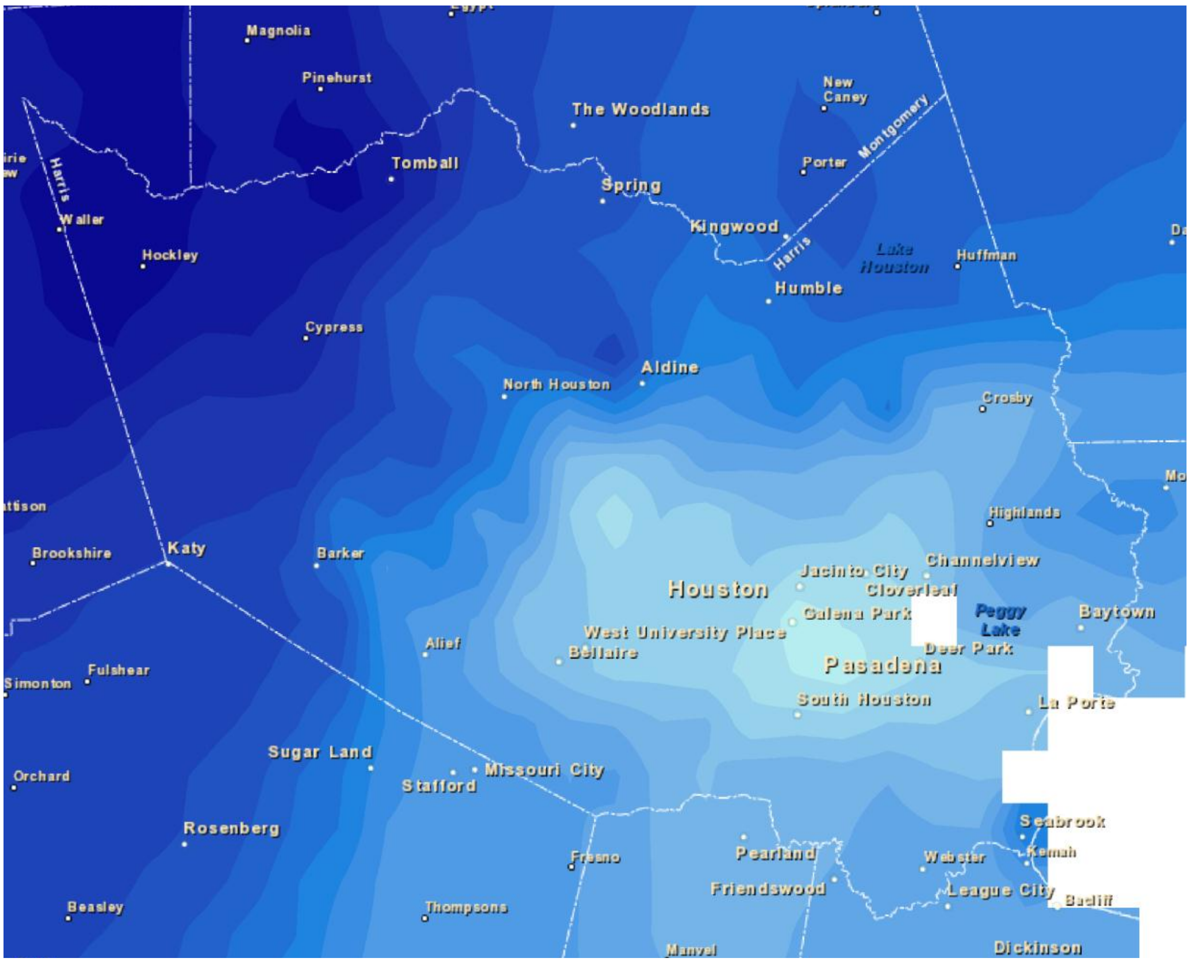
Subsidence Mapping in Harris County, Texas



Water Levels 1973

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CE 394K – GIS in Water Resources
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Table of Contents

Project Background

The Harris-Galveston Coastal Subsidence District was created in 1975 to control subsidence in the eastern coastal part of Texas that includes the greater Houston area and Galveston. This area has seen extensive subsidence mainly from groundwater pumping. Subsidence has increased the frequency and severity of flooding, damaged infrastructure, and caused substantial loss of wetland habitat. A visual example of the subsidence in the area is shown in Figure 1.

Figure 1: *This pump in Baytown, Texas, was level with the surface of the ground when first installed. Image provided by John M Sharp, PhD., at the University of Texas at Austin.*

The primary municipal groundwater sources in the Houston-Galveston region in the past century have been from the Chicot, Evangeline, and Jasper aquifers, which is a part of the Gulf Coast Aquifer system shown in Figure 2. Since 1973, the U.S. Geological Survey (USGS) and Texas Water Development Board (TWDB) have monitored water levels in the region along with clay compaction in Harris and Galveston Counties.

Figure 2: *The Major Aquifers of Texas are shown above. Harris County is shown in orange overlying the Gulf Coast Aquifer System.*

As shown in the cross section in Figure 3, several minor aquifers lie below Harris County and adjacent counties as part of the Gulf Coast Aquifer System. The Chicot aquifer is the topmost aquifer. All the aquifers in this region thicken and dip towards the coast.

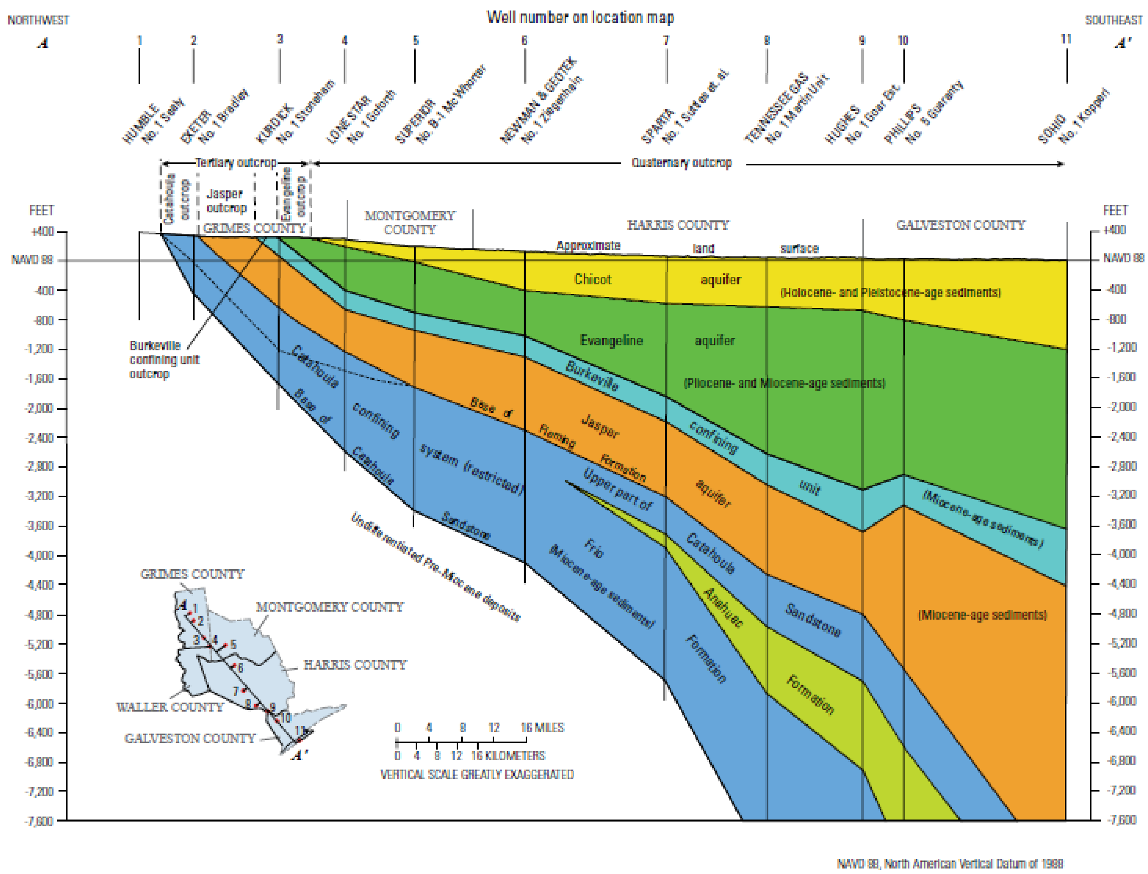


Figure 3: *The hydrogeologic cross secion A – A' cuts through the Houston-Galveston region. Harris County lies above the Jasper, Chicot, and Evangeline aquifers, which are a part of the Gulf Coast Aquifer.*

Subsidence and Compaction

Subsidence occurs when groundwater levels decrease in unconsolidated confined aquifers. When the potentiometric-surface declines, hydraulic pressure decreases, which creates a vertical load on the skeletal matrix of the sediments in the aquifer and adjacent confining units. Most aquifers are heterogeneous and contain an assortment of clay layers and sand layers. Clay layers are usually more affected by decreasing water levels than sand layers. Sand layers are more transmissive and allow water to pass through more easily. Clay layers have a low permeability and dewater more slowly than the sand layers. When a load is applied, the individual grains of the clay layers realign themselves to be perpendicular to the vertical force. This causes the clay layers to decrease in porosity, decrease in groundwater storage capacity, and compact. The amount of vertical stress, the hydraulic conductivity of the layers, and the thickness of the layers determine how much the layers compress. Approximately 90 percent of this compaction is permanent. Therefore, if the clay layers are repressurized, only a small amount of rebound occurs. Consequently, subsidence is measured by the compaction of the clay layers.

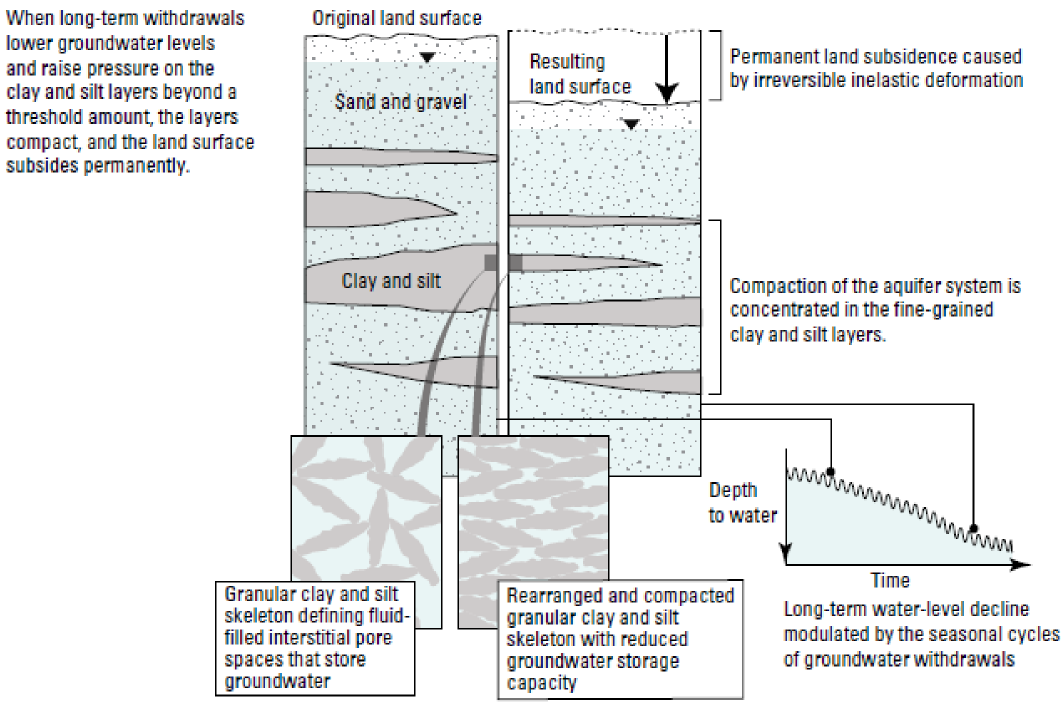


Figure 4: *The compaction process is shown in a sand, gravel, clay, and silt aquifer. The low permeability units show greater compaction than the low permeability layers.*

Borehole Extensometers

Compaction is measured using borehole extensometers. The extensometers are installed by drilling a borehole to a specific depth, generally the depth of the expected water-level decline. A steel outer casing added to the borehole. The extensometer pipe is then inserted into the outer casing. Next, a concrete slab is poured at the surface. A steel table is attached to the slab and an analog recorder is mounted to the table and connected to the top of the inner pipe. Borehole extensometers are designed to help eliminate the continuous shrinking and swelling of the clayey surficial sediments associated with soil-moisture changes. Changes in land-surface altitude are recorded to measure cumulative compaction.

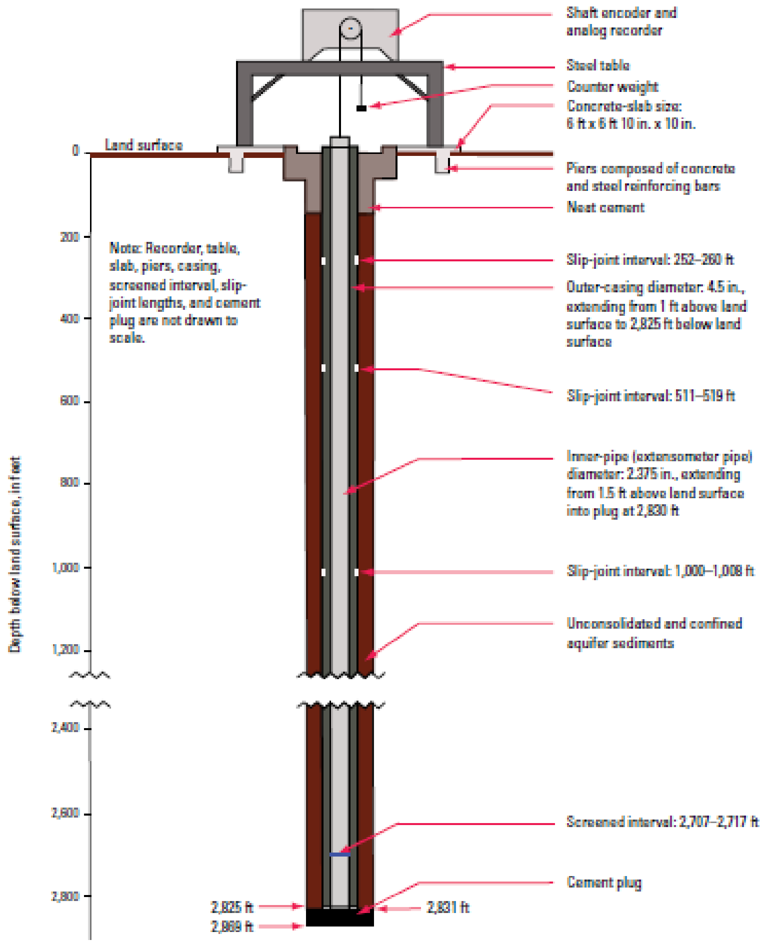


Figure 5: The cross-section of the borehole extensometer in Pasadena, Texas [LJ-65-322] is shown. All depths are referenced to land surface.

Data Sources

Base Maps

The shapefile for the counties of Texas was obtained from Geospatial Data Gateway, which contains county shapefiles under NRCS Counties by State. The counties for Texas were downloaded and then Harris County was isolated in a separate layer in ArcMap.

Harris County lies above the Jasper, Chicot, and Evangeline aquifers, which are a part of the Gulf Coast Aquifer. Shapefiles of the major aquifers of Texas, including the Gulf Coast Aquifer, can be found at the TWDB website.

Water Levels

Groundwater Database Reports were obtained from the TWDB website. For Harris County, the "Well Data Table" and "Water Level Table" were downloaded as comma-delimited text files. These tables contain data on the GIS coordinates of the wells and the water levels recorded in each well as far back as 1921.

Water levels from the TWDB have more monitoring points compared to water levels from the USGS. However, the TWDB does not provide clay compaction measurements.

Clay Compaction Measurements

The USGS and Harris-Galveston Coastal Subsidence District have been tracking subsidence at 13 different borehole extensometers at 11 sites. Values are given in terms of cumulative clay compaction, which corresponds to subsidence. Out of the 13 extensometers, 12 are located in Harris County. Extensometer Number and Site Name were obtained from the report "Water-Level Altitudes 2012 and Water-Level Changes in the Chicot, Evangeline, and Jasper Aquifers and Compaction 1973–2011 in the Chicot and Evangeline Aquifers, Houston–Galveston Region, Texas." The companion files for the report (specifically, Tables 4A – 4L of the USGS report) contain the USGS site number and compaction numbers since installation for each extensometer. The extensometers are listed in Table 6 in the *Methods* section of this report. No data is given for extensometer LJ–65–32–424, which is the second site at Clear Lake. Therefore, 11 extensometers are used for this study. According to the USGS report, this site is not included because measurements at both Clear Lake sites are similar.

The latitude and longitude (NAD27), associated aquifers, and other useful information about each site, can be found at on the USGS website by going to the Groundwater Watch page for Harris County, Texas, and clicking on the site number. The extensometers that measure compaction of the Chicot aquifer are East End [LJ–65–22–622], Johnson Space Center [LJ–65–32–401], Baytown C–1 [LJ–65–16–930], and Seabrook [LJ–65–32–625]. The extensometers that measure compaction of the Chicot and Evangeline aquifers are Lake Houston [LJ–65–07–909], Northeast [LJ–65–14–746], Southwest [LJ–65–21–226], Addicks [LJ–65–12–726], Baytown C–2 [LJ–65–16–931], Clear Lake [LJ–65–32–428], and Pasadena [LJ–65–23–322].

Methods

The section provides, in detail, the steps taken to create rasters of groundwater levels and clay compaction in Harris County, Texas, using ArcGIS.

Using Arc Hydro Groundwater

For this project, Groundwater Analyst in Arc Hydro Groundwater is required. The steps to configure Arc Hydro Groundwater Tools are given below.

1. Add the Arc Hydro Groundwater Toolbox by right-clicking anywhere in the *ArcToolbox* window and selecting the *Add Toolbox* command. In the *Catalog* browse to *System Toolboxes* and open *Arc Hydro Groundwater Tools*.
2. Load the *Arc Hydro Groundwater Toolbar* by right clicking on any visible toolbar and selecting the toolbar.

Since geoprocessing tools are being used, set the tools to overwrite outputs by default, and automatically add results to the map.

1. Select *Geoprocessing* → *Geoprocessing Options* → *Geoprocessing* tab.
2. Activate *Overwrite the outputs of geoprocessing operations.*
3. Activate *Add results of geoprocessing operations to the display.*

Mapping Water Levels

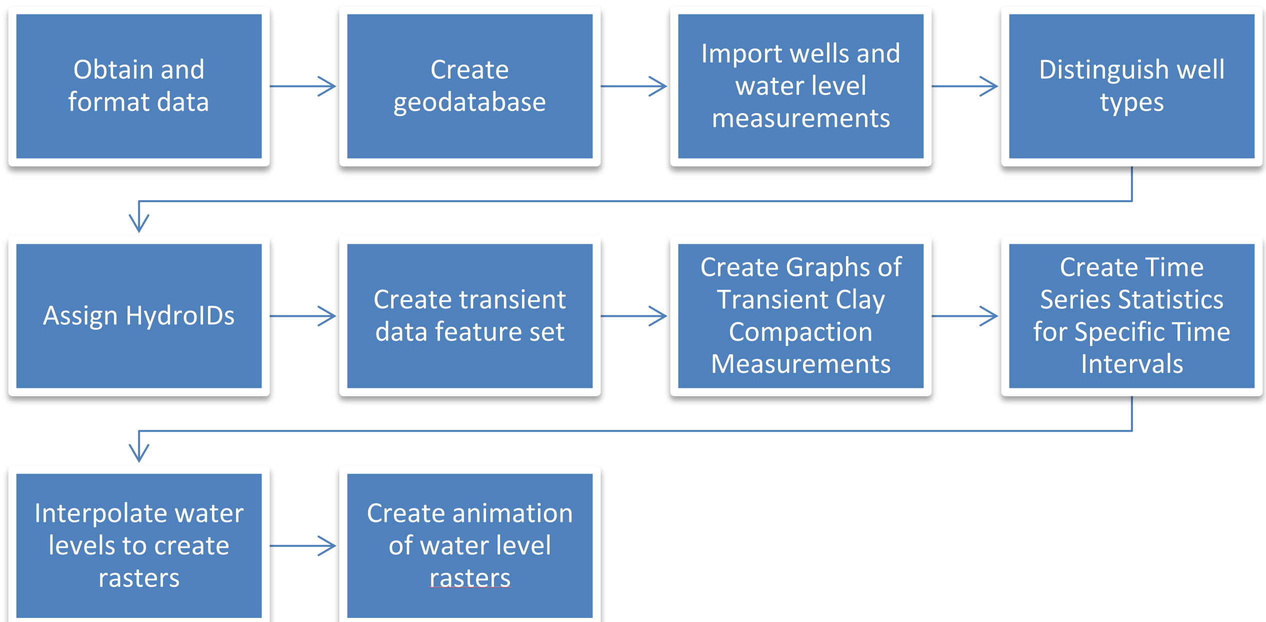


Figure 6: An overview of the steps to create water level maps is shown in a diagram.

Create the GeoDatabase

1. Create a GeoDatabase called "Harris_Wells" and a feature dataset class called "Data" with the Geographic Coordinate System "GCS_North_American_1983" and the Datum "D_North_American_1983."
2. Create "Wells" point feature class within "Data."

3. Add fields to "Wells": "HydroID" as type Long, "AquiferID" as type Long, "HydroCode" as type String, "AquiferCode" as type String, "LandElev" as type Double, "WellDepth" as type Double, "HGUID" as type Long, and "FType" as type String.
4. Create a "TimeSeries" table within the geodatabase.
5. Add fields to "TimeSeries": "FeatureID" as type Long, "VarID" as type Long, "TsTime" as type Date, "UTCOffset" as type Long, "TsValue" as type Double, "Elevation" as type Double, and "TsValue_Normalized" as type Double.

Import County Data

1. Add the shapefile "county_nrcs_a_tx" to the map. This is the name given to the file from Geospatial Data Gateway.
2. In the Attribute Table of "county_nrcs_a_tx" use Select by Attributes to choose "COUNTYNAME" = "Harris".
3. With Harris county selected, right click on "county_nrcs_a_tx" and go to "Selection" then "Create Layer From Selected Features".

Import Well Data

1. Use the *Text Import* command on the *Arc Hydro Groundwater Toolbar*.
2. In the *Harris County* folder, select and open the "HarrisCo_Well_Data.txt" file (downloaded from the TWDB). At the top of the *File Import Wizard*, turn on the *Comma* toggle and turn off the *Space* toggle in the *column delimiters* section. Turn off the *Treat consecutive delimiters as one* toggle. Turn on the *Heading row* toggle. This indicates that the first row contains headers for the data. The columns for the table (directly from the USGS) include "state_well_number", "lat_dec", "long_dec", "aquifer_id1", "elev_of_lsd", "well_type", "well_depth", and other data.

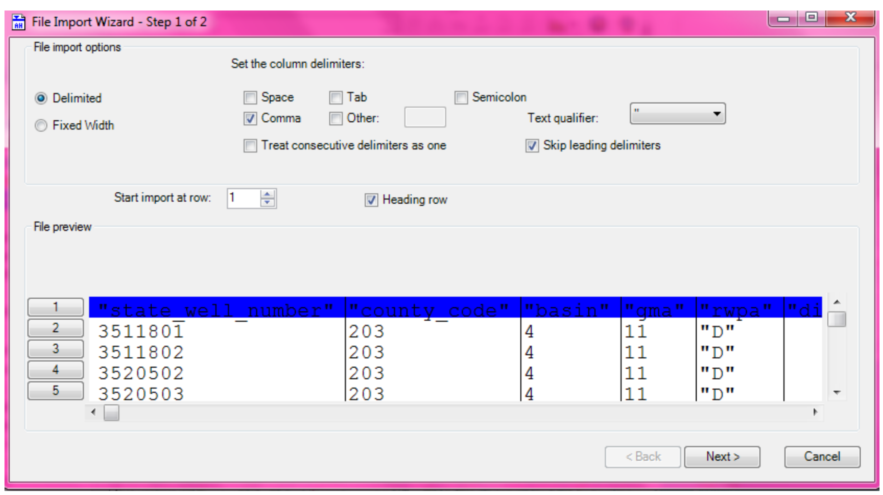


Figure 7: *Data is imported using the* Text Import *command in the* Arc Hydro Groundwater Toolbox*. The first step of the import wizard is shown.*

3. Select the *Next* button to go to the next step of the wizard.
4. Select "Wells" in the *Create Features/Rows in:* combo box.
5. In the first column with a *Header* value = "*state_well_number*", double-click on the *<not mapped>* item in the *Type* row, and select "HydroCode**"**.
6. Repeat the previous step to create the following relationships:

Table 1: *Text import relationships*

Header	Type
state_well_number	HydroCode
lat_dec	Y
long_dec	X
aquifer_id1	AquiferCode
elev_of_lsd	LandElev
well_type	FType
well_depth	WellDepth

7. Select the *Finish* button to complete the import process and see wells on the map.

Distinguish Well types

1. In the Table of Contents, right-click on the *Well* layer and select the *Properties* command.
2. Select *Symbology* → *Categories* → *Unique Values.*
3. Choose “FType” as the value field and click the *Add All Values* button.

Assign HydroIDs

HydroIDs are used as unique identifier across the entire geodatabase.

1. Right-click on the “Wells” layer in the ArcMap Table of Contents window and select *Open Attribute Table*.
2. Right-click on the “HydroID” field and select the *Field Calculator* command.
3. Set “HydroID” equal to “HydroCode”.

Add Time Series Data

1. Reformat the “HarrisCo_Water_Levels.txt” file (downloaded from the TWDB) by copying and pasting the file into Excel as a comma delimited text file. When importing the file activate the *Comma* toggle, the *Tab* toggle, and the *Skip Leading Delimiters* toggle. Turn off any other toggles.
2. Create another column in Excel called “Date”.
3. In the first row under the header in the “Date” column, use the Excel command *DATE(year,month,day)* to turn the 3 separate year, month, and day columns into one date column.
4. Save the Excel file as “HarrisCOWL” and paste the file into Notepad to create another text file. Save the text file as “HarrisCOWL.txt”. The table should now contain columns of “state_well_number”, “depth_from_lsd”, “Date”, and other data.
5. Back in ArcMap, open the *Text Import Wizard.*
6. Open “HarrisCOWL.txt”.
7. Turn on the *Tab* toggle and the *Heading row* toggle. Turn off any other toggles.
8. Select the *Next* button.
9. Make sure that the “TimeSeries” option is selected.
10. Double-click on the *<not mapped>* items in the *Type* row and create the following relationships as shown in Table 2.

Table 2: *Text import relationships*

Header	Type
state_well_number	FeatureID
depth_from_lsd	TsValue
Date	TsTime

11. Click *Finish* to exit the wizard.
12. Next, open the “TimeSeries” table.
13. Right-click on the “VarID” field in “TimeSeries” table and select the *Field Calculator* command.
14. Click *Yes* at the warning.
15. Enter “1” in the bottom part of the Field Calculator to have all “VarID” values equal to 1.
16. Close the “TimeSeries” table then right-click on the table and select *Joins and Relates* → *Join.*
17. Select “FeatureID” for *1*, “Wells” for *2*, and “HydroID” for 3.
18. Click on the *OK* button to complete the join.
19. Next, right-click on the “TimeSeries” table and select the *Open* command.
20. Right-click on the “TsValue_normalized” field and select the *Field Calculator* command.
21. Enter the expression “[Well.LandElev] + [TimeSeries.TsValue]”.
22. Click *OK* to complete the operation.
23. Remove the join.

Create a Transient Data Feature Set

1. Open the *Make Time Series Statistics* tool in *Arc Hydro Groundwater Toolbox* → *Groundwater Analyst*.
2. Enter the inputs as shown in Figure 8. For the *Output Feature Class* option, save the new feature class as “water_level_all” in the “Harris_wells” geodatabase.

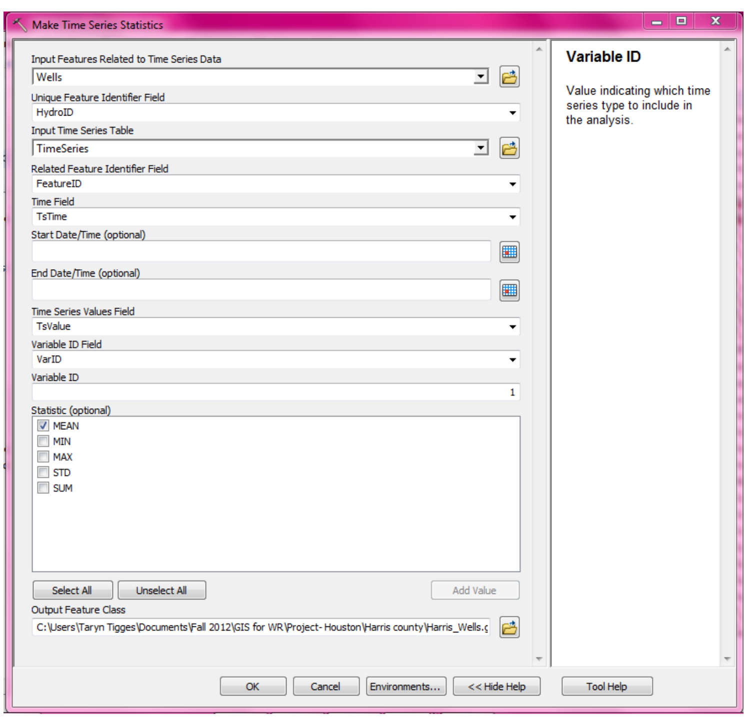


Figure 8: *Make Time Series Statistics Tool*

3. Click *OK* to execute the tool to see a new set of wells displayed on the map.
4. Right-click on the “water_level_all” layer and select *Properties*.
5. Select *Symbology* → *Quantities* → *Graduated Colors*.
6. Change *Value* to FREQUENCY and change the *Classes* setting to 4. Change Symbol sizes to 4.0, 6.0, 8.0, and 10.0.

Create Time Series Statistics for a Specific Time Interval

The next steps include creating mean water levels measured over specific time intervals.

1. Open the *Make Time Series Statistics* tool
2. Enter the inputs as shown in Figure 9. Save the *Output Feature Class* in the geodatabase.
3. Click *OK* to execute the tool. The steps in *Time Series Statistics for a Specific Time Interval* can be repeated for multiple time intervals.

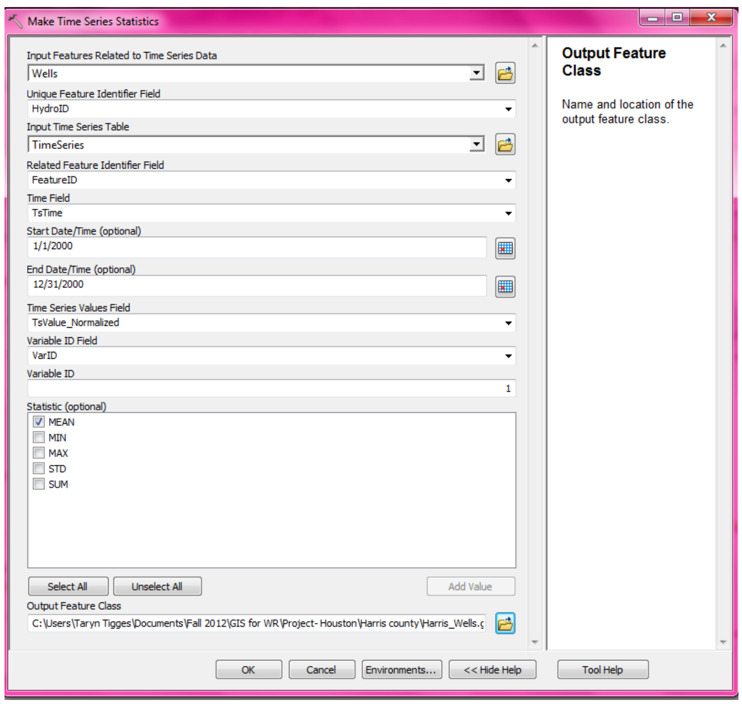


Figure 9: *Make Time Series Statistics Tool*

Interpolate Water Levels

Next, the values for each time interval are interpolated to a raster generate a map of water levels of Harris County.

1. Open *ArcToolbox* → *Spatial Analyst Tools* → *Interpolation* → *IDW*.
2. Enter the inputs shown in Figure 19. Set the location of the raster such that it is one level above the geodatabase so that the next step will not result in an error.

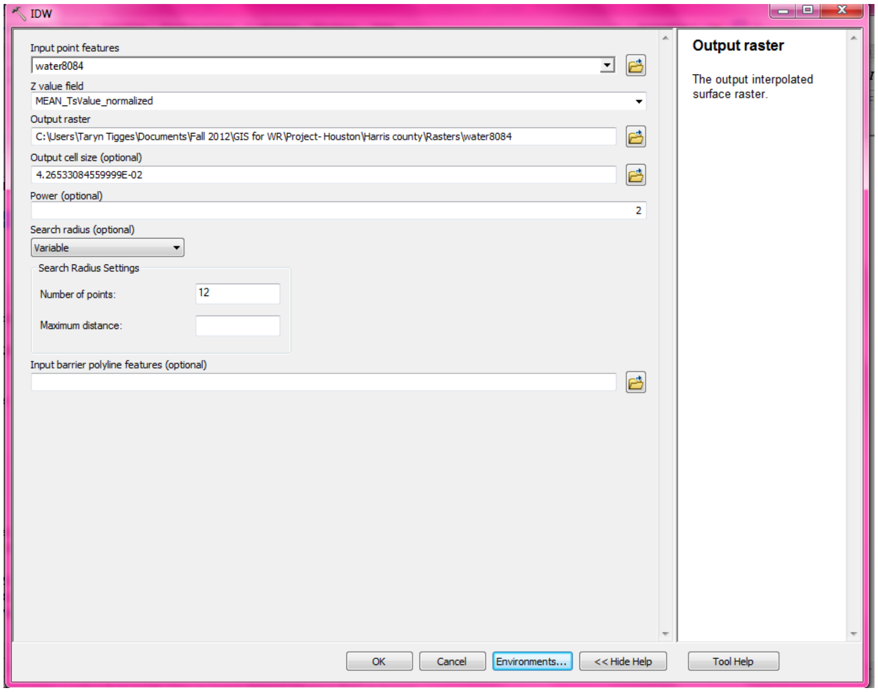


Figure 10: *IDW interpolation input parameters*

3. Click on *Environments*.
4. Under *Processing Extent* change the *Extent* option to ***Same as layer county_nrcs_a_tx selection***. This will cause the interpolation to extend out the limits of a rectangle including all of Harris County.
5. Scroll down and expand the *Raster Analysis Settings* section and change the *Mask* option to ***layer county_nrcs_a_tx selection***. This will clip the raster to the actual boundary of Harris County.
6. Select the *OK* button to exit the *Environment Settings* dialog and then to execute the *IDW* tool.
7. For raster symbology, use "Classified. If rasters are going to be compared change the number and value of intervals manually. Set display to "Bilinear Interpolation (for continuous data)."

Create a Model

Since multiple rasters are being created, create a model to automate the process.

1. The first step in creating a model is to add a new toolbox in Arc Toolbox. Right clicking anywhere in the window and select *Add Toolbox* and open *New Toolbox*.
2. After the new toolbox is added, right click and select *New Model*.
3. Add *Make Time Series Statistics* to the model by dragging the tool for Arc Toolbox or from the Results tab. The model in the Results tab will have already defined parameters.
4. In the model right click on *Make Time Series Statistics* and select *Make Variable → From Parameter → Start Date*.
5. Repeat step 4 for *End Date* and then *Output*.
6. Select *Auto Layout* to display the parameters in an orderly way.
7. Right click on *Start Date* and select *Model Parameter*. A "P" will appear.
8. Repeat step 7 for *End Date* and then *Output*.

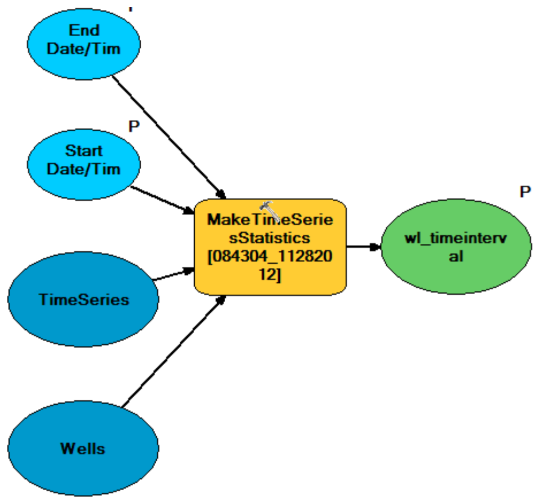


Figure 11: *Using model building in ArcMap to automate a process*

9. Double click on the *Make Time Series Statistics* tool in the model specify the other parameters.
10. Save the model and next time it is reopened the *Start Date*, *End Date*, and *Output Feature Class* parameters exposed as input parameters.
11. To create transient feature sets of multiple time periods, create a *Batch*. Right click on the model and select *Batch*. Input the desired time periods and click OK.

Create an Animation

1. Add the *Animation* Toolbar.
2. Under *Animation* select *Create Group Animation.*
3. Leave the defaults and select *OK.*
4. Open *Animation Controls.*
5. Under *Play Options* activate *By Number of Frames*. Also check the "Play only from" box to select the specific frames to include in the video. The frames for the animation of water levels are the 6 water level layers with data from 1980 to 2011. These dates are shown in Table 3.
6. Under *Animation* select *Export Animation* and export as a ".avi" file.
   Although the animation cannot be included in this report, the frames of the resulting animation are displayed in the Results section.

Table 3: *Time intervals used to create rasters used in animation*

Interval	Dates
1	1/1/1980 – 12/31/1984
2	1/1/1985 – 12/31/1989
3	1/1/1990 – 12/31/1994
4	1/1/1995 – 12/31/1999
5	1/1/2000 – 12/31/2004
6	1/1/2005 – 12/31/2011

Mapping Clay Compaction

The second half of this study is to map subsidence across Harris County. The data for clay compaction comes from a different source than data for water levels. Therefore, the first part of the process of formatting and importing clay compaction measurements differs from formatting and importing water level measurements. The remaining steps of creating rasters are similar.

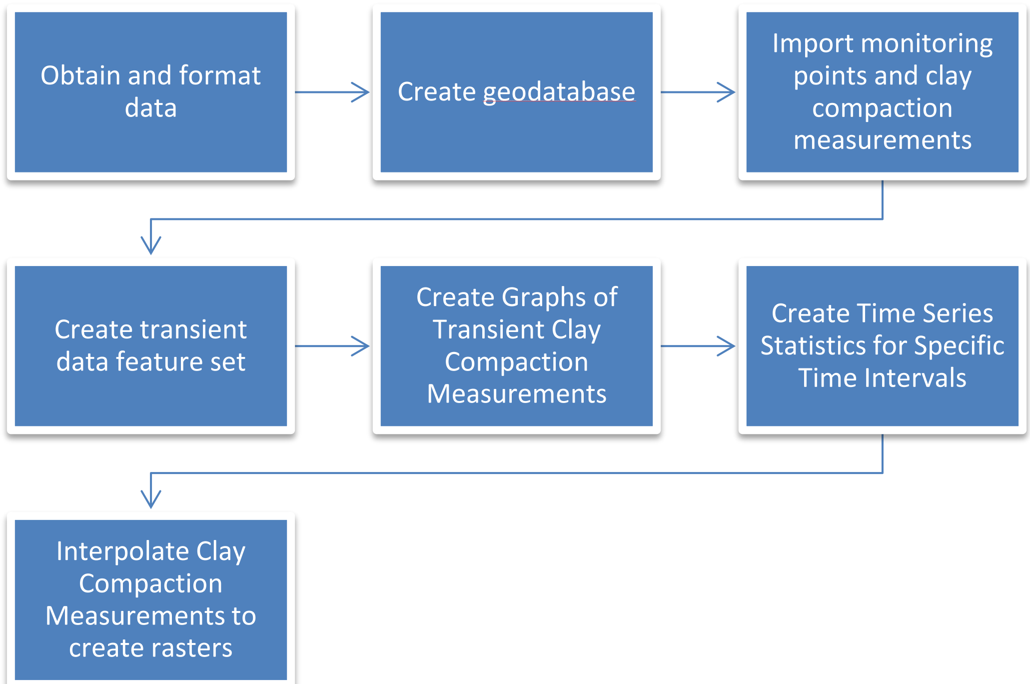


Figure 12: An overview of the steps to create subsidence maps is shown in a diagram.

Create and Project a Feature Class of Borehole Extensometer locations

1. Using the data obtained from the USGS, compile a spreadsheet in Excel of borehole extensometer locations. This spreadsheet is shown in Table 4.

Table 4: *Borehole Extensometer Data*

USGS Site Number	Extensometer Number	Site Name	Latitude (NAD27)	Longitude (NAD27)	Latitude DD	Longitude DD	Local Aquifer
294527095014911	LJ-65-16-931	Baytown C-2	29° 45' 27.3"	95° 01' 49.9"	29.7576	-95.0305	Evangaline
294206095162601	LJ-65-22-622	East End	29° 42' 06.2"	95° 16' 26.6"	29.7851	-95.2741	Evangaline
294527095014910	LJ-65-16-930	Baytown C-1	29° 45' 27.5"	95° 01' 49.0"	29.7576	-95.0303	Chicot
293352095011601	LJ-65-32-625	Seabrook	29° 33' 52.2"	95° 01' 16.6"	29.5645	-95.0213	Evangaline
293306095054101	LJ-65-32-401	Johnson Space Center	29° 33' 06.7"	95° 05' 45.7"	29.5519	-95.0960	Evangaline
294726095351102	LJ-65-12-726	Addicks	29° 47' 26.5"	95° 35' 10.1"	29.7907	-95.5861	Evangaline
294237095093204	LJ-65-23-322	Pasadena	29° 42' 35.5"	95° 09' 32.7"	29.7099	-95.1591	Evangaline
293348095070604	LJ-65-32-428	Clear Lake (Deep)	29° 33' 48.3"	95° 07' 08.2"	29.5634	-95.1189	Evangaline
295449095084105	LJ-65-07-909	Lake Houston	29° 54' 47.6"	95° 08' 43.9"	29.9132	-95.1455	Evangaline
294728095200106	LJ-65-14-746	Northeast	29° 47' 27.2"	95° 20' 02.3"	29.7909	-95.3340	Evangaline
294338095270402	LJ-65-21-226	Southwest	29° 43' 37.2"	95° 27' 02.8"	29.7270	-95.4508	Evangaline

2. Add the Excel table to ArcMap by using the *Add Data* button. When adding the Excel spreadsheet, select the individual worksheet within the spreadsheet.
3. Right click on the new table "Sheet1$", and select Display XY Data. Set the X Field to Longitude (in decimal degrees) and the Y Field to Latitude (in decimal degrees). Click Edit to change the spatial coordinate system. Since the coordinates are given in NAD27, select GCS_North_American_1927.
4. Click Ok and the borehole extensometer locations show up on the map.

Create the GeoDatabase

1. Create a GeoDatabase called "Harris_Compaction" and a feature dataset class called "Data" with the Geographic Coordinate System "GCS_North_American_1983" and the Datum "D_North_American_1983."
2. Create a feature class out of the points. Right click on the "Sheet1$ Events" layer and export the data into the "Data" feature dataset as the feature class "CompactionPts"**.** Add the points to your map. ArcGIS does the map projection automatically as part of the data export process.
3. Create a table for all points that will include normalized compaction values. Call the table "timecompall" and create the table within the geodatabase. Add the following fields:

Table 5: *Fields needed for table of transient compaction values*

Field	Type
Ex_Number	Text
VarID	Long
MDate	Date
USGS_Number	Double
Compaction1973	Double
Compaction1974	Double
Compaction1975	Double
Compaction1976	Double
Compaction1980	Double

Normalize data for each year a new extensometer was added

1. Create a table of extensometer compaction recordings by combing the 11 tables from the supplemental data for the USGS report into one Excel spreadsheet. Name the Excel table "Clay Compaction Normalized." This Excel table has 5310 measurements total from all extensometers.
2. The compaction measurements will not have to be normalized using land elevation as for the water level measurements. However, the data will need to be normalized using the date of activation. Each compaction measurement starts at 0 at the time the extensometer was activated. The first step in creating the normalized values is to find the difference between each consecutive extensometer measurement.
3. Extensometers were installed and activated in 5 different years between 1973 and 1980. Therefore, the next step is to create 5 columns of clay compaction measurements. If the extensometer was not installed at a specific year, the values for that extensometer are marked as null. However, for each year a new extensometer was activated, all values of active extensometers were set to zero. Cumulative values were then calculated until the end of 2011 using the difference column. The extensometer and activation year are shown in Table 6.

Table 6: *Borehole extensometers in Harris County*

Borehole Extensometer	Year of Activation
LJ–65–22–622 (East End) LJ–65–16–930 (Baytown C–1) LJ–65–16–931 (Baytown C–2) LJ–65–32–625 (Seabrook) LJ–65–32–401 (Johnson Space Center)	1973
LJ–65–12–726 (Addicks)	1974
LJ–65–23–322 (Pasadena)	1975
LJ–65–32–428 (Clear Lake)	1976
LJ–65–07–909 (Lake Houston) LJ–65–14–746 (Northeast) LJ–65–21–226 (Southwest	1980

The columns for the Excel table are "USGS_Site_Number", "Ex_Number", "Measurement Date", "Compaction (feet)", "Compaction Diff", "1974 Normalized Compaction", "1975 Normalized Compaction", "1976 Normalized Compaction", and "1980 Normalized Compaction".

4. Turn the "Clay Compaction Normalized" Excel table into text file by copying and pasting into Notepad and saving as ".txt".

Import Clay Compaction Measurements

Now that we have imported the monitoring features, we are ready to import transient clay compaction measurements into a table. Each record in the table will represent a clay compaction measurement at a particular monitoring point at a particular time. The records in the table will be related to the wells using the "USGS_Site_Number" field.

1. In the AHGW Toolbar, select the *Arc Hydro GW* → *Text Import* command. Select and open the text file. Turn on the *tab* toggle and turn off the other delimiter types. Turn off the *Treat consecutive delimiters* as one toggle, and turn on the *Heading row* toggle. Select the Next button. Make sure that "timecompall" is selected. Double-click on the <not mapped> items in the Type row and create the following relationships:

Table 7: *Text Import specifications*

Header	Type
Ex_Number	Ex_Number
MeasurementDate	MDate
USGS_Site_Number	USGS_Number
Compaction (feet)	Compaction1973
1974 Normalized Compaction	Compaction1974
1975 Normalized Compaction	Compaction1975
1976 Normalized Compaction	Compaction1976
1980 Normalized Compaction	Compaction1980

2. Click *Finish* to exit the wizard.
3. Next, open the "timecompall" table.
4. Right-click on the "VarID" field and select the *Field Calculator* command.
5. Click *Yes* at the warning.

6. Enter “1” in the bottom part of the Field Calculator to have all “VarID” values equal to 1.

Create a Transient Data Feature Set

1. Double-click on the *Make Time Series Statistics* tool in the *AHGW Toolbox → Groundwater Analyst* toolset.
2. Enter the inputs as shown in the Figure below. Be sure to specify the value field using data from the appropriate set of extensometers. Save the output in the “Harris_Compaction” geodatabase. Type ***TimePts”Years”*** (“Years” is 1973, 1974, 1980 – 1984 etc.) as the name of the new feature class.

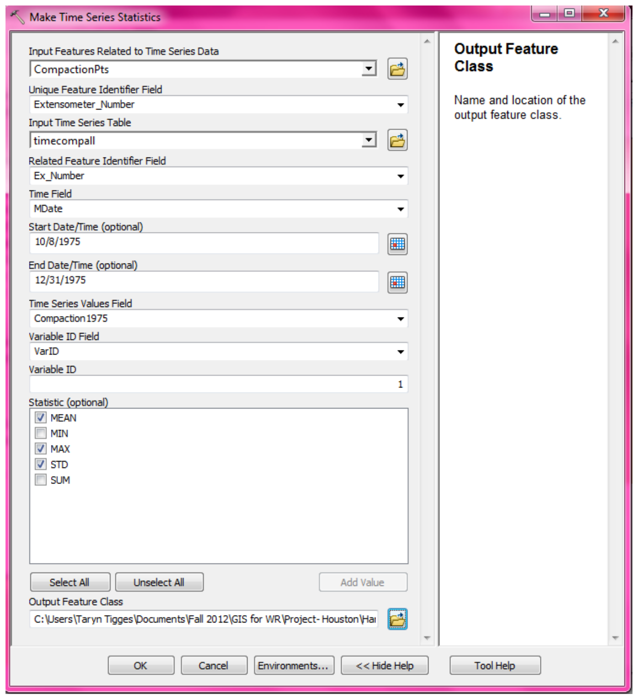


Figure 13: *Make Time Series Statistics Tool*

3. Click *OK* to execute the tool.
4. Create a map of the frequency of measurements in a similar manner as a map of the frequency of measurements was created for water levels.

Interpolate Clay Compaction Measurements

Use the IDW tool to interpolate clay compaction measurements in a similar manner as was used to interpolate water levels. The *IDW* tool is found in *ArcToolbox → Spatial Analyst Tools → Interpolation*. For the “Z-value field” use “MEAN_Compaction.”

Create an Animation

An animation can be created for clay compaction rasters with the animation tools used previously for water level rasters.

Results

Mapping Water Levels

Well Types in Harris County

The TWDB Board uses single character codes to identify well types. The codes used in the wells in Harris County are M, O, P, R, S, T, and W and represent the well types given in Table 8.

Table 8: *Types of monitoring wells in Harris County*

Code	Well Type
M	Mine
O	Observation
P	Oil or Gas
R	Recharge
S	Spring
T	Test hole
W	Withdrawal

In Harris County, there are 15 mine wells, 13 observation wells, 16 oil and gas wells, 1 recharge well, 1 spring well, 26 test hole wells, and 3275 withdrawal wells. Although well fluxes are not given, the map shown in Figure 14 supports the theory that groundwater pumping is a leading case of subsidence in Harris County. Notice that most of the wells are withdrawal (W) wells.

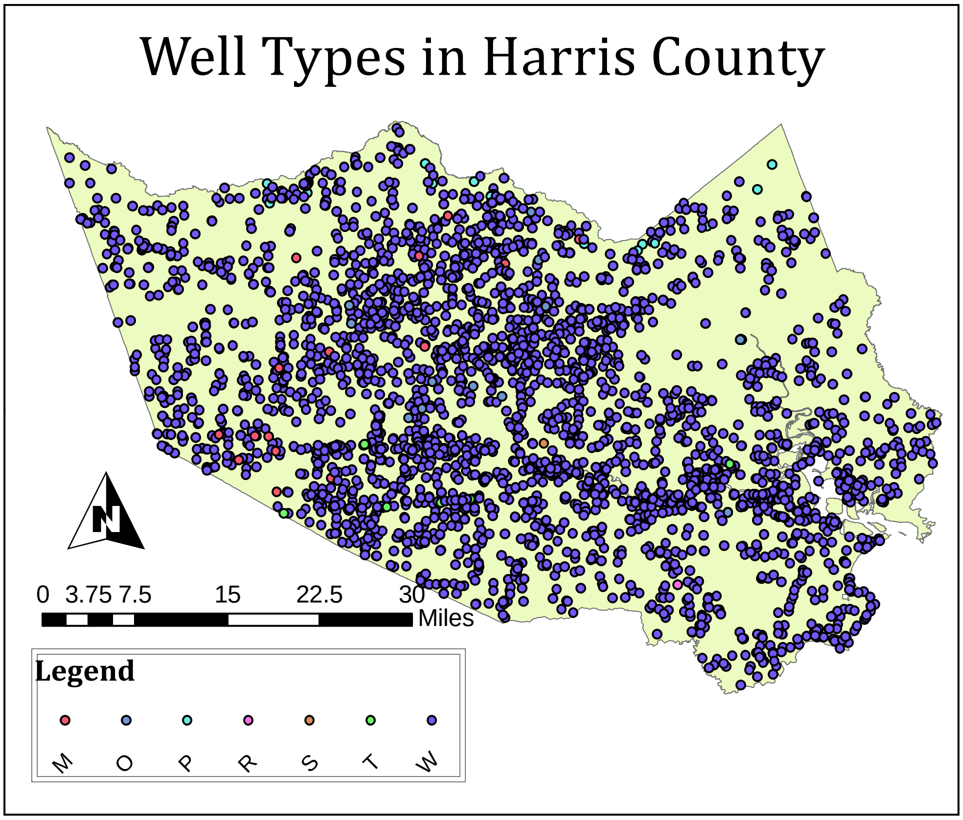


Figure 14: *Distinguishing monitoring wells*

Frequency of Measurements

Figure 15 demonstrates that some monitoring points measured water levels more frequently than others. All points are used in this study**.** Later, this map is compared to the frequency of clay compaction measurements. Although there are less monitoring points for subsidence measurements, subsidence measurements are more frequent than water level measurements.

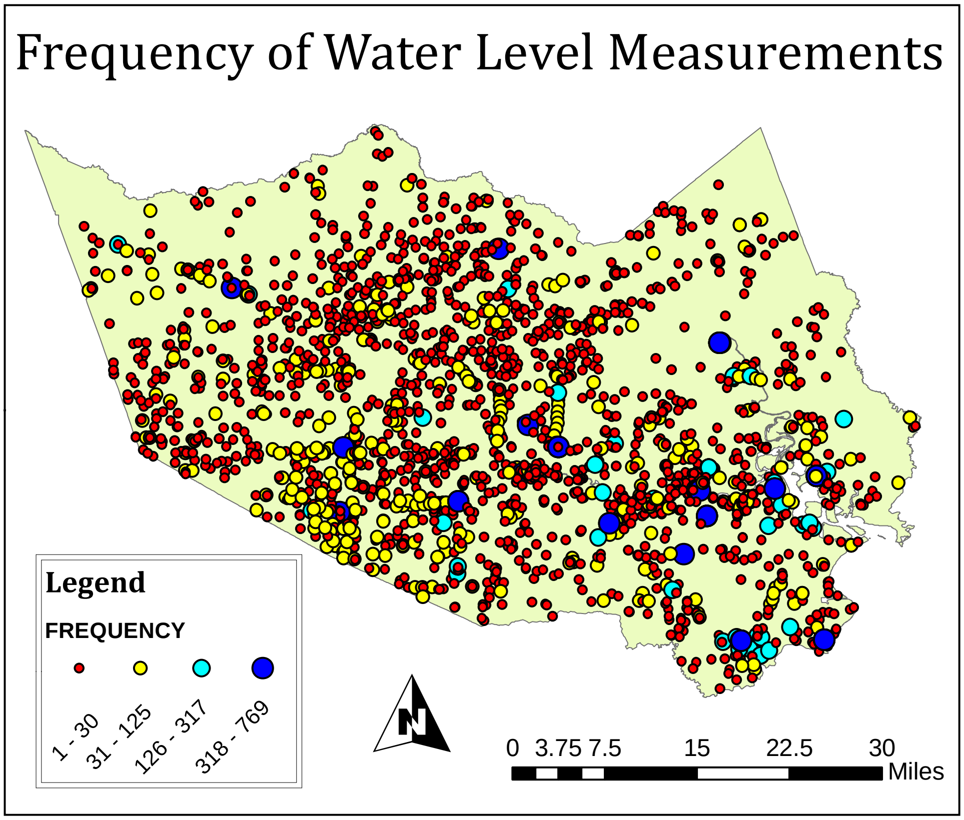


Figure 15: *Number of transient water level values per well*

Water Level Rasters

Figure 16 shows a map of the water levels in 1973. Notice how the lowest water levels are near Houston and are between elevations of -350 ft to -300 ft.

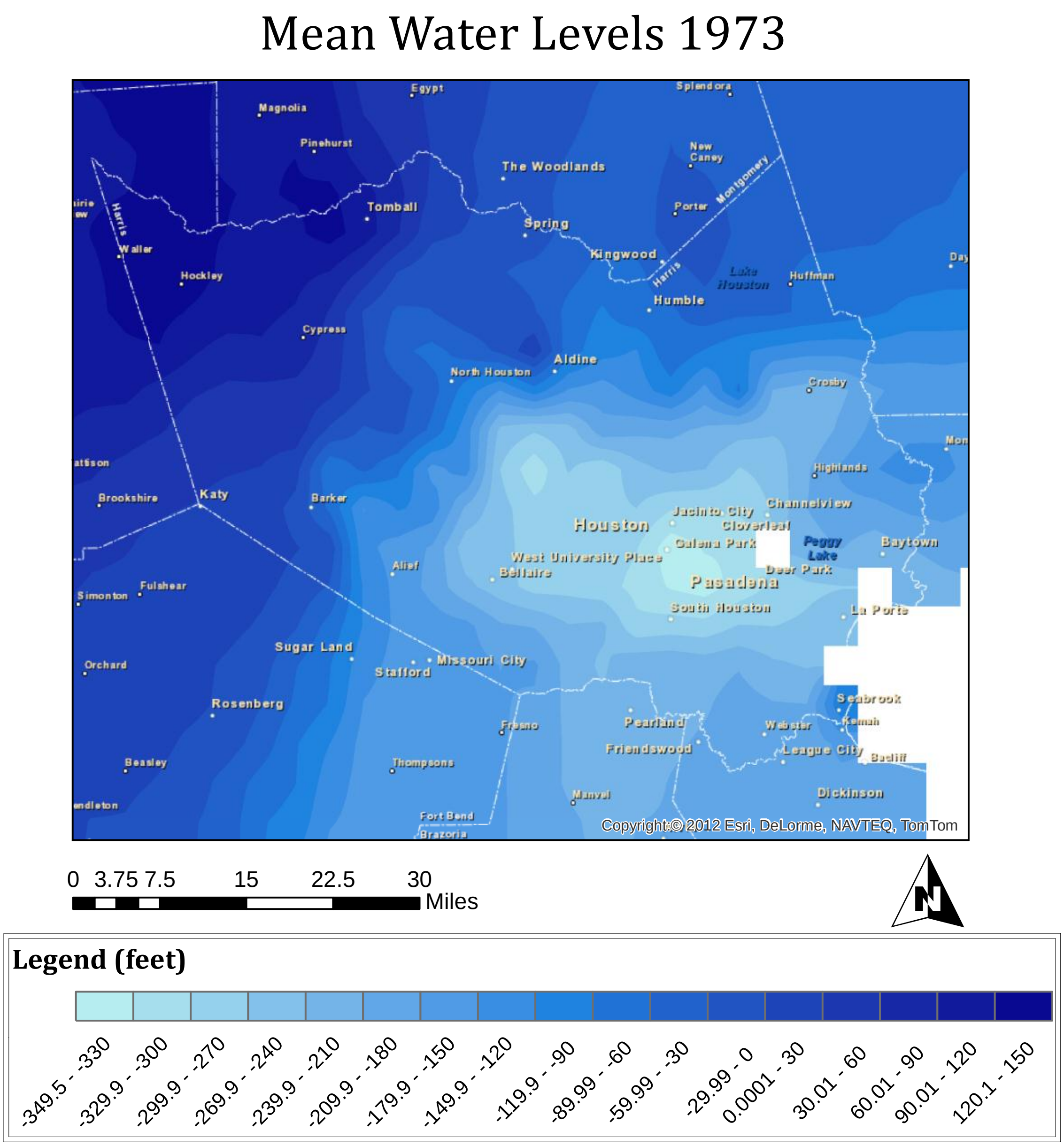


Figure 16: *Water levels in Harris County in 1973*

Figure 17 shows a map of the water levels in Harris County in 2011. One of the possible explanations for the shift in low water level areas is that Houston used to be highly pumped for groundwater and now the rural areas are starting to see an increase in pumping as well. Also, the lowest water levels are now at elevations between -240 and -274 ft. There has been an improvement in water levels since the implementation of the Harris-Galveston Coastal Subsidence District.

Mean Water Levels 2011

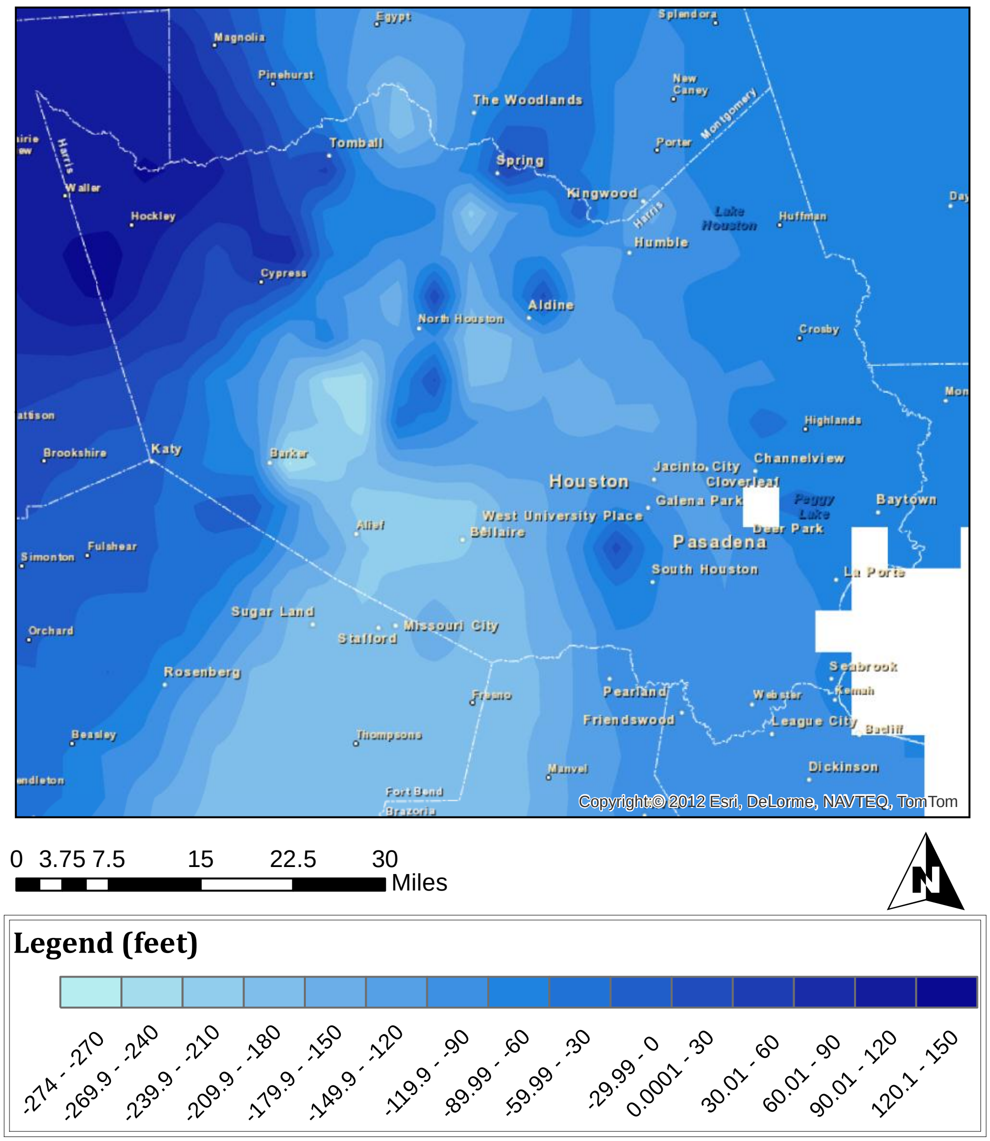


Figure 17: *Water levels in Harris County in 2011*

Figure 18 displays maps of water levels starting at 1980 and ending at 2011. This time period was chosen because not all monitoring points were installed or activated until 1980. There is a slight shift in the center of the light blue areas to the northeast. Also, the center of the map is more accurate than the outer edges because the monitoring points are located within Harris County.

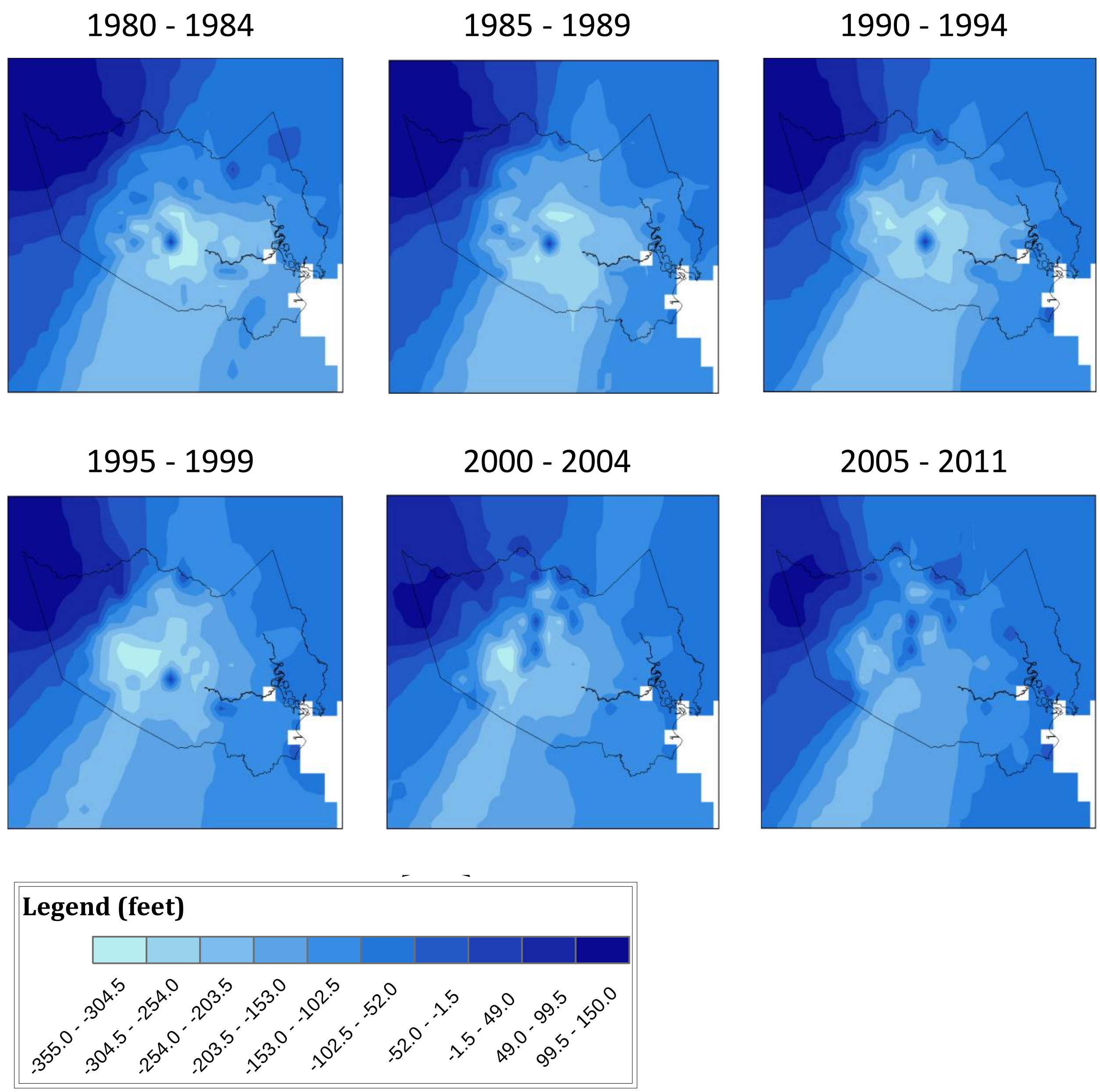


Figure 18: *Time series of rasters of water levels in Harris County from 1980 to 2011*

Mapping Clay Compaction

Frequency of Measurements

One large difference in data between water levels and clay compaction is both the number and frequency of monitoring points. There are less monitoring points for clay compaction but the measurements are generally more frequent.

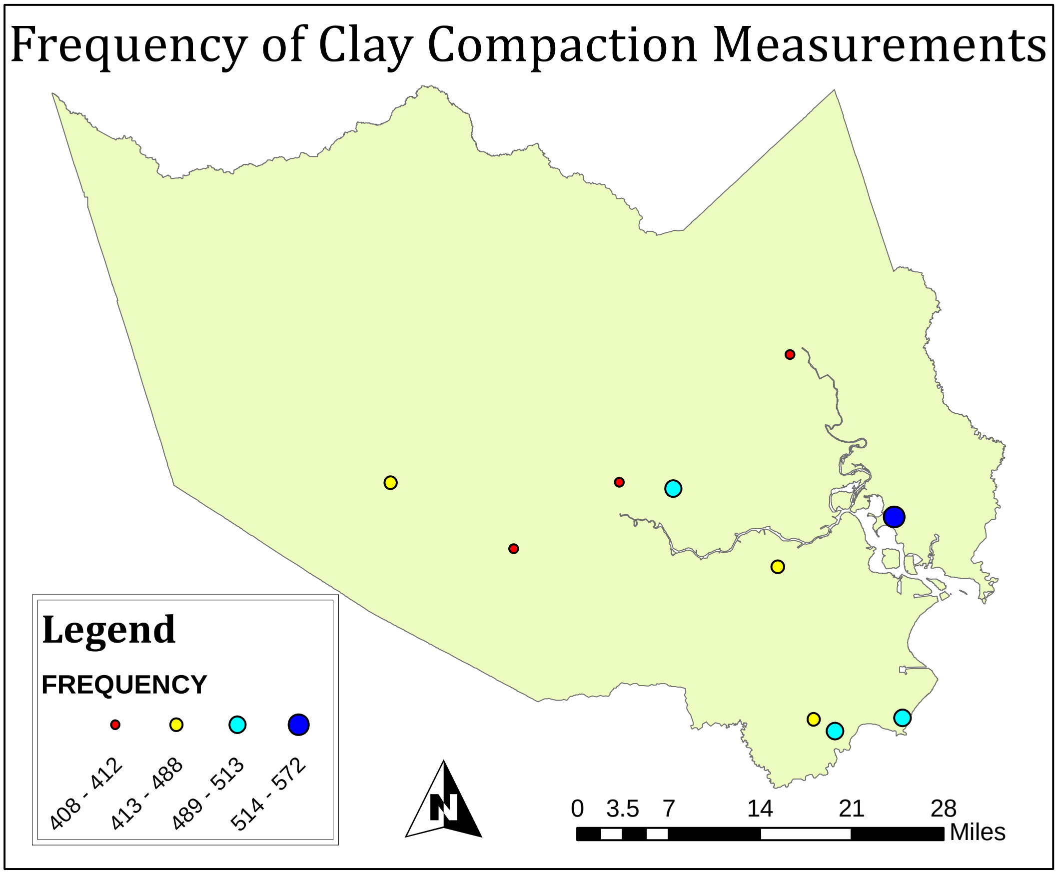


Figure 19: *Number of transient clay compaction values per borehole extensometer*

__Clay Compaction Rasters__

Table 7 shows the years each borehole extensometer was activated. Figure 20 displays the location of each borehole extensometer.

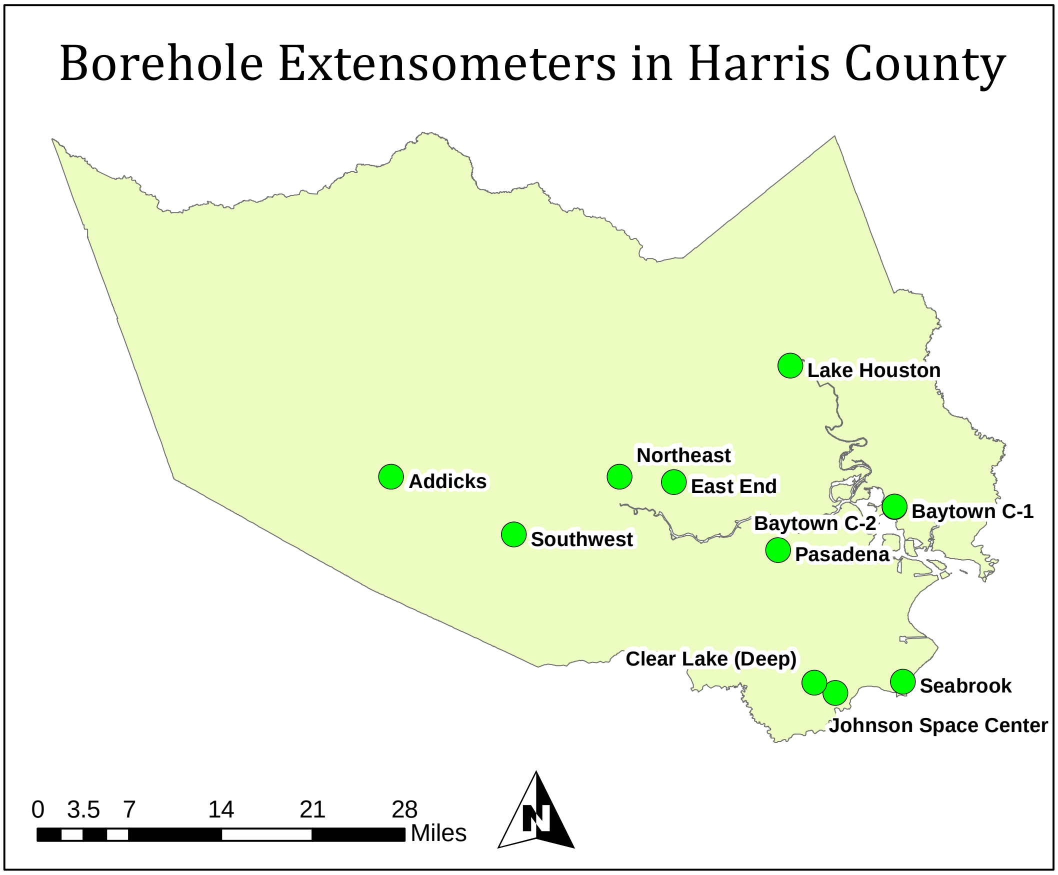
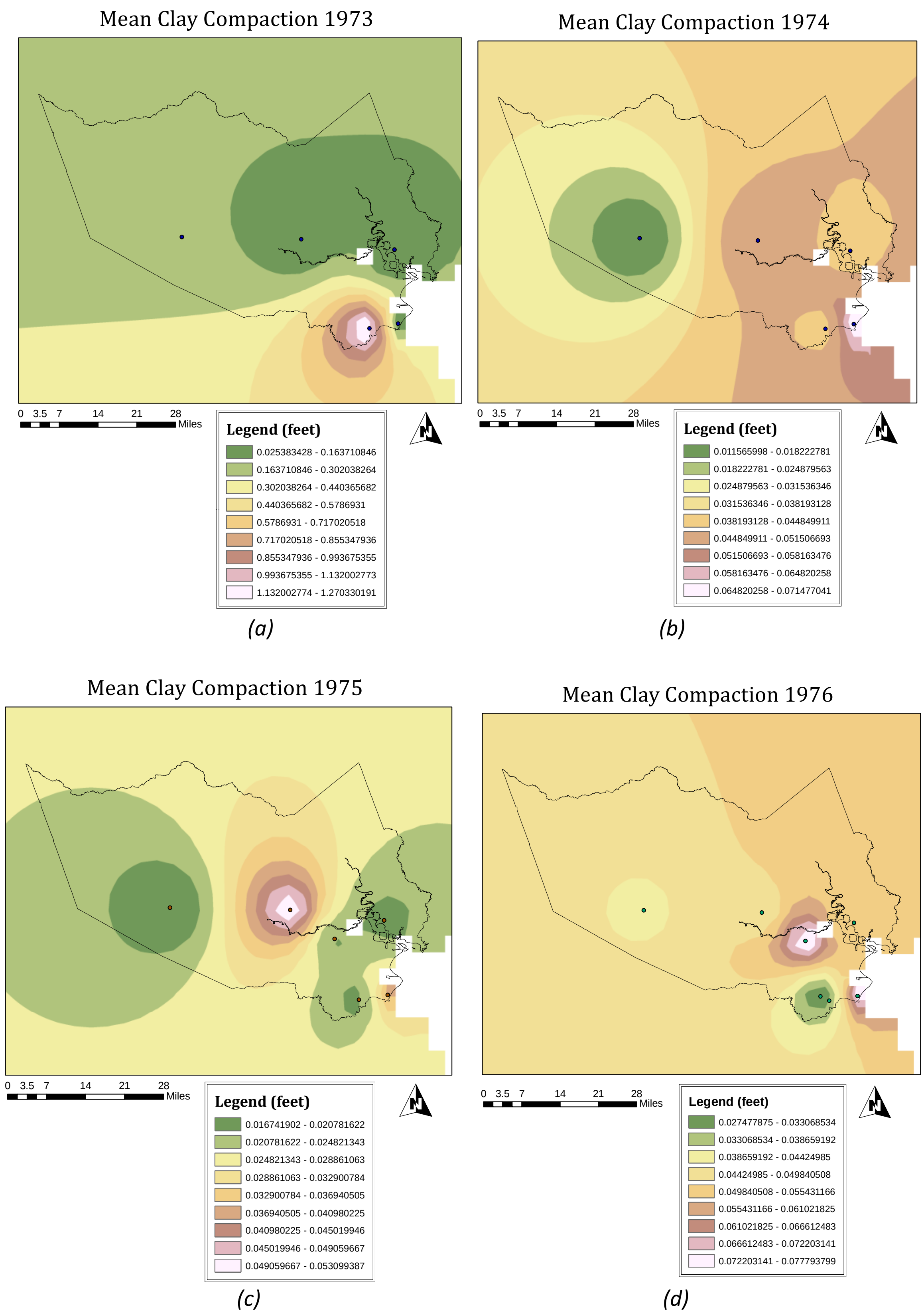
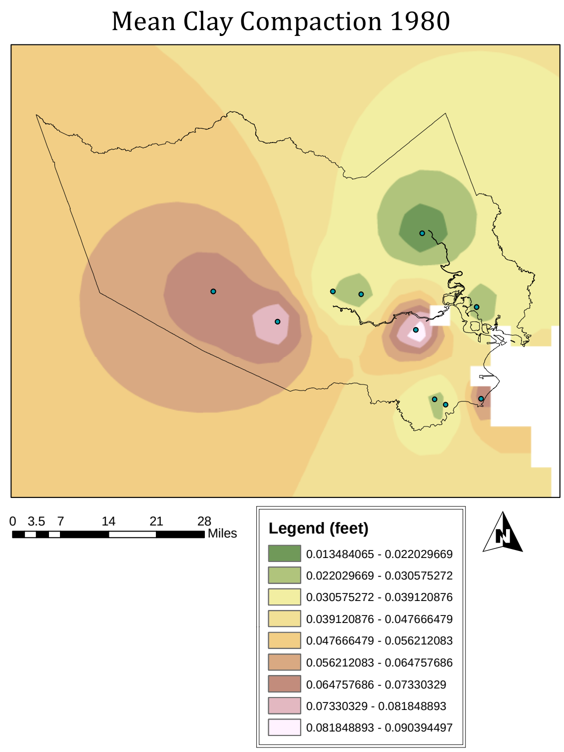


Figure 20: *Over an 8 year period in 5 different years, 11 borehole extensometer were installed and activated in Harris County*

The first borehole extensometers were activated in 1973. A mean of a set of cumulative values of Clay Compaction for 1973 is shown in Figure 21(a). A raster of mean compaction values for each year a borehole extensometer was activated is shown in Figure 21(a – e). These years are 1973, 1974, 1975, 1976, and 1980. The values shown in the rasters become progressively more accurate as borehole extensometers are added. For Figure 21(a – e), the mean compaction for each year is from cumulative data points over the entire year. However, the mean compaction between years is not cumulative. Out of these 5 years the most compaction occurs in 1973 followed by 1980, 1976, 1974, and 1975.


Mean Clay Compaction 1973
0 3.5 7 14 21 28 Miles
Legend (feet)
0.025383428 - 0.163710846
0.163710846 - 0.302038264
0.302038264 - 0.440365682
0.440365682 - 0.5786931
0.5786931 - 0.717020518
0.717020518 - 0.855347936
0.855347936 - 0.993675355
0.993675355 - 1.132002773
1.132002774 - 1.270330191
(a)
Mean Clay Compaction 1974
0 3.5 7 14 21 28 Miles
Legend (feet)
0.011565998 - 0.018222781
0.018222781 - 0.024879563
0.024879563 - 0.031536346
0.031536346 - 0.038193128
0.038193128 - 0.044849911
0.044849911 - 0.051506693
0.051506693 - 0.058163476
0.058163476 - 0.064820258
0.064820258 - 0.071477041
(b)
Mean Clay Compaction 1975
0 3.5 7 14 21 28 Miles
Legend (feet)
0.016741902 - 0.020781622
0.020781622 - 0.024821343
0.024821343 - 0.028861063
0.028861063 - 0.032900784
0.032900784 - 0.036940505
0.036940505 - 0.040980225
0.040980225 - 0.045019946
0.045019946 - 0.049059667
0.049059667 - 0.053099387
(c)
Mean Clay Compaction 1976
0 3.5 7 14 21 28 Miles
Legend (feet)
0.027477875 - 0.033068534
0.033068534 - 0.038659192
0.038659192 - 0.04424985
0.04424985 - 0.049840508
0.049840508 - 0.055431166
0.055431166 - 0.061021825
0.061021825 - 0.066612483
0.066612483 - 0.072203141
0.072203141 - 0.077793799
(d)



(e)

Figure 21 (a – e): *Mean compaction values for each year a borehole extensometer was activated*

Figure 22 shows the mean compaction for the year 2011, cumulative since 1973. Although water levels are better managed, there is still and increase in clay compaction since 1973. The increase in water levels only slowed the rate of compaction. Additionally, the area of lowest water levels in Harris County has shifted to be northwest of Houston and this area is experiencing a relatively large amount of compaction. As mentioned previously, approximately 90 percent of compaction is permanent.

Mean Clay Compaction 2011

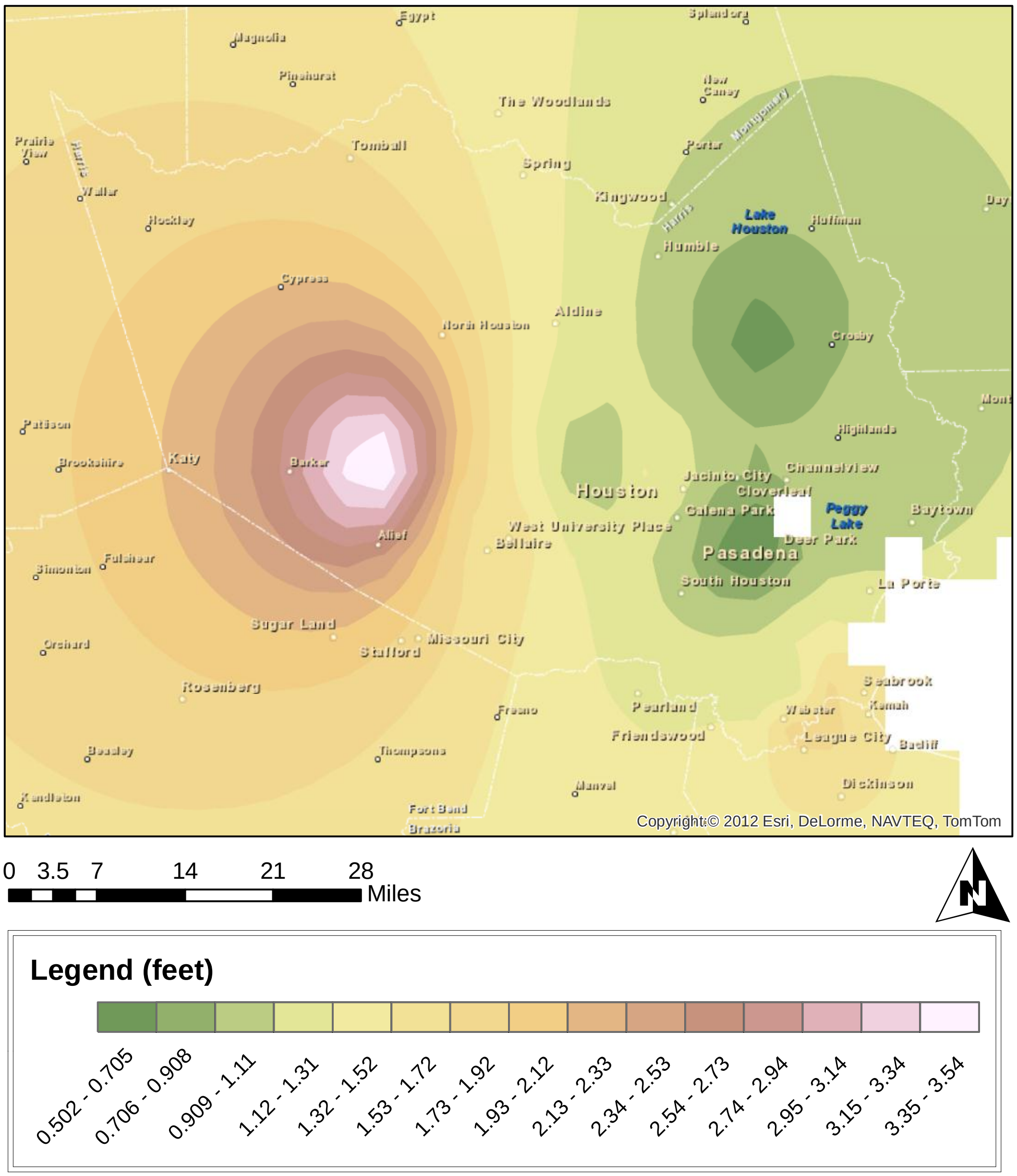


Figure 22: Mean compaction for the year 2011, cumulative since 1973

Below, the cumulative mean compaction measurements since 1980 are compared in five year intervals. The last borehole extensometer was activated in 1980, therefore the following maps display data interpolated from the 11 borehole extensometers used in this project. The compaction recorded by each extensometer has been normalized to start at zero in 1980.

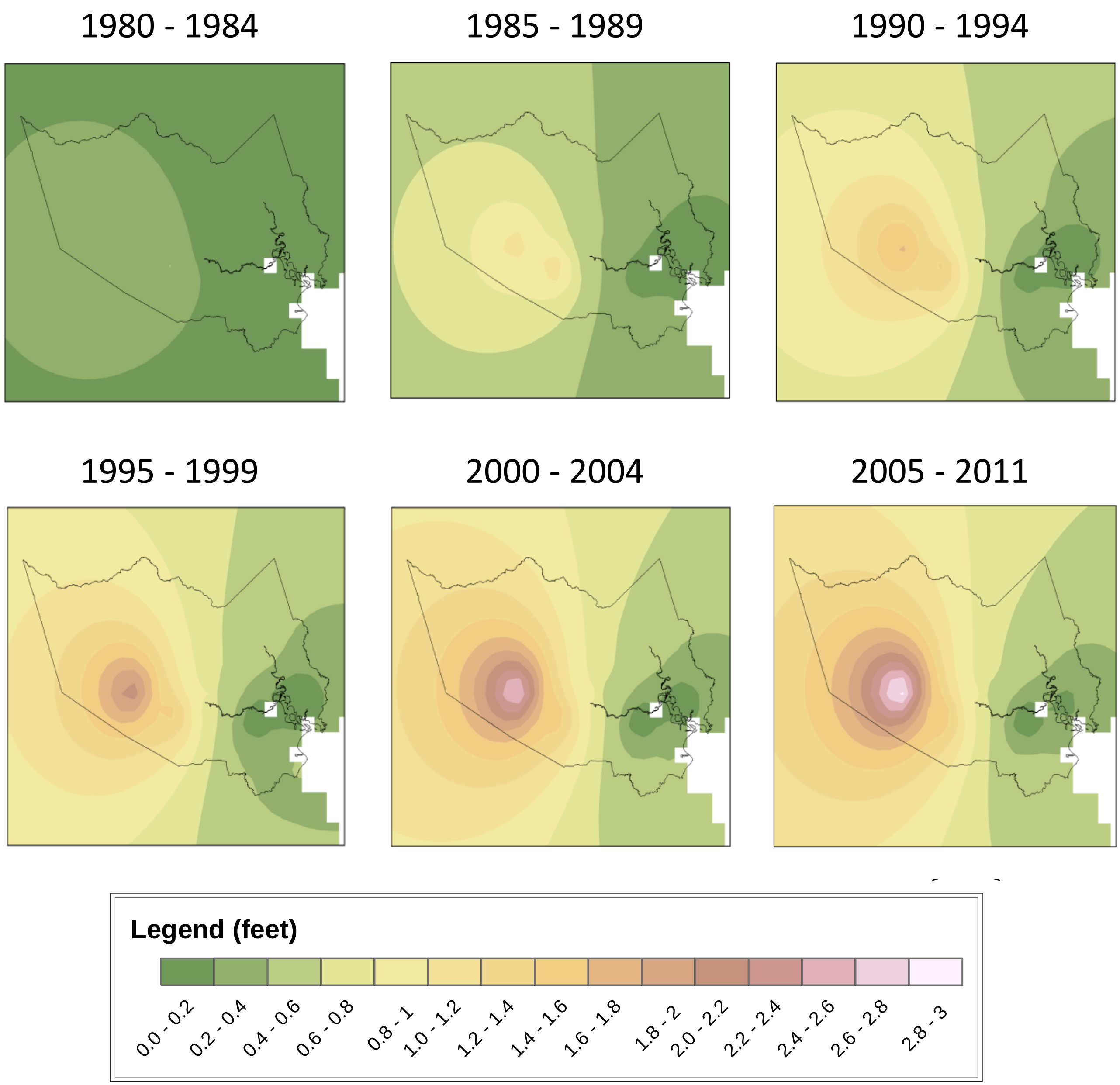


Figure 23: *Time series of subsidence in Harris County from 1980 to 2011, cumulative since 1980*

As shown in the above maps, subsidence has increased since 1973 up to approximately 3.5 feet. According to Kasmarkek et al. (2010), 77 – 97 percent of the subsidence in the Houston-Galveston region occurred before the installation and activation of the extensometers in 1973. The rate and amount of subsurface sediment compaction varied from site to site because the groundwater withdrawal rates varied from site to site. Additionally, the ratio of clay to sand in the underlying sediments varies from site to site.

<u>Comparison of Clay Compaction Measurements and Water Levels</u>

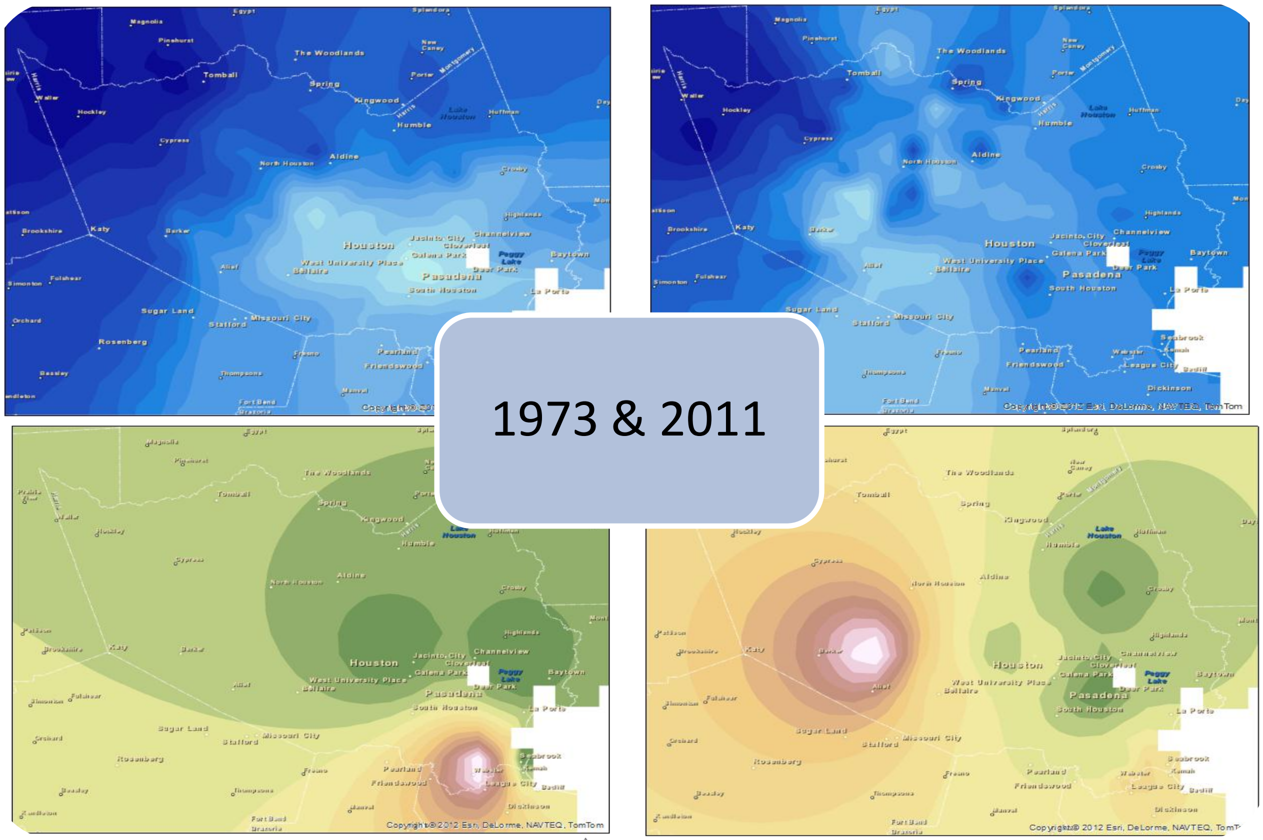


Figure 24: *Water levels and subsidence in Harris County in 1973 and 2011*

Visually, there is some correlation between water levels and subsidence. This correlation is especially noticeable in the lighter, lower level, areas in 2011. As the water levels rise from 1973 to 2011 and the hydrostatic pressure increases, the rates of compaction decrease. Additionally, the area to the northwest of Houston shows a considerable amount of compaction and this correlates with the observation that the lowest water levels are in the area to the northwest of Houston. In 1973, although Houston is the area with the lowest water levels, the area to the southeast of Houston has the most compaction. This may be because the ratio of clay to sand in the underlying aquifer systems is greater to the southeast of Houston. However, calculating this ratio is not covered in this study and this statement can only be hypothesized.

Summary

This study found that water management, including the creation of the Harris-Galveston Coastal Subsidence District, has helped Harris County increase groundwater levels since 1973. Houston has especially seen a large increase in water levels since 1973. However, this increase in groundwater levels only slowed the rate of compaction. Additionally, the area of lowest water levels in Harris County has shifted to be northwest of Houston and this area is experiencing a relatively large amount of compaction. The maps created for 2011 show subsidence has increased across Harris County since 1973. Additionally, in gathering data for this study, it was found that more data exists for water level measurements than for subsidence measurements. This study shows that groundwater levels and subsidence are related and this can be visualized using ArcGIS.

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