Table of Contents

Infiltration Basin Focused Site Suitability Analysis for Managed Aquifer Recharge – The State of Texas

Abstract

This project aims to collect, analyze, evaluate and weigh different parameters associated with artificial recharge of groundwater classified into two categories viz., Surface Parameters (Elevation, Land-Use, Soil Characteristics (Clay Percentage, Soil Thickness, Surface Slope) and Water Table Depth, Hydraulic Conductivity classified as subsurface characteristics. Recharge of groundwater by employing Infiltration Basin (chunk of land highly suitable for seepage of water underground) has advantage of natural infiltration of Water and easy to capture Stormwater and discharge in artificially created basins. Study area selected for this project is the State of Texas. Users will pick county of their choice and an application will perform spatial analysis and evaluate whether Area of Interest (AOI) in a selected county by cumulatively adding precalculated weight parameters mentioned.

Introduction

Groundwater is a very important asset to our ecosystem. Its application lies in the field of Irrigation, Drinking Water, and Domestic Use. According to USGS, 22% of freshwater in the US in 2010 came from Groundwater sources. A balance is to be maintained between natural recharge of Groundwater and pumping. Increased population and rapid Urbanization lead to increased pumping of Groundwater. Consequently, Groundwater levels are declining and in near future bore wells might run dry. The best way to recharge is to put more Water underground. Water which travels through the vadose zone and reaches to a depth of Water Table is termed as recharge. This process is like a tree where roots are spread in the ground in search of Water. Depth at which roots are extended is Water Table Depth in context of Groundwater Recharge. Techniques developed to artificially increase Groundwater levels are known as "Managed Aquifer Recharge" or MAR. Most common methods used for MAR are:

- Injection Well
- Infiltration Basin (Lakes, Ponds)

This project's aims to explore site suitability with Infiltration Basin for Groundwater Recharge. An Infiltration Basin is a chunk of land highly suitable for seepage of Water underground. Injection wells are another technique wherein a bore well is used to feed Water in (as opposed to being pumped out) used in some cases to increase recharge. However, quality of Water, in this case, must be very good, since water is directly fed into Groundwater. In case of Infiltration Basin different parameters needed to be considered to evaluate site suitability are:

- Elevation Topography
- Soil Characteristics
  - Clay percentage (# of soil particles < 2mm in size)
  - Layer Thickness
  - Surface Slope
- Land Use/Land Cover
- Vadose Zone Thickness
- Sub-surface Parameters
  - Hydraulic Conductivity
  - Storativity
  - Aquifer Type

Elevation topography is important because ideally an Infiltration Basin should be created in an area which has higher elevation in North-South direction with respect to basin. This will facilitate natural gravity drainage of Stormwater. Clay percentage is important because soil, where Stormwater will be discharged has to have characteristics to support seepage of Water underground. Clay soil does not support seepage of Water because soil particles are less than 2mm in size and hence high Water holding capacity.

During initial phases of project, intention was to use Stormwater for groundwater recharge especially in urban metropolises where concrete led development is dominated which has close to zero permeability for Water. However, after careful study of available literature and timelines associated, scope of project was changed to spatially analyze site suitability for Infiltration Basins. This report is organized into several sections. Details of these sections are as follows:

Literature Review

This section is to follow immediately after Introduction. It will carefully outline study papers used as references for development of this project. Some of concepts such as Weighted Linear Combination (WLC) and parameters used to evaluate Site Suitability were borrowed into this project (not all parameters).

Objective and Scope

This will outline clearly defined objectives assumed to be met for this project along with scope of this project.

Study Area and Data Sources

This section will outline Study Area (The State of Texas) selected along with their source from where Data was downloaded. It should be noted that; Public Data which is available free of cost was being used as part of this project. Desktop-based GIS Software ArcGIS Pro 2.1 was used (not available as free) to spatially analyze data. One another term was used, "Area of Interest (AOI)". AOI is a sub-part in Study Area. Selection of AOI is optional though highly recommended. Section to follow for further details.

Methodology

This section will outline details of spatial process used for assessing Site Suitability. This project was broken down into two stages:

- Preprocessing
- Postprocessing

Section to follow for further details.

Results

This section will outline details of Potter County from the Panhandle area in the State of Texas. Even though it shows results of Potter County, Desktop based application can be used to produce results of any county in the State of Texas. Details in section to follow.

Conclusion

This section will outline details of attempt towards contribution Groundwater Recharge.

Limitation and Future Scope

This section will outline some of the limitations of this project such as unavailability of Web-based application to perform spatial analysis. This section will also comment on future scope of this project such as Publishing ArcGIS ModelBuilder as a Geoprocessing Service. Details in section to follow.

References

This section will outline published digital material used as reference for scope of this project.

Definitions

Infiltration: Ability of soil to seep water underground. Measured in inches/hour

Infiltration Basin: An area of a land highly suitable for seepage of water underground

Aquifer: Rocks through which water travels most easily

Water Table: upper level of underground surface where rocks are permanently saturated with Water

Hydraulic Conductivity: Amount of water an aquifer can transfer over a period. Generally measured as ft/day

Vadose Zone: part of Earth where Groundwater is at atmospheric pressure

Managed Aquifer Recharge (MAR): A relatively modern term used to define implementation mechanisms for distinct types artificial recharge of Groundwater. Injection Well, Infiltration Basin are some of examples

Literature Review

1. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge

M. Azizur Rahman, Bernd Rusteberg, R.C. Gogu, J.P. Lobo Ferreira, Martin Sauter

This report focuses primarily on spatial multi-criteria decision analysis (SMCDA) software development. It combines Analytical Hierarchical Process (AHP) along Weighted Linear Combination (WLC) and Ordered Weighted Averaging (OWA) to perform spatial analysis. Study Area for this paper was Algarve Region, Portugal. This tool was developed and integrated into ArcGIS as an ArcMap Add-In for performing spatial analysis. Methodology, in brief, explained from below flowchart:

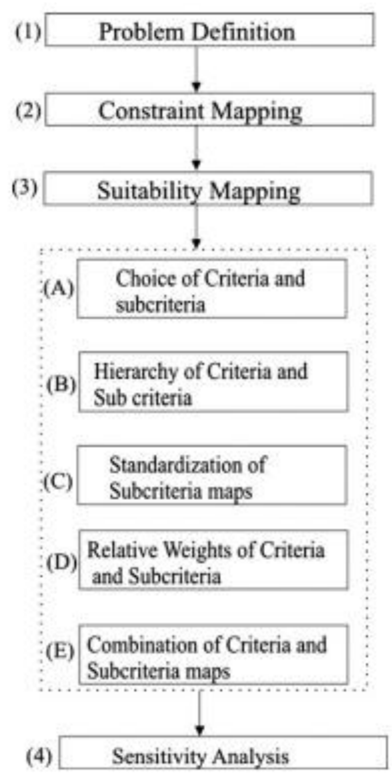

Fig 1 Procedure for MAR site suitability mapping

Constraint Mapping process screens out areas which are non-feasible for MAR to avoid conflict. Suitability Mapping is a step where definition of criteria and sub-criteria such as Topographic Elevation, Surface Geology, Aquifer Hydraulic Conductivity, Storativity, etc. are defined. Step 3(B) from Fig. 1 starts with statistical process such as AHP. In last step, Relative weighting is performed, and maps are produced. Please refer Fig. 2 for corresponding maps. Sensitivity analysis is optional step which may be performed where uncertainty is very high. It can be also used to study robustness of site.

For Algarve Region, Portugal results showed that total of 11.2% of study area classified (map below) as Very Good (an area falling in range of 80-100 in below map).

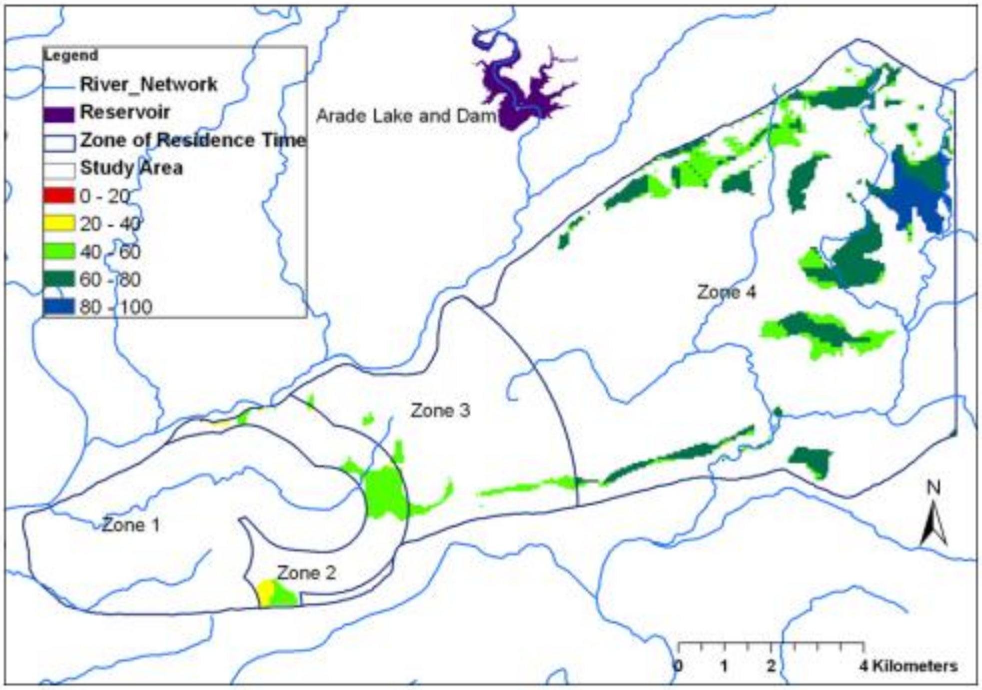

Fig 2 Site Suitability for MAR based on Weighted Linear Combination (WLC)

An idea of assigning weight and Weighted Linear Combination (WLC) was borrowed from this paper. However, for selected AOI only Site Suitability Score was calculated in context of this project. ArcMap Add-In is data independent. However, availability of data is only for Algarve Region of Southern Portugal. In other words, geographical area which falls under scope of this project is limited.

2. Assessment of Managed Aquifer Recharge Site Suitability Using a GIS and Modelling

Tess A. Russo, Andrew T. Fisher, Brian S. Lockwood

This report focuses on two-step regional analysis of coastal groundwater basin of Pajaro Valley Groundwater Basin, California. First step being GIS-based analysis and second being Numerical modeling using MODFLOW-2005 and Farm Process Package (Schmid and Hanson 2009; Hanson et al. 2010) to study hydrologic impact. Below were parameters for which data collected, manipulated and integrated:

Land Surface Parameters

- Surficial Geology
- Soil Infiltration Capacity
- Land Use
- Elevation (Topographic Slope)

- Verified (measured) infiltration and recharge rates

Land Subsurface Parameters

- Aquifer Thickness
- Aquifer Hydraulic Conductivity
- Confining Layer Thickness
- Aquifer Storativity
- Vadose Zone Thickness
- Historical Changes in Water Table elevation

Main theme for this paper is to perform GIS analysis (dealing with Surface Parameters) along with numerical analysis (dealing with sub-surface parameters) to determine MAR Site Suitability. Impact of Seawater intrusion was studied (does not fall in scope of this project) with respect to MAR. Maps for different parameters for Site Suitability produced in Fig. 3.

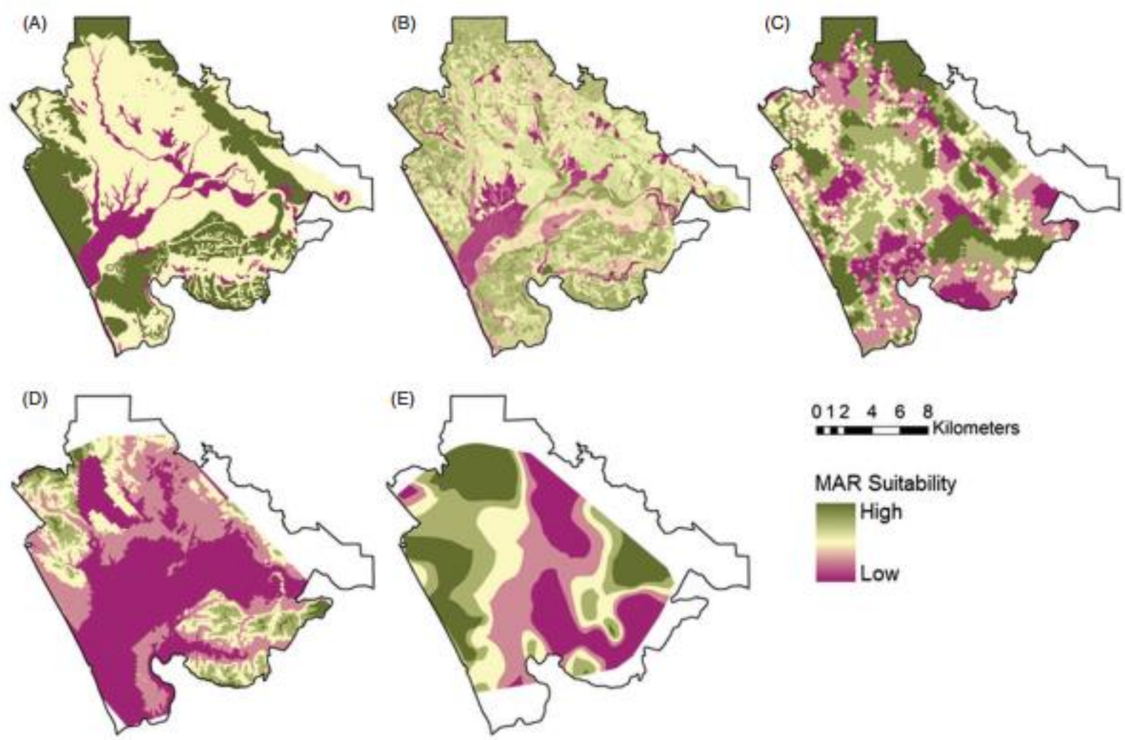

Fig 3 A) Surficial Geology B) Effective Infiltration C) Effective Transmissivity D) Storage Availability E) Change in Groundwater Elevation

This paper clearly outlines distinction of MAR with respect to Surface and Sub-surface parameters. This concept was borrowed for development of this project for collection of data for the State of Texas.

Objective

After careful study of literature and details of MAR techniques such as Infiltration Basin, Injection Well, it was decided that this project will majorly focus on utilization of Infiltration Basin for Groundwater Recharge. Infiltration Basins provide natural water attenuation as it seeps underground and they have low cost of maintenance. For purpose of this project, following were objectives decided:

- Larger Geographical Area (the State of Texas)
- Data Independent Process Workflow
- Utilization of Surface and Sub-surface parameters
- Common scaling mechanism for both type of parameters
- Providing highest automation experience to a user
- Estimate Groundwater Recharge timelines

Scope

As mentioned in Introduction section, initial plan was to capture Stormwater and discharge into Infiltration Basin for seepage into Groundwater. However, there are few things to consider such as, capture mechanism, transport infrastructure, discharge mechanism, etc scope was changed to changed to Site Suitability for MAR.

Fig 4 Storm Capture

As shown in Fig. 4, this is most general mechanism to capture Stormwater in Urban areas. There are different cases in application though. Considering all these parameters, scope was redefined for Site Suitability assessment for Infiltration basin. In other words, this project ignores capture, transport mechanism and attempts to evaluate Site Suitability if we decide to put Infiltration Basin for any of county in the State of Texas of our choice.

Study Area and Data Sources

After careful study of literature and parameters required for spatial analysis, it was decided that geographical area would be the State of Texas for Data Collection. For following parameters data were collected:

Primary Datasets

- Elevation Spots (TNRIS)
- Wells of the Texas (TWDB)
- Aquifers of the Texas (TNRIS)
- Land Cover/Land Use (TNRIS)
- Soils of the Texas (USGS)

Secondary Datasets

- County Boundaries for the State of Texas (TNRIS)
- Mean Precipitation Data (US Climate Data)

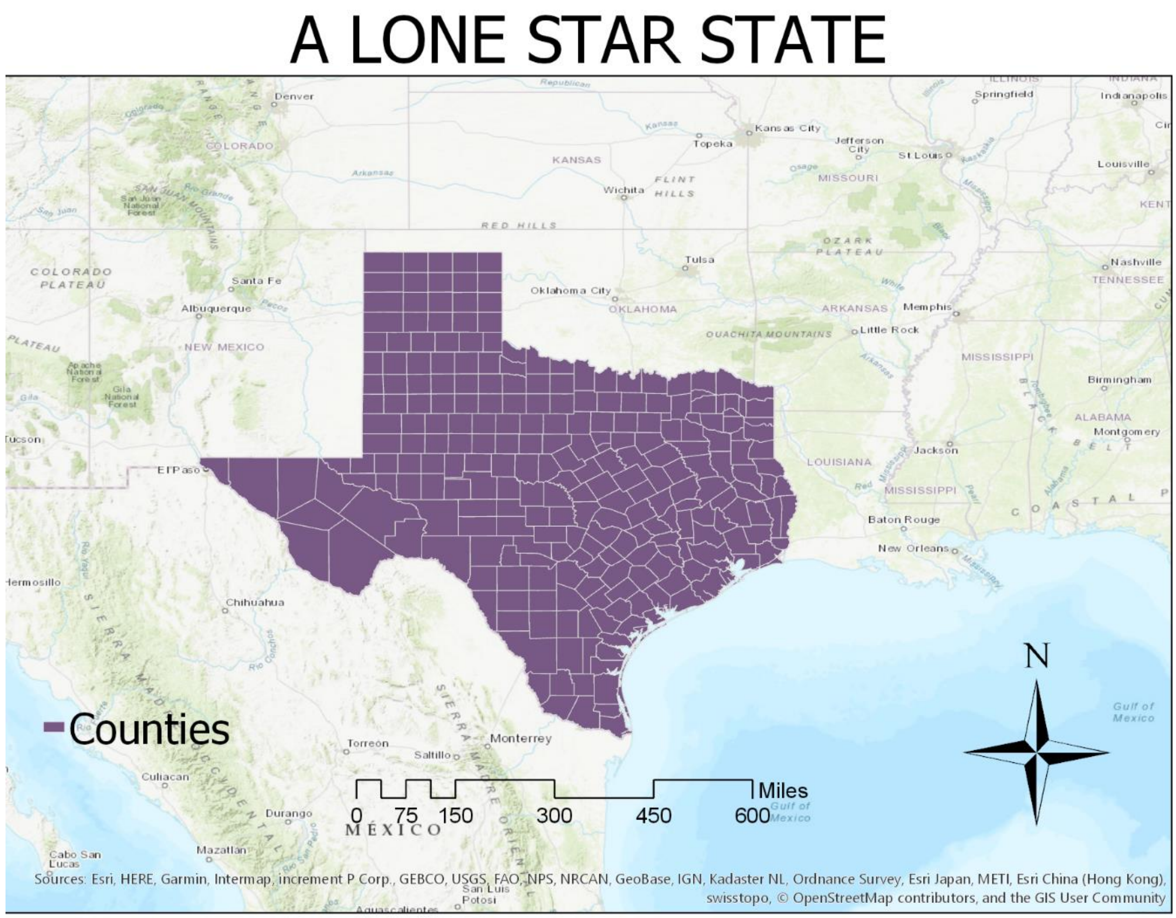

Fig 5 The State of Texas County Boundaries

Elevation Spots

While assessing Site Suitability we want to know Elevation Topography of Area of Interest because we want to utilize drainage of Water due to gravitational force. In case of Elevation, most commonly used data source is Digital Elevation Model (DEM). However, for purpose of this project, DEM would have required several gigabits of Storage requirements. Geoprocessing would have taken extra time for spatial analysis. Hence, DEM's were omitted and Elevation Spots were used. This resulted in better throughput and overall performance. For the State of Texas 527,481 Elevation Spots are available and collected from Texas Natural Resources Information Systems (TNRIS). These were clipped to county level for spatial analysis and those Elevation Spots which falls under selected county were later rasterized using Topo to Raster tool in ArcGIS Pro. This tool has advantage of creating hydrologically correct raster as opposed to interpolating elevation from know Elevation Spots. Interpolation internally is used, but hydrologically correct rasterized elevation will help us identify natural water drainage based on gravitational force. Below is map outlining coverage of Elevation Spots in the State of Texas.

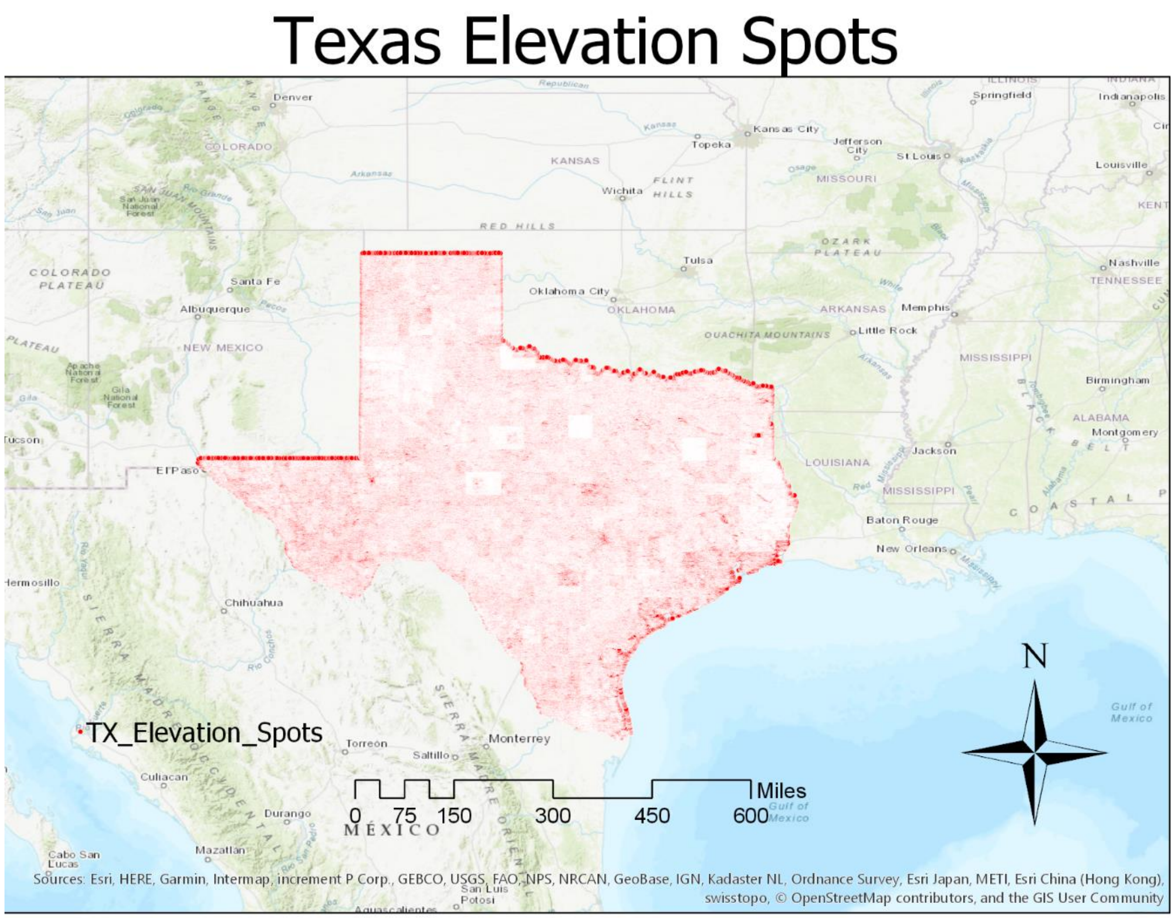

Fig 6 Texas Elevation Spots

Wells of Texas

Wells or Bore wells of the Texas data were required for information about "how deep Groundwater Flow is observed?" This information is important because Infiltration Basin where Water is going to be discharged needs to seep to this depth for Groundwater Recharge along with soil characteristics explained subsequently.

There were 120,958 observations are available for the State of Texas and collected from Texas Water Development Board (TWDB). Wells database contains all types of Wells such as Irrigation Well, Drinking Water Well, etc. Oil and gas type were skipped as they don't fit in scope of this project. Contributors to Wells database are both public and private members.

Soils of Texas

Soils of the State of Texas was one of most important datasets collected from State Soil Geographic Database (STATSGO) published by USGS in association with NRCS. This data is available for Counterminous United States divided into 18 regions which was extracted and reduced to the extent for the State of Texas. It has rich information in its database such as:

- Clay Percentage (particles of soil < 2mm in size)
- Soil Thickness (in inches)
- Available Water Capacity (in inches)
- Permeability of Soil (in inches/hour)
- Surface Slope (expressed in %)
- Liquid Limit of soil (expressed in % moisture by weight), etc.

From this available information, following were parameters finalized for scope of this project

- ➢ Clay Percentage
- ➢ Permeability of Soil
- ➢ Thickness of Soil
- ➢ Surface Slope

Land Cover/Land Use of Texas

This dataset one most important too was collected from TNRIS. This dataset is available as 30mX30m spatial resolution. TNRIS classified dataset as 16-member class definition. Some of pixel definition are as follows:

Pixel Value	Definition
11	Open Water
23	Developed, Medium Intensity
31	Barren Land
71	Grassland

For application of this project, it was decided that Site Suitabiliy will be assessed for Pixel Value (71) because of this land is development-free. One more requirement would be to check whether we have collection of linear pixels together. This will be explained in Methodology section to follow. Below is map for Land Cover of Texas.

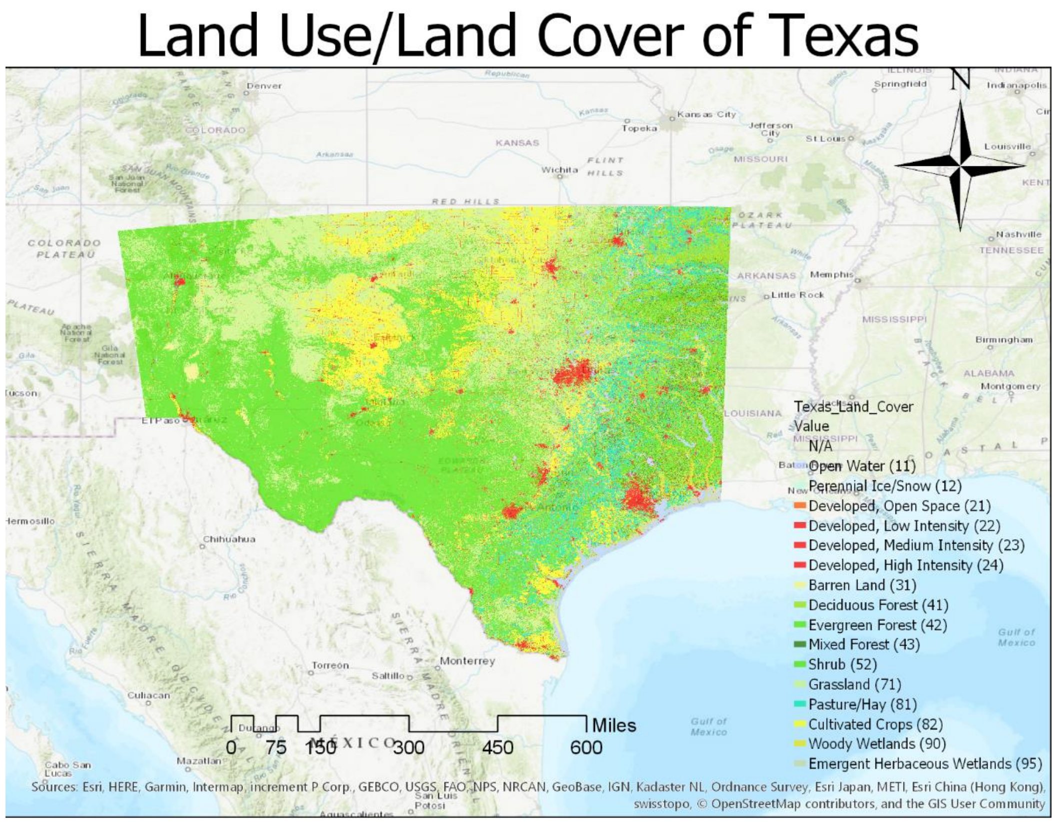

Fig 7 Land Cover/Land Use of Texas

Aquifers of Texas

Aquifers as mentioned in definitions section is a bedrock through which water travels most easily. This dataset was required to establish boundaries for Hydraulic Conductivity of Aquifers in the State of Texas. Texas Water Development Board (TWDB) have published Groundwater Availability Models Reports for different Aquifers of Texas. These reports contain Hydraulic Conductivity of Aquifers of Texas. This dataset was mapped to correspond to Wells Database and field containing K-factor (K is standard notation to denote Hydraulic Conductivity in Hydrology) was added in Wells database.

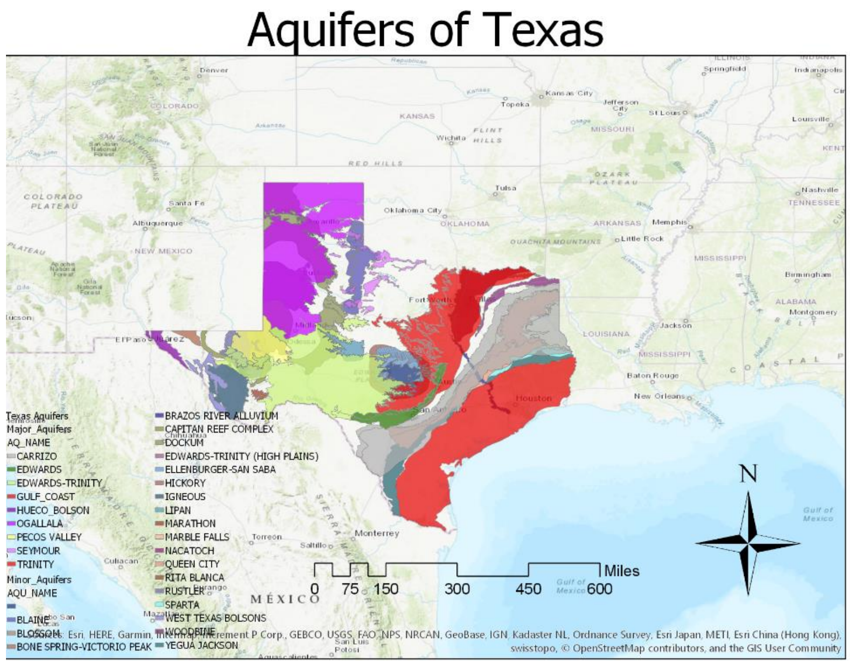

Fig 8 Aquifers of Texas

Other Relevant Data

Data such as Precipitation, County Boundaries for the State of Texas is relatively very easy to find. County boundaries needed to be established because Site Suitability analysis will be based on county level. Precipitation data was helpful to assess how Stormwater can be harvested to discharge into Infiltration Basin.

Weighted Linear Combination (WLC)

As mentioned in Literature Review section, Weighted Linear Combination(WLC) was borrowed from paper 1 for Site Suitability Assessment Decision. Below were the parameters selected for weighting:

- Elevation (default 10)
- Land Cover (default 10)
- Well Depth
- Clay %
- Soil Thickness
- Surface Slope %

These scores were based on scale of 1-10 where 1 being lowest and 10 being the highest. Elevation and Land Cover gets default 10 (highest score) because after preprocessing step (explained subsequently), there is a small manual intervention where a user is selecting Area of Interest (AOI) in a county where continuous polygon with pixel value 71 (Grassland) are found with relatively lower to mid-elevation. In other words, we're picking up best possible geographical area with known elevation and vacant land. Hence, these two factors get default 10. Rest of the factors are weighted as follows:

- **Well Depth**
  Higher depth will be assigned lower score and vice versa. Since, higher the Groundwater level from bore well is pumping water from, higher time it will take to seep infiltrated water. Hence, higher depth will get higher score.
- **Clay %**
  Clay is defined as percentage of as soil particles with less than 2mm in size. Clay can hold on to water. Hence, more the clay in soil lower soil infiltration rate and vice versa. Based on this, higher percentage of clay in soil will get lower score and vice versa.
- **Soil Thickness**
  This dataset from Soils of Texas provides information with respect to how thick layer of soil is observed. Measured in inches, thicker the soil, more time it will take to seep water underground. Hence, score for thicker soil will get lower score and vice versa.
- **Surface Slope**
  This dataset from Soils of Texas provides information with respect to variation is Surface Slope. In other words, it will provide us with information as to "how stable soil surface is for defined area of soil". Higher Surface Slope will get lower score and vice versa.

Total weighted score inclusive of all parameters mentioned above was calculated out of 60 (default 20 for elevation and land use and rest 40 for 4 parameters). For illustration purpose, a case study was done for Potter County in the State of Texas and weighted score turned out to be 49.88. This score can be classified as very good score.

Methodology and Results

This project was mainly divided into 2 sub-steps viz., Preprocessing and Postprocessing. Detailed flowchart is shown below:

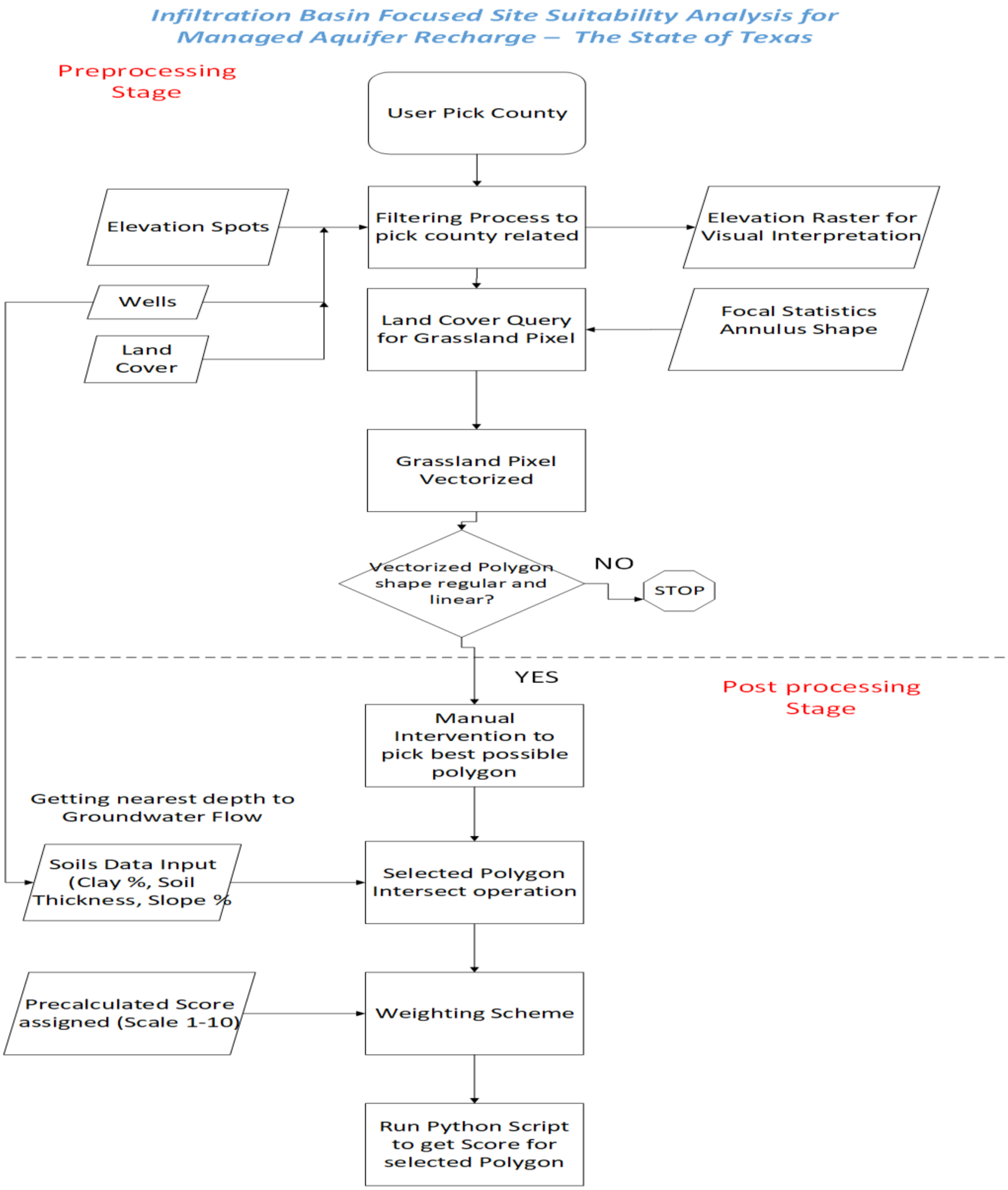

Fig 9 Processing Flowchart

Preprocessing

This step starts with a user inputting county in the State of Texas.

1. Relevant data such as Elevation Spots, Land Cover, Wells Database will be filtered on map.
2. In next sub-step, model will create rasterized version of Elevation Spots found county selected in previous step
3. This is most critical in preprocessing step. For clipped Land Cover to an extent of county selected at first, we will run Focal Statistics Operation with below details:
    - Neighborhood Type: Annulus
    - Inner Radius: 5 Pixels
    - Outer Radius: 15 Pixels
    - Statistics Type: MAJORITY

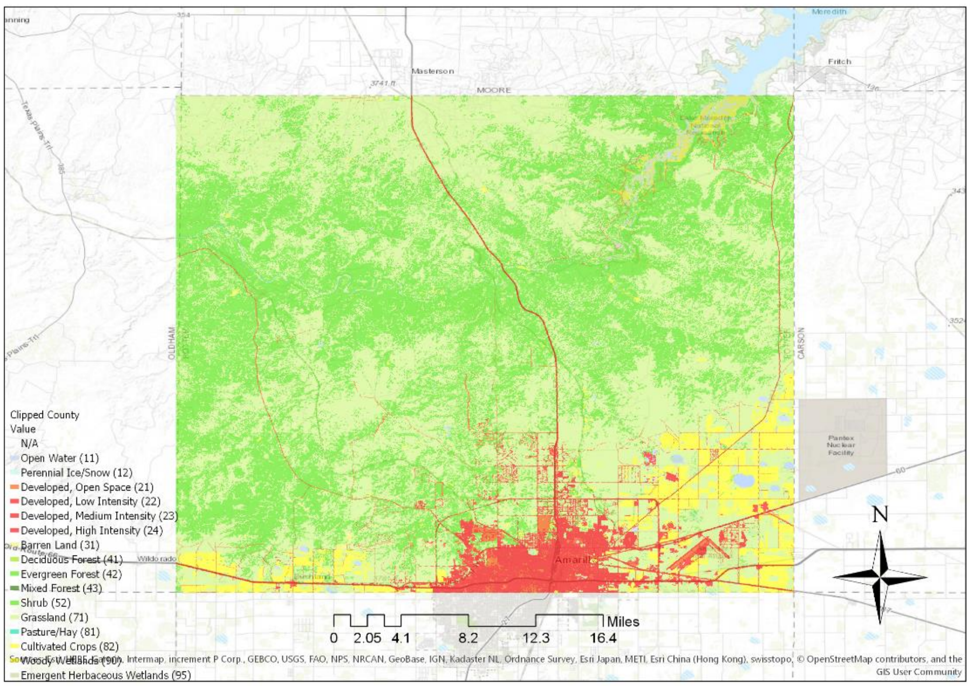

Fig 10 Land Cover (Potter County)

As we can see in Fig 10, south side of Land Cover in Potter County is dominated by developed (urban area - City of Amarillo) areas while north area of Potter county is dominated by Grassland/Herbaceous areas desired for purpose of this project. We need to have linear and large enough chunk of land to have Infiltration Basin for making substantial contribution to Groundwater Recharge. Hence, we need to run Neighborhood Operations available in Spatial Analyst toolbox with ArcGIS Pro. Below is the result:

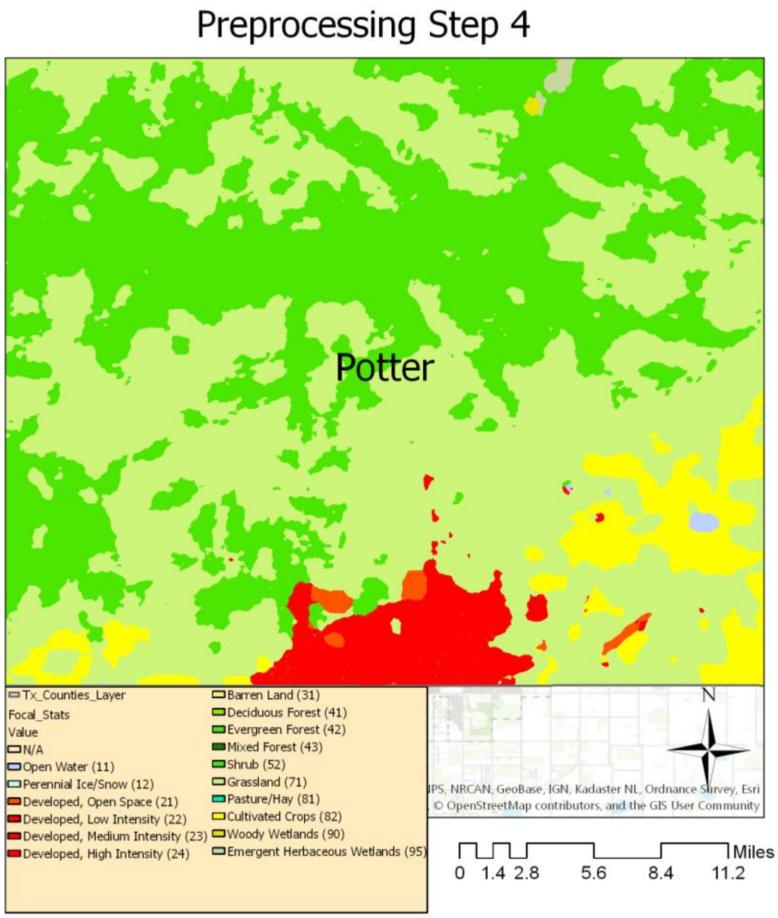

Figure 11 Focal Statistics Operation Result (Potter County)

We know the Spatial Resolution of 30mX30m from our dataset of Land Cover. Outer radius of 25 pixels will yield 30*25 = 750mX750m rectangle and MAJORITY Statistic operation gives Grassland Pixels as shown in Fig 11. In brief, output of above operation reveals that light green areas are candidate locations for Infiltration Basin.

4. Next step is to vectorize these locations for further Spatial Analysis. Below is result of mentioned operations.

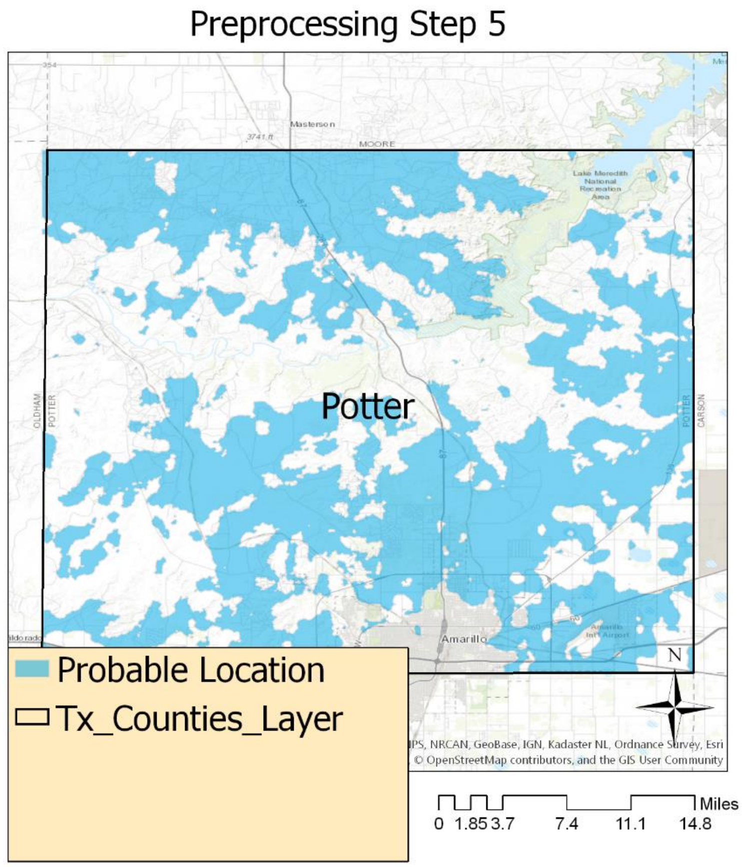

Fig 12 Vectorization of Candidate Locations

Preprocessing is completed at this stage. There is a small manual intervention at this stage explained subsequently. Next step will be to assess soil characteristics and analyze Groundwater depth at Area of Interest (AOI). AOI will be manually selected by a user.

Postprocessing

As shown in Fig 12, blue areas are candidate polygons which pass criteria we set in Preprocessing stage (750mX750m rectangle with available vacant land).

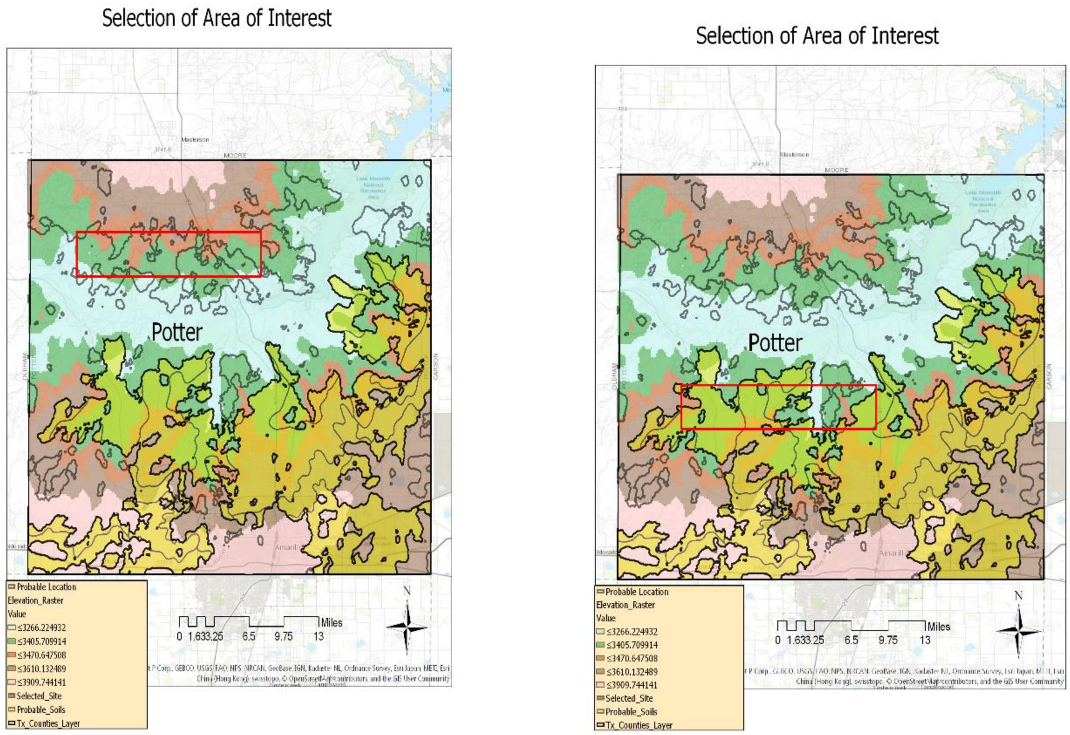

Fig 13 Selection of Area of Interest

We have two options to select AOI from vectorized polygon from Fig 12, either North Side or South Side of Canadian River (shown as light blue color in Fig 13). We want to utilize drainage of Water resulting from Gravitational Force. Hence, to help user pick right area, vectorized polygons are overlaid on top of elevation profile (created in preprocessing step). Below are some of detailed sub-steps in postprocessing:

1. Soils of Texas Data for AOI

   AOI selected manually before this step from candidate polygons will geometrically intersected with Soils of Texas data for information with respect to Soils.

2. Wells of Texas

   AOI selected manually before this step from candidate polygons will be geometrically intersected with Wells of Texas data for information with respect to Groundwater Depth

3. Calculation of Weighted Score

For previous two steps, new polygon features will be created containing Weighted Score associated (this score is precalculated and added as a new field in attribute table of relevant data). A Python script will run to read these features and calculated total score by adding individual score associated with these newly created polygons. Below table for AOI in Fig.13:

	Water Table (in Feet)	Clay % (Soil particles < 2mm in size)	Thickness (in Inches)	Surface Slope (expressed as %)	Weighted Sum
AOI 1	260.2	23.22	65.26	6.44	49.88
AOI 2	343.1	24.58	69.58	5.24	48.87

Table 1 Weighted Score for AOI

For illustration purpose AOI 1 (north side of Canadian River) was finalized for Site assessment since it was (and map to follow):

- Away from Developed Land
- Lower Groundwater Depth

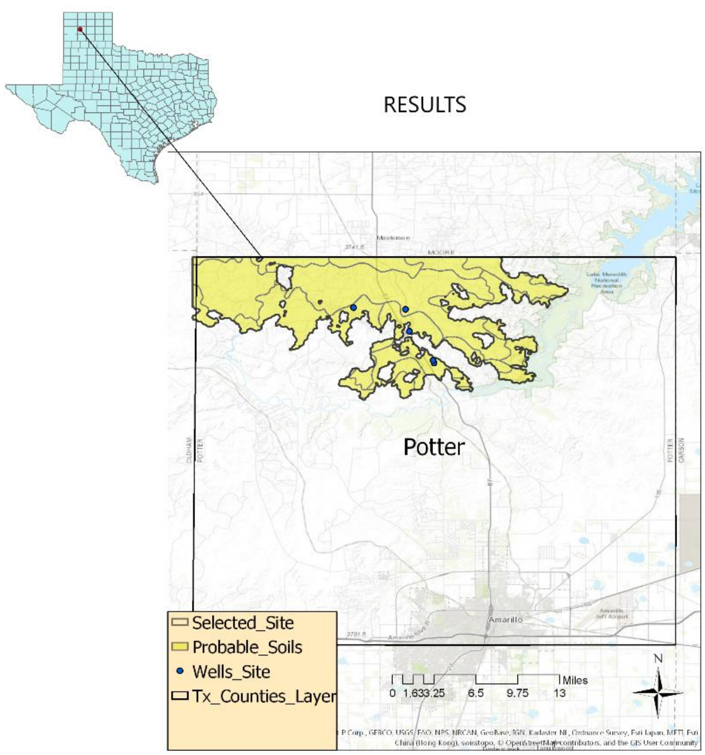

Fig 14 Site for MAR Assessment

Pecos County Example

Let's take an example of Pecos county in the Southwest part of the State of Texas. Pecos County is majorly dominated by Evergreen Forest. Hence, when we run preprocessing with Focal Statistics operation, we have a map which looks like:

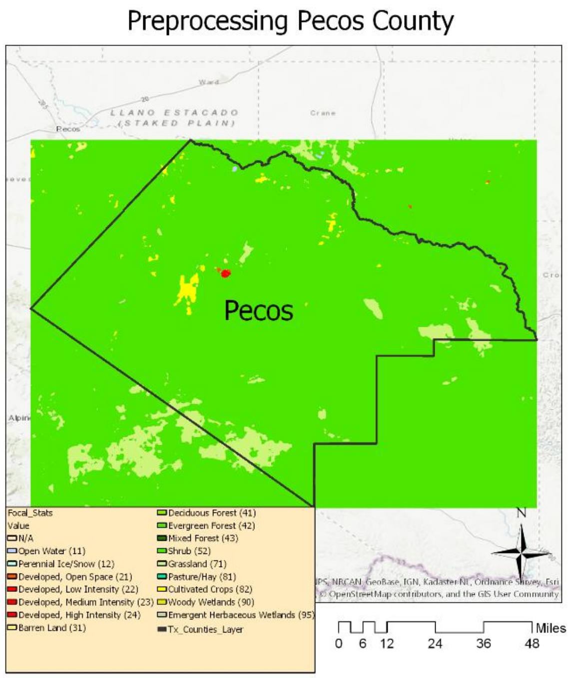

Fig 15 Preprocessing Pecos County

As seen from above fig, we see very few candidate polygons for having Infiltration Basins (light green polygons). It may not be a good idea to have Infiltration basin in Pecos County (subsequently proceed with Postprocessing). However, if a user wishes to continue to spatially analyze soils and Groundwater depth he/she can proceed.

Conclusion

During initial phase of this project, literature review was done extensively to understand technical traits with respect to Groundwater Recharge such as

- Surface Parameters (Elevation, Land Cover/Land Use)
- Sub-surface Parameters (Soil Characteristics, Groundwater Depth)

As mentioned in objectives section, Larger Geographical Area was one of key issue planned to be addressed. Indeed, this objective was met with success.

Another key objective established was Data Independent Process Workflow. This objective was met with one small manual intervention step (to manually select AOI after processing).

A co-ordination among surface and sub-surface parameters required to be met for efficiently analyzing Suitability.

At the end, a rough Groundwater Recharge timeline after doing Suitability study was established initially. This objective was partially met because one component for correct prediction (Vadose Zone Thickness) was ignored due challenges in collecting data.

Overall this project has statewide data for major parameters and process required to assess Site Suitability all at one place. There are quite a few things which can make it more effective and accurate explained subsequently in section to follow.

Future Scope

These are some of useful things to expand on this project for making results more accurate.

- **Go WWW**
  This project was developed as a Desktop-Based application with ArcGIS Pro 2.1. In future, this project can be deployed on online GIS Platform such as ArcGIS Online for easy access and wider audience.
- **Explore ASR**
  This project can be utilized to assess potential sites for ASR. ASR is a different MAR technique where water is discharged and allowed to seep underground until a specific level and pumped out when required. A MAR technique employing this phenomenon sometimes termed as "Underground Lake".
- **Injection Well Integration**
  Injection well is relatively very easy technique of MAR. Bore wells are used to pump water in as against pumping out from Groundwater. However, quality of water is a critical issue when pumping water in as it will become part of Groundwater.
- **Integration of DEM from Web Imaging Service**
  As mentioned earlier, for purpose of this project, Spot Elevation was used for better throughput and escape larger storage space. In future though, DEM can be integrated as they provide better accuracy using Web Imaging Service and load relevant data at run-

time for efficient processing. In other words, online Web Imaging Service can be queried to load data relevant Study Area we wish to assess for application of MAR.

Limitations

Like any other projects, this project is also constrained by following terms:

- **Vadose Zone Thickness**
  Vadose zone (see Definitions) thickness plays a key role for making accurate assessments for Groundwater Recharge. It is also sometimes referred as "Unsaturated Zone". This area of soil lies immediately below surface of soil. Basically, this area of sub-surface of soil is a combination of pores between soil particles, air and soil itself. It is difficult to measure exactly how deep this zone lies before we reach Groundwater Depth. Water seeping from surface of soil may not reach Groundwater Level since, Vadose zone may carry it downstream and later become part of Springs.
  In brief, data corresponding to this layer of soil is very difficult to collect (having these data Statewide is again different story).
- **Spatial Resolution of Output**
  As mentioned in Methodology section, Elevation is built on-the-fly from Spot Elevations. We are using Land Cover Raster Dataset with 30m spatial resolution. However, on-the-fly raster for elevation will have coarse resolution compared to Land Cover dataset. This issue can be addressed by utilizing Web Imaging Service to retrieve DEM for Study Area of our choice.

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