Modifying Ohio's DRASTIC ground water potential pollution model to account for karst limestone voids and sinkholes

Thesis

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Abstract

In the 30 years after the publication of the DRASTIC model for groundwater sensitivity analysis, a number of researchers have revised or altered the model to better suit regional needs and geologic conditions. DRASTIC; initially developed in and calibrated for Ohio was built as a first step model with readily available dataset inputs, allowing for communities of all sizes to generate their own relative pollution potential maps, decreasing costs associated with hiring a consulting firm to complete this work. However, the simplicity that makes DRASTIC accessible for small community land use zoning also results in an overgeneralization of complex geologic conditions. Moreover, specialized updates to the model have not been incorporated into the accepted text, and in its present version and the model cannot sufficiently account for increases in pollution potential resulting from calcium carbonate limestone (karst) voids in the geologic profile. This research will identify the hypothetical effect of altering DRASTIC by comparing its outputs to karst calibrated models, then these findings will be incorporated into a new modified version of DRASTIC that will be used to generate karst-sensitive pollution potential maps. Delaware County, Ohio will be used as a case study due to its well-known karst bands and the existence of a DRASTIC pollution potential map that can be compared to this modified DRASTIC output as verification of concept.

Dedication

To my loving parents, friends, and teachers of all kinds who supported and encouraged me to seek ever-greater depths of knowledge and aim to make a difference.

Acknowledgments

Dr. Julie Weatherington-Rice; Mike Angle, Craig Nelson, and Douglas Aden of the Ohio Department of Natural Resources Division of Geological Survey; Dr. Ann Christy; and Dr. Eun Kyoung Kim.

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Chapter 1. Introduction

DRASTIC, the United States Environmental Protection Agency’s (US EPA) standardized system for evaluating groundwater pollution potential (GWPP) is a land use planning tool. DRASTIC’s inputs are data from easily accessible sources (see Table C-1 for examples) that are used to assign sensitivity values to land areas with constant hydrogeological parameters, generate sensitivity indices, and compare said indices to other regions within the study area (Aller, et al., 1987). These sensitivity maps can be used by small communities to preclude contamination of essential ground water resources. A key factor in the model’s popularity is the relatively low investment required to create and maintain these GWPP maps. When compared to site specific surveys, the only expert intervention required with GWPP maps is to verify and or adjust the ratings values once the map has been generated to ensure the results are as accurate as possible.

During the 1980's, the US EPA funded a National Ground Water Association effort to assess aquifer vulnerability for the United States. *DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings* (Aller et al., 1987) was designed as an improvement on the existing LeGrand Hydrologic System for Evaluating Waste Disposal Sites (LeGrand, 1983). Two years of conversation and consideration went into the design and parameterization of the model between the initial draft printed in 1985 and its final publication. As a result of this development, Ohio chose to utilize DRASTIC as the state standard for rating aquifers and their surrounding landmass based on their relative sensitivity to pollutant contamination. Subsequently, the Ohio Department of Natural Resources Division of Water (ODNR DOW) was designated as overseer of the model's generation. Since then, the Division of Geologic Survey (ODNR DGS) has inherited the efforts to comprehensively map the GWPP schema of the state of Ohio. This series of decisions means that the Ohio Environmental Protection Agency supports the outputs of this GWPP model. Therefore, the best solution to ensure uniform land use decisions are made is to incrementally improve upon the DRASTIC model.

In the 30 years since its inception, researchers have tailored the DRASTIC model for their unique study area or designed entirely new GWPP models to suit their needs. The model itself has been updated by the original authors, yet the US EPA has not incorporated any updates and as such the model remains incapable of accounting for certain hydrogeological conditions (Ivan & Madl-Szonyi, 2017). This project aims to improve the DRASTIC model by establishing a methodology to address its inability to account for calcium carbonate (karst) limestone geology based on other successful GWPP models.

Model Formulation and Working Assumptions

The name DRASTIC is an acronym for the parameters utilized in the original model which considers weighted values of: Depth to groundwater, net Recharge of water within the watershed, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity of the aquifer, to create map overlays and numerical indices by which the area's general contamination sensitivity can be represented (Equation 1-1). DRASTIC assigns sensitivity values to land areas with constant hydrogeological parameters (known as distinct units) as compared to other distinct units within the study area (Aller, et al., 1987). The values are based on the summation of parameter weights (found in Table 1-1) multiplied by predetermined ratings tables using publicly available datasets (Aller et al., 1987).

Equation 1-1: DRASTIC Formula

$$GWPP = D_W * D_R + R_W * R_R + A_W * A_R + S_W * S_R + T_W * T_R + I_W * I_R + C_W * C_R$$

$Where$:

$x_R = Rating\ of\ each\ Variable$

$x_W = Weight\ of\ each\ Variable$

$D = Depth\ to\ groundwater\ (feet),$

$R = Net\ Recharge\ of\ water\ (inches),$

$A = Aquifer\ media,$

$S = Soil\ media,$

$T = Topography\ (\%\ slope),$

$I = Impact\ of\ the\ vadose\ zone,$

$C = Hydraulic\ Conductivity\ of\ the\ aquifer\ (Feet/Day)$

Table 1-1: Standard weight values for DRASTIC model parameters

Parameter	Weight
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of the Vadose Zone	5
Hydraulic Conductivity	3

The purpose of DRASTIC is not to assess the likelihood that a given "distinct unit" containing unique combinations of the 7 stated hydrogeological parameters within the area of study will become polluted. Instead, DRASTIC GWPP indices indicate the likelihood of contaminant transport to aquifers, and to drinking water aquifers in particular for land use planning purposes, if a surface spill should occur within the distinct unit as compared to another distinct unit within the area of study (Figure 1-1)**Error! Reference source not found.**. Outputs of this equation for each distinct unit are called the unit index and fall within categories of increasing sensitivity Table 1-2.

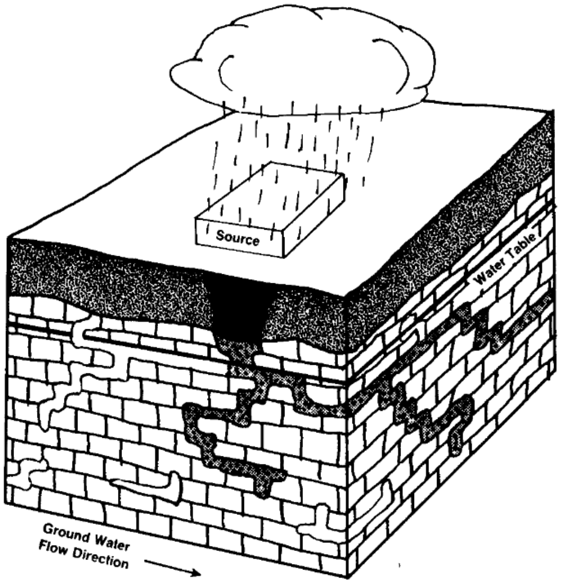


Figure 1-1: DRASTIC visualization of the effect of a surface contaminant spill within a karst impacted aquifer region

Table 1-2: DRASTIC model index sensitivity ranges

Relative Sensitivity	GWPP index value range
Lowest Risk	< 79
↓	80 – 99
	100 – 119
	120 – 139
	140 – 159
	160 - 179
	180 – 199
Highest Risk	> 200

Child models by originator model type

A variety of GWPP models have been created since 1987; some derived from DRASTIC, others using GLA and EPIK which were created in 1995 and 1996, respectively (Ivan & Madl-Szonyi, 2017). Some of these models have been calibrated to consider the effect of karst limestone and as such can provide context for updating DRASTIC (Al Kuisi, El-Naqa, & Hammouri, 2006; Casale, Celico, De Mascellis, De Vita, & Genco, 1999; Doerfliger, Jeannin, & Zwahlen, 1999; Kralik & Keimel, 2003; Ravbar & Goldscheider, 2007; van Beynen, Niedzielski, Bialkowska-Jelinska, Alsharif, & Matusick, 2012; Taheri, Taheri, & Mohsenipour, 2015). While many of these karst-sensitive models blend two existing methods or alter parameter weights to account for karst, several models were found that are distinct from DRASTIC thanks to the addition of new parameters. Six of these models were chosen for component analysis as potential modifiers of the existing DRASTIC methodology including: KARSTIC, DRISTPI, SIN-DRASTIC, COP+K, KAVI, and SI (Davis, Long, Nazir, & Xiaodan, 1994; van Beynen, Niedzielski, Bialkowska-Jelinska, Alsharif, & Matusick, 2012; Jimenez-Madrid, Carrasco, Martinez, & Gogu, 2013; Taheri, Taheri, & Komail, 2017; Ravbar & Goldscheider, 2007).

For models based directly on DRASTIC, the resulting indices for distinct units lacking karst should be comparable to indices from DRASTIC. As an example, the KARSTIC model took care to modify "...parameters from the original DRASTIC method (Aller and others 1987) so that the KARSTIC parameters also could be applied to non-karstic aquifers within the region of study with no loss of accuracy in the comparison of sensitivity" (Davis, Long, & Wireman, 2002). The indices obtained from models that are not direct children of DRASTIC may be less accurate due to the different soils and geology used to calibrate them and will need to be converted to ensure the range of values matches the DRASTIC sensitivity ranges. As an example, unit conversions will be required for models built outside of the United States to ensure all inputs are in imperial units (Table C-4).

While numerous GWPP models exist; all models not explicitly identified above were removed from consideration either because of their relative similarity to the selected models listed in the above table, overly specific configurations that are inappropriate for application across many different hydrogeological settings, or their need for detailed data resulting from extensive field study. This was done in order to retain the essence of DRASTIC's accessibility for smaller communities. Because Ohio has already pledged to use DRASTIC for pollution sensitivity mapping purposes, the goal is not to find the most precise model to serve this purpose, but instead to provide incremental improvement of the chosen model to provide reasonable simulations of actual conditions for users. One effective way to confirm success of a modestly updated approach for karst sinkhole incorporation would be to generate a GWPP map for an area of study that already has an established DRASTIC map so that a comparison of the pre- and post-karst incorporation can be visually represented.

DRASTIC’s benefits and shortcomings

Shortly after publication, training sessions for researchers to perform DRASTIC analyses were established, and the model was adopted by many U.S. state and international agencies to examine GWPP. The primary driver for adoption of this model is the empowerment of communities to minimize the need to hire consultants for site or regional surveying and lower the costs of high-level pollution potential mapping. Another benefit is the relatively low field surveillance effort required to generate pollution sensitivity maps.

Despite DRASTIC’s ‘simple’ formulation, there are two major issues with the model in its current state; its ability to identify commonly occurring, yet complex hydrogeological conditions, and the requirement of secondary expert review to ensure accuracy for any GWPP map. This simplicity and accessibility have resulted in the need for frequent reviews and updates to the methodology to account for aberrant regional conditions. One ‘unofficial’ model update occurred in 1995 in Ohio when the original authors realized that DRASTIC lacked the ability to account for the ‘double-block’ porosity of glacial till; which incorporates “...both primary porosity (flow through the glacial till matrix of silt and/or clay) and secondary porosity (flow through fractures, worm holes, root holes, and along preferential pathways such as varves or other depositional features)” (Weatherington-Rice, Christy, Angle, Aller, & Gehring, 2006).

First, critical conditions, such as open-water conduits from abandoned underground mines or calcium carbonate (karst) limestone remain unaccounted for in the model. When exposed to acid compounds, karst limestone dissolves; creating sinkholes and voids in the geologic column. This reduces fluid dispersion and sorption pathways between the ground surface and aquifers if they develop in the vadose zone (Alpha, Galloway, & Tinsley III, n.d.). Ohio in particular contains large regions of sulfurous shale formations that historically overlie karst. When exposed to water and air, the shale readily creates sulfuric acid, breaking down underlying karst layers and decreasing pollution resilience for the surrounding hydrogeological area (Appendix B). These dissolved regions in the profile are problematic because people often identify the surficial depressions that form as a result of the collapse of overlying materials as ideal dumping sites, filling them with waste products such as cars and refrigerators whose retained liquid contaminants including oils and refrigerant then are directly conveyed deeper into the ground and potentially to aquifers (Taheri, Taheri, & Komail, 2017; ODNR DGS, personal communication, December 6, 2018).

Second, the model is not capable of generating indices at a high level of accuracy and requires the indices to be analyzed by an experienced geologist, hydrogeologist, or environmental consultant with region specific knowledge (Aller et al., 1987). This issue is caused by the generalized descriptions for parameters ratings; meaning that indices for distinct units can vary and accuracy depends on selecting the most appropriate value. Most community created maps use average values for all parameter ratings, leading to indices that are likely to be too low or too high. In addition to the ‘unofficial’ Ohio 1995 update, many other alterations to the model have been created to suit specific regions, proving that the model is holistically applicable, but too generalized without additional information to represent the most complex hydrogeological conditions. None of these alterations were overseen or managed by the US EPA and as a result, 400 researchers have altered or otherwise improved the sensitivity of DRASTIC to suit unique geographic regions (Appendix B, Kim, 2018)

The aim of this research is not to produce a wholly new model capable of perfectly identifying the lowered pollution resilience in karst landscapes, but to provide an incremental update to better reflect this increased sensitivity while retaining the essence of DRASTIC. This approach is necessitated because Delaware County and the entire state of Ohio has committed to the use of DRASTIC for pollution potential determinations. Because the other models require a higher level of precision and specialization in data layers, these models reduce the fundamental structure of simplicity that makes DRASTIC so accessible for smaller communities for land use planning. The karst incorporation method to be analyzed moving forward will be the addition of a data layer comprised of easily accessible datasets (i.e. LiDAR point clouds and roadway and land use feature classes) to recalibrate GWPP values. This methodology will be applied to Delaware County, Ohio; a county with known karst features and a pre-existing GWPP map that can be compared to this recalibrated version of the model.

Case Study: shortcomings of DRASTIC methodology in Delaware County

The presence and impact of these karst features results from both marine and glacial formations with a key factor being the rise of the Cincinnati arch from the ocean between the end of Devonian and beginning of the Mississippian era. When the Ohio shale was lifted above sea level, it was no longer subject to saturated, anaerobic conditions and began to weather away, creating sulfuric acid compounds that dissolved portions of the underlying carbonate limestone formations, enhancing the natural karstification of the limestone layers.

This geologic activity resulted in karst limestone bodies throughout the state of Ohio that can be observed today, not only where the shale can be observed overtopping the karst limestone, but in regions where the shale has been fully weathered away. The inconsistent weathering due to the Cincinnati arch and subsequent marine basins on either side of the arch facilitated additional depositions over the shale and karst limestone in the Eastern portion of Delaware County and the rest of the state.

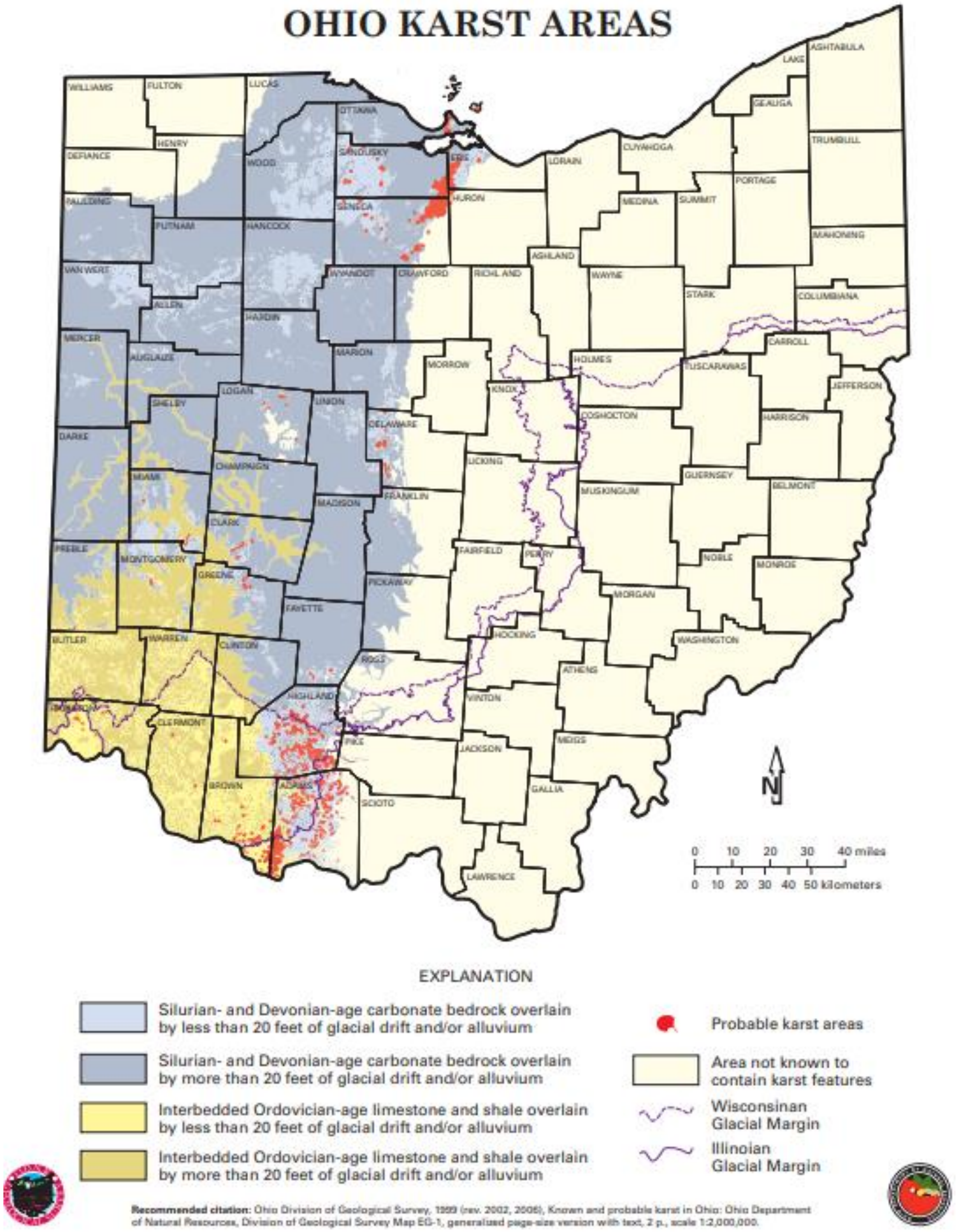
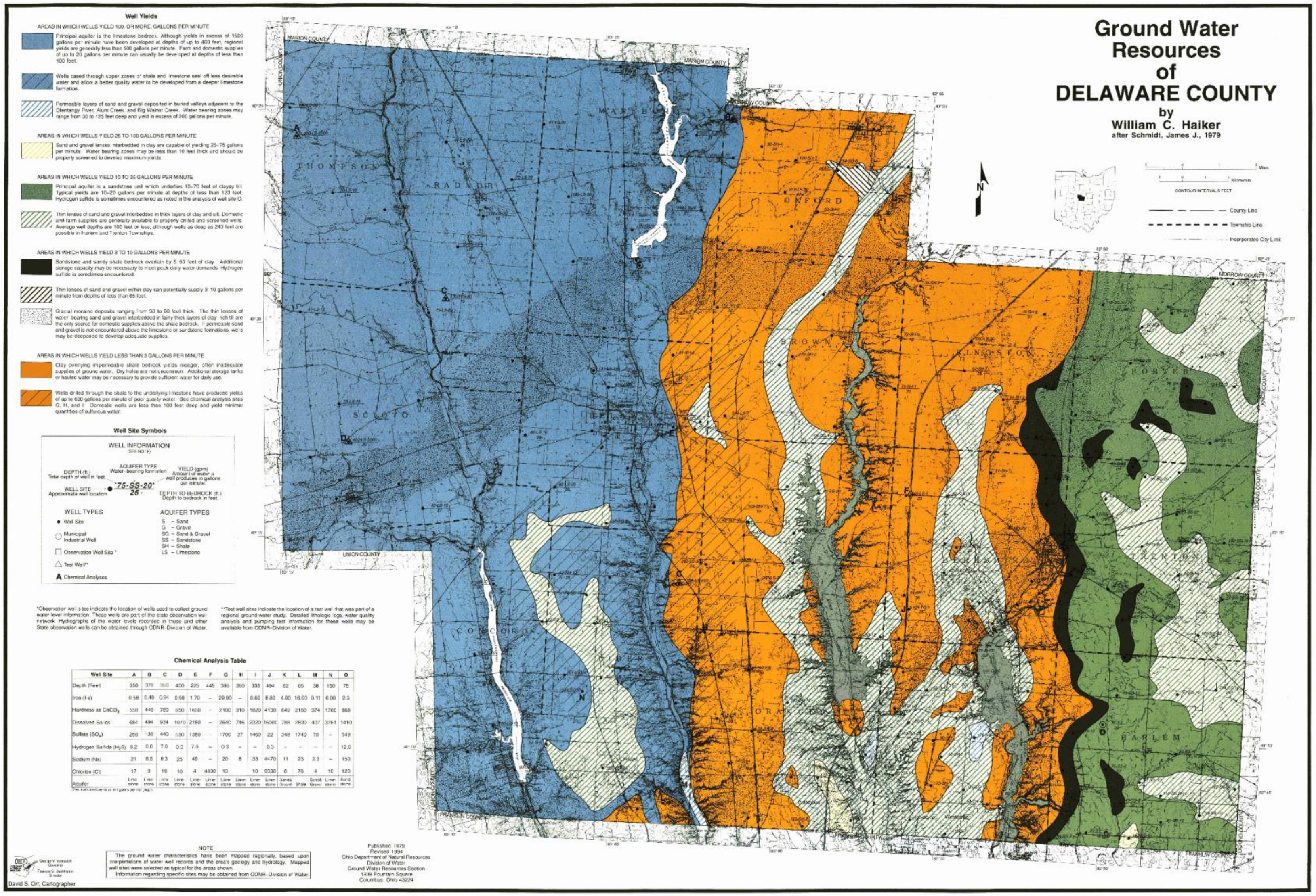


Figure 1-2: Known karstified regions in Ohio. Ohio Division of Geological Survey (Survey, Map EG-1: Known and probable karst in Ohio, 1999 (rev. 2002, 2006))

Fracturing of the shale and karst limestone began with the lifting of the Cincinnati arch and was perpetuated by weathering. The permeable combination of fractured shale and karst limestone aquifer geology in the West of Delaware County results in ground water yields exceeding 100 gallons per minute but also the highest vulnerability to water contamination (Figure 1-3). The existing geologic voids and channels of karst limestone are a concern today, but with anthropogenic acidification of precipitation, the likelihood of new and enhanced karst features increases.

The inability of DRASTIC to account for karst features is a problem even in the state of the model's creation, where ODNR DGS employees have identified and confirmed over 350 sinkholes in and around Delaware County, Ohio that are not represented in the GWPP map (Figure 1-4). It is known that Ohio has areas of carbonate limestone exposed to acidic conditions from overlying sulfurous shale (Figure 1-2 and Figure 1-4), yet these features are not appropriately represented in the 2005 DRASTIC GWPP map (Figure 1-5).

The unanticipated karst sinkholes of Delaware County have plagued construction projects and caused road failures in the Western half of the county. Analysis of the county's 2005 DRASTIC map does not suggest the presence of these sinkholes that play a key role in transporting pollutants to groundwater bodies and aquifers (Taheri, Taheri, & Komail, 2017).



Chemical Analysis Table

Well Site	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Depth (Feet)	350	370	350	400	225	445	395	350	335	494	62	65	38	150	75
Iron (Fe)	0.58	0.40	0.94	0.98	1.70	–	29.00	–	0.60	8.80	4.00	16.00	0.11	6.00	2.3
Hardness as $CaCO_3$	560	440	780	650	1630	–	2100	310	1820	4130	640	2160	374	1760	868
Dissolved Solids	684	494	924	1070	2180	–	2640	746	2320	16000	788	2830	407	3261	1410
Sulfate (SO_4)	250	130	440	530	1380	–	1700	27	1460	22	348	1740	70	–	549
Hydrogen Sulfide (H_2S)	0.2	0.0	7.0	0.0	7.0	–	0.3	–	–	0.3	–	–	–	–	12.0
Sodium (Na)	21	8.5	8.3	25	49	–	20	8	33	4470	11	23	2.3	–	150
Chloride (Cl)	17	3	10	10	4	4400	13		10	9330	6	78	4	10	120
Aquifer	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Sand & Gravel	Shale	Sand & Gravel	Limestone	Sandstone

Figure 1-3: Groundwater Resources of Delaware County - ODNR Division of Water

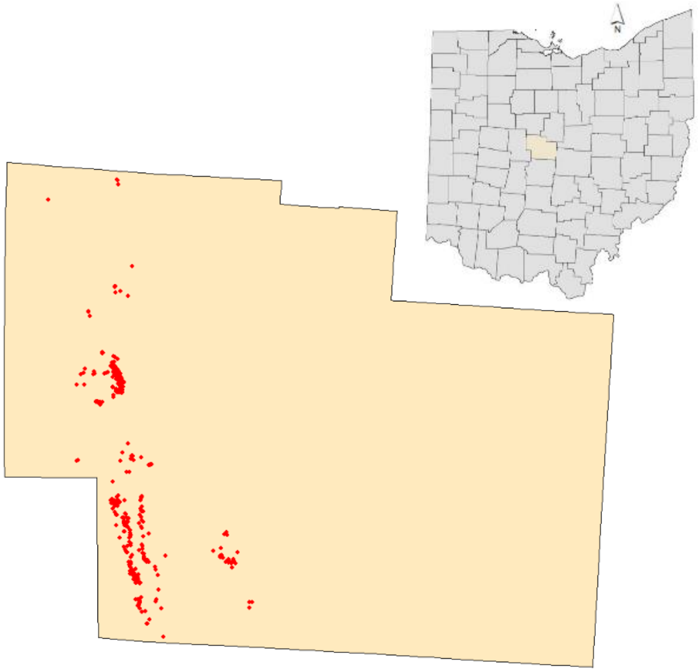


Figure 1-4: Known and Suspected Sinkholes within Delaware County, Ohio

These sinkholes and voids which exist in contradiction to the existing GWPP map have a direct impact on increased aquifer pollution potential and will affect construction efforts and zoning decisions. In the rapidly growing county, this necessitates a GWPP map recalculation to accurately identify areas of high aquifer vulnerability with the added benefit of developing a tool to help new construction projects avoid failures due to karst sinkholes (Figure 1-4).

Existing consideration for karst in Delaware County GWPP

ODNR DGS was aware of karst increased pollution potential and accounted for this within the bounds of the DRASTIC by selecting the 7ac hydrogeological setting associated with “glacial till over solution limestone” to increase the 'karst' info ratings in the northern region of the county only. However, an aquifer media rating of 6 was commonly assigned to these distinct units when it should have been 8, and Impact of vadose zone was not accounted for by raising its rating value (Aller, et al., 1987). GWPP indices in the present Delaware County map range from relatively low (85) to high (153) sensitivity (Figure 1-5) but did not include the increase in sensitivity caused by sinkholes. While the map creation considered the protective nature of glacial till bands overlying karst limestone by classifying these distinct units with the DRASTIC hydrogeologic setting of “glacial till over solution limestone (7ac), it applied that protection only to areas where it was known that the till was compromised or thin (Figure 1-5). Because it is known that the western portion of the county contains karst limestone and glacial till, the question becomes “how much protection does glacial till mitigate the increase in sensitivity from karst voids?”

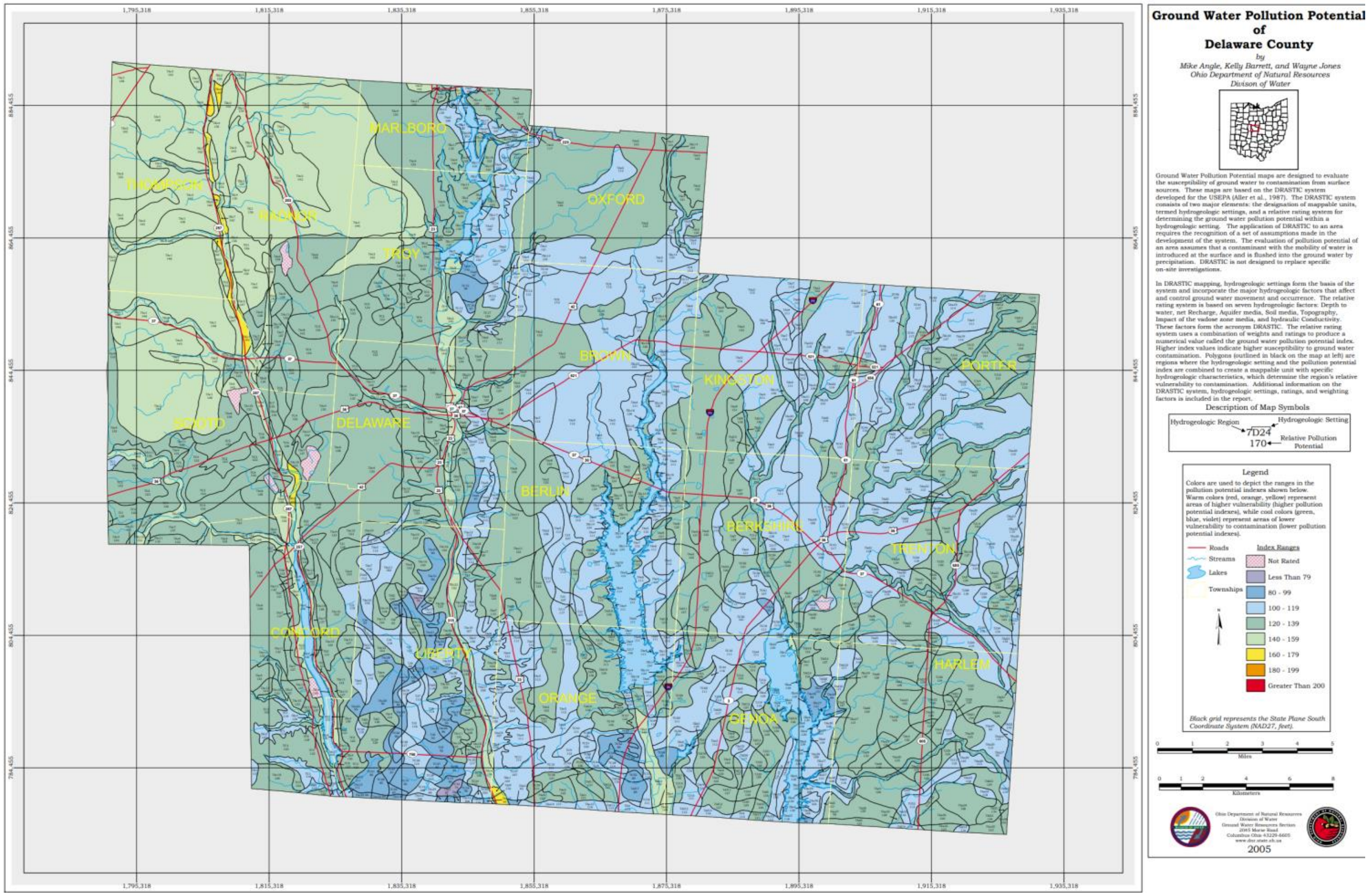


Figure 1-5: Ohio Department of Natural Resources Division of Geological Survey Groundwater Pollution Potential Map for Delaware County (Angle, Barrett, & Jones, 2005)

Research scope and objectives

The objectives of this thesis are to determine the extent to which karst limestone voids make a noticeable difference in the sensitivity of a region by:

1. Identifying the best karst-sensitivity approximations from GWPP models
2. Incorporating those features into a new DRASTIC parameter called the "+K" layer
3. Applying that updated methodology to generate a new Delaware County Ohio GWPP map

These objectives will be achieved by selecting representative GWPP models and analyzing their outputs as compared to the map created by ODNR DGS in 2005 and implementing a formula for the +K layer that will increase the GWPP of karst sinkhole containing distinct units. Appropriately increasing the sensitivity of these units is a straightforward effort once the quantification of direct karstified conduits to groundwater resources occurs. Discerning the relationships between the locations and extents of karst sinkholes, the extent of their subsurface connectivity, the topography, and thickness of glacial till within an area of study will facilitate the reverse engineering of a process to incorporate this increased sensitivity. The outcome of this effort should be a maximization of GWPP values for those karst-containing distinct units within Delaware County, Ohio. This new GIS based procedure can then be applied to the 10 remaining Ohio counties without DRASTIC maps (Figure 1-6), while easing the workload of ODNR DGS as they normalize GWPP values across the entire state of Ohio.

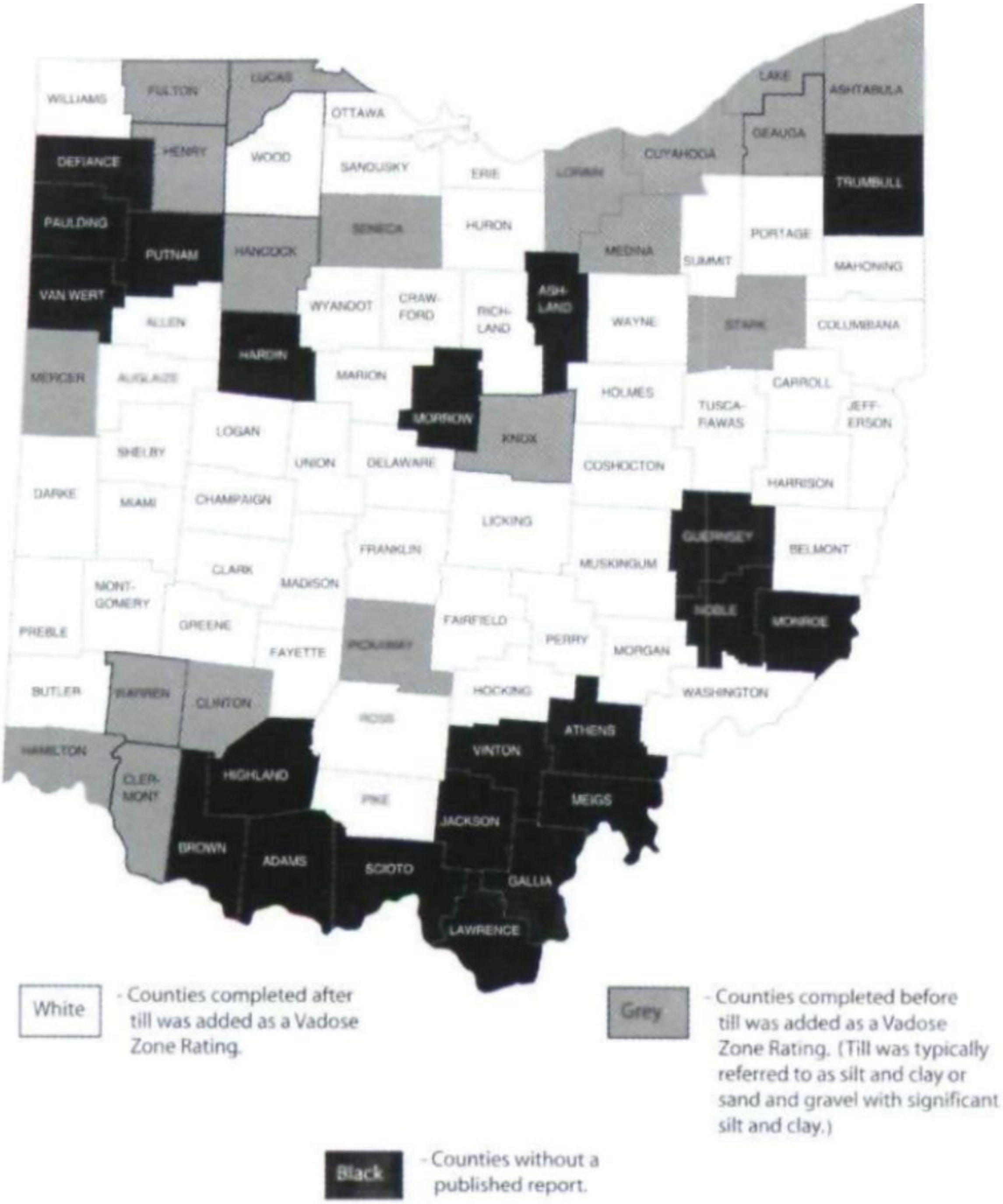


Figure 1-6: Counties with and without completed DRASTIC assessment as of November 2005 (Weatherington-Rice, Christy, Angle, Aller, & Gehring, 2006)

Chapter 2. Identifying Best Fitting Models for modifying DRASTIC

There are many ground water vulnerability models that evolved from DRASTIC and use small adjustments to calibrate outputs. A statistical analysis of several models from different parent trees will reveal the most appropriate parameters to more accurately reflect the complex hydrogeological conditions present in karstified regions (for further details see Chapter 1: Child models by originator model type). The seven models selected for component analysis (KARSTIC, DRISTPI, SIN-DRASTIC, COP+K, KAVI, SI, and an Altered Weight DRASTIC with A and C weight values increased from 3 to 5) may not provide identical GWPP results when applied to Delaware County, but they still hold crucial information to establish a methodology to account for karst sinkholes. Nearly all other GWPP models listed in Table C-3 (adapted from Ivan and Madl-Szonyi, 2017) have been removed from consideration either because their inputs were not readily compatible with the environment of Central Ohio or because the precision required for analysis were irreconcilable with the nature of DRASTIC.

The DRASTIC GWPP model's benefits include relatively low field surveillance effort requirements where existing data can be found; while the original surveys of Ohio counties were completed on paper, the capabilities of Geographic Information Systems

(GIS) such as ESRI ArcMAP and modeling software such as MATLAB allows for the same amount of work to be completed with fewer resources in less time. MATLAB simulations of these seven models were used to create sensitivity indices and GIS overlays. These outputs were then compared to the current Delaware County GWPP map using three different statistical analyses to determine the most accurate model(s) for representing karstified regions. These findings guided the development and implementation of the +K layer in the subsequent chapter.

Data sources, processing, and assumptions

Pre-existing GIS data files containing the current Delaware County GWPP information were converted into file formats that MATLAB recognizes, were gathered into ArcMAP 10.6, manipulated for consistency, and their attribute tables were converted into excel .xlsx files (Table 2-1).

Table 2-1: Data sources used in the statistical analysis of select GWPP models

Source	**Manipulation of dataset**
Natural Resource Conservation Service	
Soil Survey Geographic Database	N/A
STATSGO2 U.S. General Soil Map	N/A
Ohio Statewide Imagery Program	
2006 – 2010 LiDAR Tiles	Thinned to bare earth reflections only
Digital Elevation Model	Clipped to the extent of Delaware County and converted from raster to polygon

Continued

Table 2-1 Continued

ODNR Division of Geologic Survey	
Surficial geology map	N/A
Groundwater resources map	Manually generated from image overlay to correct geolocation
Consolidated aquifer map	N/A
Unconsolidated aquifer map	N/A
Drift thickness	Converted from raster to polygon
Water well logs	Generated thiessen polygons to create static water table layer
Mine locations	N/A
Known and suspect karst features	Removed known non-karst data points, where only points existed, buffered to identify potential sinkhole extents Additional potential depressions from LiDAR appended Measure tool used to identify major axial length
OEPA Division of Oil and Gas Resources	
Inactive and Vertical Oil and Gas Wells	N/A

These data include the seven DRASTIC model parameters in addition to the variables associated with the six other models (KARSTIC, DRISTPI, SIN-DRASTIC, COP+K, KAVI, and SI) selected for comparison. For ease of visualization and organization, these variables been categorized by general region at or below the ground surface (Figure 2-1 and Table 2-2). In terms of comprehensiveness, Table 2-2 suggests that SIN-DRASTIC and COP+K are the most suitable models. SIN-DRASTIC in particular includes the effect of karst sinkholes and the effect of water table decline while still maintaining the essence of DRASTIC (unlike COP+K which has its own formulation), so we must investigate its suitability.

DRASTIC data for the studied county, including the raw data used to generate the current DRASTIC maps (see Table 2-1) were requested directly from ODNR DGS but the files were unavailable for distribution. Consequently, some assumptions were required to fill out the dataset. Net recharge and hydraulic conductivity values were assigned as the values from the 2005 DRASTIC GWPP map because sufficient guidance to generate these values was not provided in the original publication (Aller, et al., 1987). These parameters were not available because they were generated based on expert knowledge and the cumulative overlays of the depth to water table, aquifer media, soil media, topography, and impact of the vadose zone data layers.

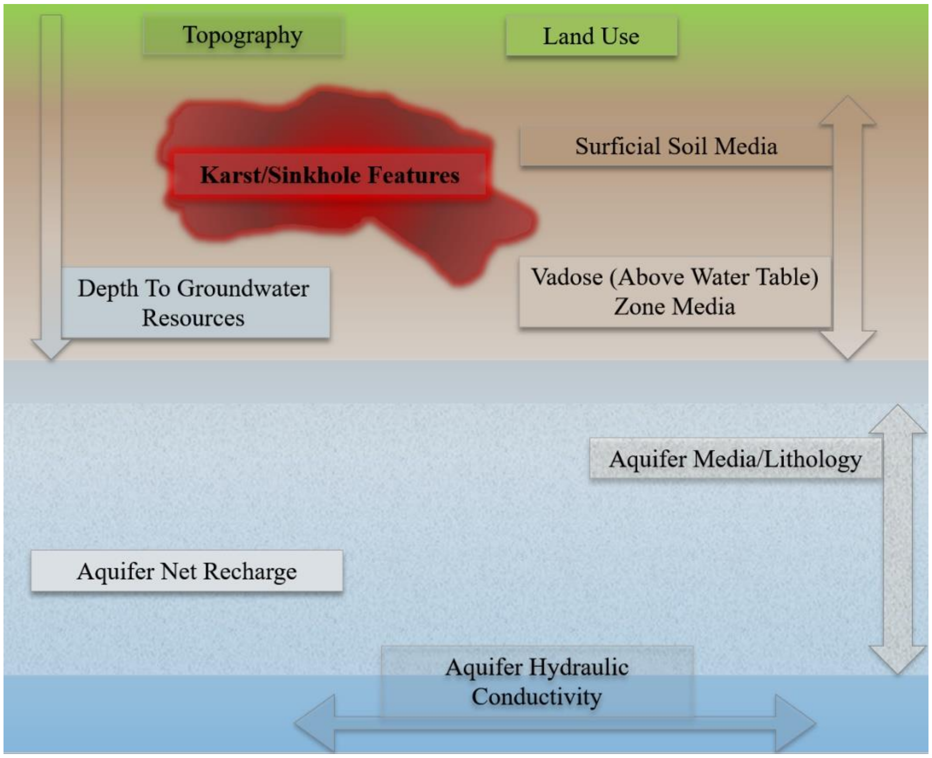


Figure 2-1: Representation of DRASTIC parameters within the soil and geologic profile including the Karst location parameter.

Consolidated potentiometric map polygons were subtracted from the elevation polygons in an attempt to create a static water level map for the county. This approach was unsuccessful due to the 50-foot gap between contour lines obscuring the shallowest depth to water values, thus the DGS water well static water level values were used with the thiessen polygon tool instead to create a depth to water table proxy layer.

Table 2-2: Categorization of explicit GWPP input parameters by selected model

	Parameter	DRASTIC	KARSTIC	DRISTPI	SIN-DRASTIC	COP+K	KAVI	SI	Alt. DRASTIC
Surficial	Topography	x	x	x	x	x		x	x
	Land use						x	x	
	Presence of roads						x		
	Vegetation type or density					x	x		
	Precipitation					x			
Between ground surface & floor of vadose zone	Soil media & permeability	x	x	x	x	x			x
	Impact of vadose zone	x	x	x	x				x
	Shallow karst or sinkhole features & connectivity		x	x	x	x	x		x
	Depth to water table	x	x	x	x	x	x	x	x
Within Aquifer	Hydraulic conductivity	x	x		x	x	x		x
	Aquifer media	x	x		x	x		x	x
	Dynamic groundwater information				x	x			
	Net recharge	x	x	x	x	x		x	x

The groundwater resources map was manually generated by geo-referencing the pdf images of the maps to the county boundary and creating new shapefiles with the correct geometry and associated data. This was done because no digitized versions of these files existed. These files were created before the advent of digital processing and have not been converted to GIS shapefiles.

LiDAR file tiles were converted from tiled point clouds into a .tin image to reveal surficial depressions per the approach detailed in (Rajabi, 2018). The ArcMAP Point Thinning tool was applied to exclude all refractions except those striking bare earth to ensure that ground cover and features such as buildings were not incorporated into the analysis. In contrast to the 35.3 ft^2 LiDAR dataset precision utilized by Rajabi, the maximum precision available for Delaware County was 100 ft^2 area regions meaning that the overall dataset will be less precise than the results from Rajabi in identifying surficial depressions (Rajabi, 2018). After the LiDAR conversions were completed, it was determined that ArcMAP does not have the appropriate software to re-project these datasets in either .lasd or .tin format. Because of this, the LiDAR data was incorrectly projected 6’ by 106’ to the south of the Delaware County boundary. To overcome this, the known and suspected karst feature class was copied and shifted south to display correctly on top of the .tin file in order to identify any unaccounted-for surficial depressions from the file.

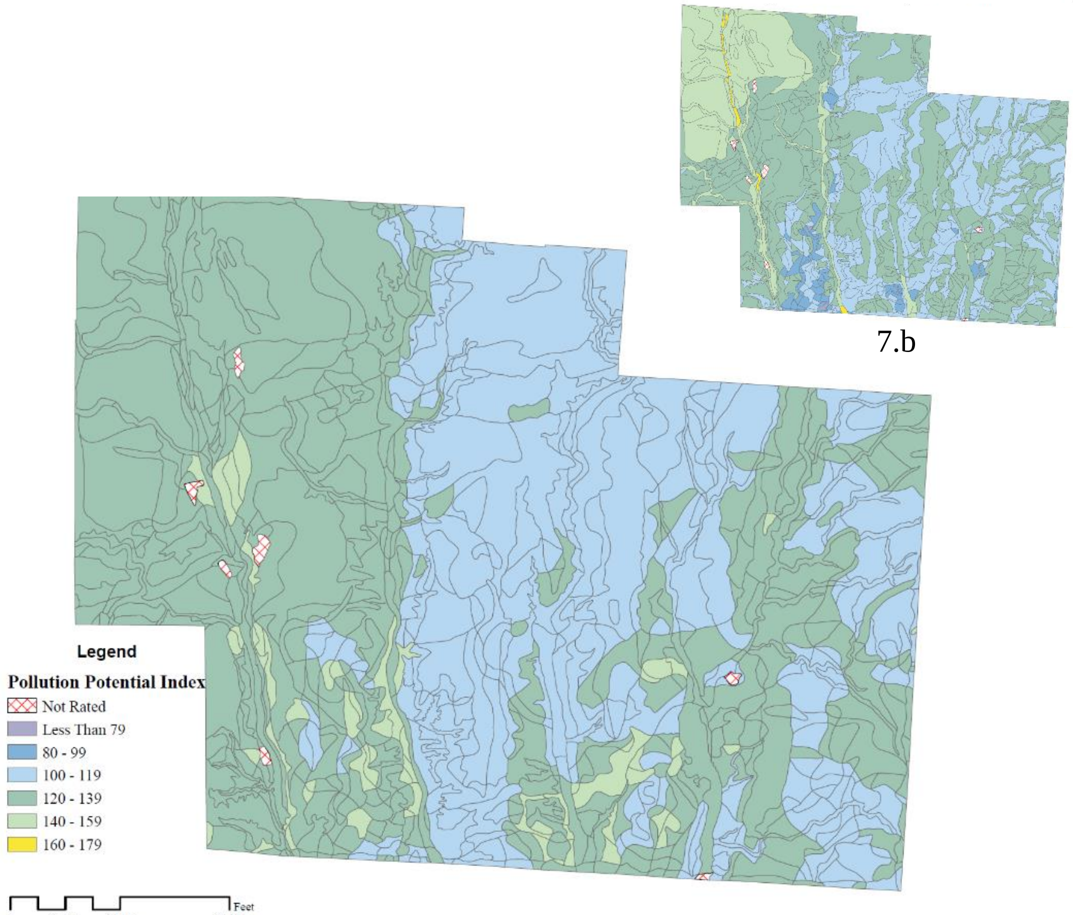
For karst sinkhole locations, the ODNR DGS Delaware County point feature class containing all features of interest, was obtained (Aden, et al., 2011). This feature class was queried to only display known karst sinkhole points and then the buffer tool was used at a distance of 1,000 feet to generate a polygon shapefile where any overlap of buffer regions would represent the potential connectivity of subsurface features. This karst polygon shapefile was overlaid with a georeferenced statewide probable karst map to identify additional regions of potential karstification. Probable closed depressions were added as new features to the existing feature class by assuming that all depressions indicated by a 1 foot or greater elevation drop from the crest to the lowest point were sinkholes. The feature major axial length and average depth were estimated using the identify tool and then the new known and suspected karst points feature class was re-projected to the correct spatial location and saved for analysis.

Once all shapefiles were generated and confirmed to properly overlap the Delaware County boundary in the NAD 1983 State Plane FIPS Southern Ohio 3402 feet coordinate system, the datasets were all combined with the distinct units identified from the seven parameter overlays in the 2005 GWPP map using the ArcMAP spatial join feature and the resulting attribute table was converted to an .xlsx for incorporation and analysis within the MATLAB simulation environment.

Statistical comparison of MATLAB models

MATLAB r2018a was used to generate the selected GWPP models as functions, using if-else tables with numeric and nominal input choices correlating to the specific ratings values for each model (found in Equations and MATLAB Code for Statistical Analysis). First, the current ODNR DGS output table was used as input data for a simulated MATLAB DRASTIC model as a test case to confirm that the approach would be successful. This simulated DRASTIC output was visually compared to the expert classified map to confirm whether the MATLAB simulation could approximate or exceed the precision of the original Delaware County map (Figure 2-2). This test case revealed that though the MATLAB simulation can replicate the general distribution of GWPP values, there are key areas of decreased sensitivity, particularly within the Western half of the county where karstified limestone is known to exist. This difference in GWPP indices was likely the result of using average values for all parameter ratings as opposed to selecting other values within the range based on foreknowledge of the region. This suggests that the MATLAB simulations are only capable of creating the ‘first pass’ indices and expert re-classification is needed to represent the reality of the region.

Note that all statistical comparisons for these data are necessarily spatial, where the independent variable is the unique identification number of one of the 813 distinct units and the dependent variable is the GWPP sensitivity. This is because there is no direct correlation between two distinct units on the landscape.



7.b

7.a

Figure 2-2: Comparison of average determination (7.a) vs. expert intervention (7.b) DRASTIC GWPP values

The inability of the simulated DRASTIC model to replicate the outputs of the expert verified model foreshadowed the overall insensitivity of the GWPP maps from other models such as KARSTIC, SI, and Altered DRASTIC (Figure A-1, Figure A-2, Figure A-3). Indices from the SI model were missing 27% of the GWPP values for distinct units (Figure A-2). This was likely due to a mismatch in categorization of the original land use shapefile or because the land use shapefile did not have coverage of the entire county.

This results in a map with large regions of unrated sensitivity that must be resolved by ensuring harmony between the model's land use option descriptions and the input dataset.

Similarly, the outputs for the European based COP+K and DRISTPI models were sparse and or completely empty due to a mismatch of input categorizations for Delaware County's hydrogeological features. Because the outputs of these models could not render without additional data layers, these will be removed from consideration for updating DRASTIC. One solution to resolve this issue would be to translate the existing inputs from common European soil conditions to those more commonly found in the United States, but that effort can be the subject of future research. Finally, KAVI indices typically do not exceed 50 which is low sensitivity under the DRASTIC model. Indices for the KAVI model in Delaware County did not exceed 4.4 and had to be normalized by multiplying by a constant of 50 to be comparable to DRASTIC indices. This updated model is called "Normalized KAVI".

Univariate statistics

Because standard deviation represents the spread of data values around the mean of a dataset, the comparative closeness of these models to the original would imply statistically that the model outputs are close to each other and models with a greater spread of values about the mean can be considered at least as inclusive as the current model so as to avoid selecting a less sensitive model. Figure 2-3 compares the mean and

± standard deviation of the GWPP indices for these models across the 813 distinct units within Delaware County.

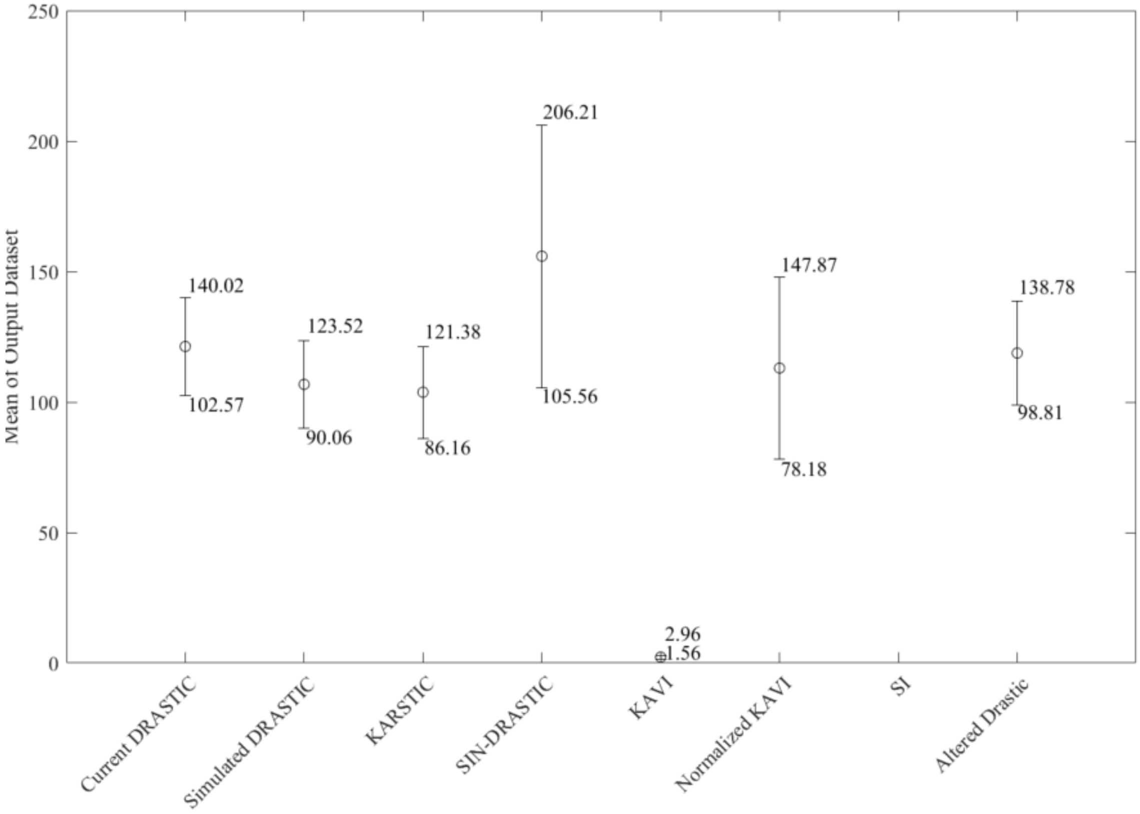


Figure 2-3: Comparison of simulated models against 2005 DRASTIC outputs with upper and lower boundary values for one standard deviation around the mean of each model

All selected model output means are close to each other as the result of correlation and not causation as the 2005 DRASTIC distinct units were applied to all the simulated models. Subsequently, this analysis can only accurately be used to remove models from consideration. Figure 2-3 shows that SI should considered for removal as a result of the model not having enough data points to generate a mean or standard deviation value. This results in MATLAB being unable to identify statistical values from nonnumeric (NaN) data points. KARSTIC, SIN-DRASTIC, KAVI and the Altered DRASTIC all had greater standard deviation values than the current expert classified model and are thus still viable alternatives for component incorporation into the +K layer.

Linear regression

The MATLAB fitlm command was used to establish a linear regression equation to the current Delaware County dataset and calculate the 95% significance values of each model (Table 2-3). For this comparison linear regression equation for each of the selected models was created using 2005 DRASTIC GWPP indices as the independent variable and the selected models' indices as the dependent variable (Angle, Barrett, & Jones, 2005). While a 2nd order polynomial fit was also performed using the MATLAB fit command, the additional parameters did not increase the significance of the resulting equations, and thus only linear regression was needed. This analysis is inconclusive in that none of the models under serious consideration can be considered statistically significant as their P values are all smaller than 5% (or 5.00e-2) below. This analysis also reaffirms the need to remove the SI simulation from consideration as its P value exceeds the significance threshold resulting from the relatively limited number of data points used to fit a line to the associated data.

Table 2-3: Linear regression analysis of MATLAB simulated model outputs versus GWPP values for Delaware County, Ohio

	Regression Equation	95% P value
Simulated DRASTIC	y = 0.3806x + 60.6272	N/A
KARSTIC	y = 0.3338x + 63.2762	1.48e-25
SIN-DRASTIC	y = 0.3707x + 110.9227	7.95e-05
Normalized KAVI	y = 0.587x + 41.8279	3.08e-20
SI	y = -0.0140 + 59.84	0.583
Altered DRASTIC	y = 0.4616x + 62.8007	2.19e-38

“Best Fit” using the corrected Akaike Information Criterion (AICc)

Finally, the AICc was calculated (Equation 2-1) for each set of sensitivity indices as compared to the 2005 DRASTIC GWPP values to identify the best-fitting model to incorporate (Angle, Barrett, & Jones, 2005). This statistical approach is appropriate for models where the number of parameters is small relative to the dataset sample size (Burnham & Anderson, 2002). Burnham & Anderson identified an arbitrary ratio of sample size to estimated model parameters of less than 40. Because the sample size of the analytical dataset contains 813 records, a model not suited to the AICc would require over 20 input parameters. While the COP+K model requires 21 inputs; SIN-DRASTIC, the most intensive of the feasible models requires only 10 inputs (Table C-4).

A caution for use of the AICc is that the tool “…is useful in selecting the best model in the set” but that given poorly established models to consider, the tool will still identify which model is best even if that model does a poor job of representing the data (Burnham & Anderson, 2002). This should not be of concern given that these are published models and that several of them use DRASTIC as a base.

Equation 2-1: Corrected Akaike Information Criterion Formula

$$AIC_C = \frac{\left[n * \left[\ln\left({SSE}/{n}\right)\right] + 2K\right] + 2K * (K+1)}{n - K - 1}$$

$$where:$$

$$SSE = \ Sum\ of\ Squares\ Error = \ \sum_{i=1}^{n}[Model\ mean - Model\ Output_i]\ ^2$$

The AICc values can be compared to the threshold, established by benchmarking the 2005 DRASTIC and simulated DRASTIC models, and only those models having low AICc values will be considered a statistically good fit- that is one "…that is estimated to be "closest" to the unknown reality that generated" the data (Burnham & Anderson, 2002). The result of these calculations is that only the Altered DRASTIC model has a lower AICc value and thus is the best fit to the residuals of the DRASTIC models and the nature of this model can be incorporated into the +K layer to account for karst sinkholes Table 2-4).

Table 2-4: AICc comparison of MATLAB simulated model outputs against 2005 DRASTIC outputs for Delaware County, Ohio

	AICc Value	AICc Threshold
Simulated DRASTIC	7,584	N/A
KARSTIC	7,835	Exceeds Threshold
SIN-DRASTIC	9,010	Exceeds Threshold
Normalized KAVI	8,098	Exceeds Threshold
Altered DRASTIC	7,255	Meets Threshold

Discussion of statistical analysis results

These analyses show that of the original seven models, KARSTIC, SIN-DRASTIC, Normalized KAVI, and the Altered DRASTIC are capable of producing GWPP indices that can be compared to the 2005 DRASTIC map, but SIN-DRASTIC and the Altered DRASTIC model are most statistically similar to current DRASTIC indices when considering standard deviation and AICc values. It has not been confirmed or disproven if the model could be improved through the addition of a +K layer, but it has been confirmed that a successful approach for creating such a layer would incorporate aspects of SIN-DRASTIC and Altered DRASTIC. In creating this +K layer it is reasonable to maximize the weight of this parameter to represent the highest weight impact of aquifer media and/or hydraulic conductivity. Moreover, the ease and efficiency of map generation for small changes on a large scale is simplified by the intervention of computer modeling software such as ESRI ArcMAP.

Ultimately, none of the MATLAB simulated models were able to outperform the original model in terms of input layer requirement simplicity. This is due to both their input requirements not being fully aligned with the requirements of DRASTIC and the expert verification requirement built into the DRASTIC model. It was determined that at the simulation models present complexity it is not possible to remove the need for expert classification to verify GWPP indices. This is because an effective map requires careful selection of parameter ratings that incorporates experiential knowledge and more detail than a GWPP model's basic methodology contains. One way to overcome this within DRASTIC or the selected models would be to expand the definitions and categories for all parameters within the model to incorporate a wider range of soil and aquifer types.

This expansion of input options would accommodate detailed hydrogeological and soils databases and provide more precise and accurate results and should be the subject of future research. A second area of potential improvement for this analysis would be the categorical removal of LiDAR identified depressions that coincide with 'non-karstified' regions. These depressions, which are indistinguishable from karst sinkholes when looking only at the DEM, are often associated with broken agricultural drainage tiles or stream cuts underneath roadways (ODNR DGS, personal communication, December 6, 2018).

Conclusions for establishment of +K layer

It has been shown that MATLAB simulated GWPP models are capable of generating indices that, while not nuanced enough to eliminate the need for expert classification of the maps, were sufficient to use for comparing different outputs from the same database to select appropriate models. Thus, it is still advisable for any community creating a GWPP map to send the results to a locally experienced geologist or hydrogeologist to ensure that the hydrogeological nuances of the mapped area are represented. This research also reveals the need for explicit procedures to identify surface depressions such as using LiDAR point clouds. One can utilize the methodology as found in (Haugerud, et al., 2003; Rajabi, 2018; Green & Hartle, 2014; Tibouo, 2016; Rahimi & Calvin Alexander Jr, 2013; Launspach, 2013) however, ODNR DGS generated a partial feature class and have made it available for use in this project.

Chapter 3. DRASTIC-Karst Incorporation Methodology

DRASTIC GWPP indices are presently unsuited to accurately represent the increased sensitivity of areas containing fractured sulfurous strata overlying karst limestone that form sinkholes as acidified water flows through the geological profile (Alpha, Galloway, & Tinsley III, n.d.; Weatherington-Rice, Christy, Angle, Aller, & Gehring, 2006; Raab, et al., 2009). It was determined that while DRASTIC does not currently account for this added sensitivity, many other GWPP models have been shown to represent these more sensitive regions (Taheri, Taheri, & Komail, 2017; Davis, Long, & Wireman, 2002; Daly, et al., 2002; Mimi, Mahmoud, & Madi, 2012; Vías, et al., 2006). Preliminary analysis found very little improvement from seven selected pollution potential models based upon the DRASTIC approach that were used to generate comparative indices. Thus, to retain the simplicity of gathered data that makes DRASTIC effective only successful subcomponents of karst-calibrated models will be combined into a new parameter that can be added to the existing DRASTIC formula.

Chapter 1 of this thesis identified potential models' representative of the variety of pollution potential methodologies that have become popular since the publication of DRASTIC in 1987. Chapter 2 described a statistical analysis to identify which, if any, of the selected representative models would be appropriate for incorporation into a hypothetical karst sinkhole incorporation layer in the context of a case study in Delaware County, Ohio. Chapter 2 determined that these simulated MATLAB representative models could not outperform the original in terms of simplicity. It was also determined that while the model can be run by informed laypeople (i.e. small community land use planners), expert verification is required to ensure the resulting GWPP map is an accurate representation of the existing hydrogeology of a region.

From these determinations, it is possible to identify a process to appropriately increase the GWPP indices of DRASTIC distinct units containing or directly adjacent to these karst sinkholes. The underlying question was how to properly incorporate this new +K layer into the existing DRASTIC framework and apply it to Delaware County, Ohio. This effort was to establish a +K layer based on the SIN-DRASTIC and Altered Weight DRASTIC models identified previously, which provides an easy-to-generate representation of the impact of karst sinkholes on the landscape as well as increased weighting to ensure that distinct units containing these features are assigned the highest sensitivity. In order to increase indices appropriately, consideration was made about how detailed the formula would be. In order to avoid this parameter being overly precise and falling too far beyond the constraints of the existing DRASTIC parameters, two primary assumptions were established for the analysis in Delaware County, Ohio.

First, the increase of GWPP indices was tied to the presence of surficial sinkholes as identified by the ODNR DGS sinkhole databases. Second, the effect of average glacial drift thickness was required because of the advancement of multiple glaciers through Delaware County, overtopping existing layers of sulfurous shale and carbonate limestone. This chapter further describes the implementation and results of a method for incorporating karst-specific sinkholes to DRASTIC based on the presence, connectivity, and topographic relationships for Delaware County, Ohio.

Distinction of the +K layer from other pollution sensitivity models

This additional component; called the +K layer, takes inspiration from SIN-DRASTIC and the Altered Weight DRASTIC methods based on the univariate statistics and linear regression comparisons results of Chapter 1. In spite of this, the +K layer remains a unique effort because of the structure of its equation, considerations for sinkhole connectivity, and its incorporation of glacial drift thickness. The +K layer incorporated a maximized parameter weight, as observed with the Altered Weight DRASTIC, to emphasize the increased sensitivity of karst sinkhole containing distinct units. The layer also identified catchment areas for sinkholes and relative distance to sinkholes as observed with SIN-DRASTIC (Taheri, Taheri, & Komail, 2017). From these findings, a formula was developed that includes key factors to account for the increased sensitivity of karstified regions. These factors are the presence of sinkholes within a distinct unit, the sinkhole area relative to the area of the distinct unit that they fall within, the potential connectivity of sinkholes based on their proximity to each other, and the topographic relationships to other sinkholes within and amongst the distinct units.

Taheri, Taheri, & Komail (2017) identifies the SIN- parameter as being comprised of 2 separate factors with different weights while the +K layer combines all factors associated with sinkholes into a single formula for ease of calculation. SIN-DRASTIC weights the distinct unit distance from the nearest sinkhole as a 5 and the sinkhole catchment area representing the pooling or surface contribution as a 3 (Taheri, Taheri, & Komail, 2017). In order to ensure all distinct units containing karst sinkholes are set to the highest possible sensitivity, the +K layer will have a comprehensive weight of 5.

An additional improvement of the +K layer over the SIN-layer is a more detailed identification of the relationships between sinkholes, distinct units, and topography. SIN-DRASTIC represents sinkhole impact based on the rated sum of thiessen polygon driven catchment areas using the ArcHydro toolbox, the depth and major axial length of each sinkhole, buffered distinct unit distance from nearest sinkholes, and groundwater level decline (Taheri, Taheri, & Komail, 2017). The +K layer will identify preferential flow catchment areas to sinkhole polygons using the ArcMAP Flow Length and Flow Accumulation tools, and near distance tables between sinkholes and distinct units, all of which can be generated from either the known and suspected karst shapefile or the DEM. This ensures that the +K layer remains aligned with the original model in terms of readily accessible inputs. Finally, whereas SIN-DRASTIC applied a weight of 5 for distance to nearest sinkhole and 3 for sinkhole catchment area, the +K layer maximized the weight of the entire layer as gathered from the Altered Weight DRASTIC findings of Chapter 2.

The factors incorporated into the +K layer; presence, relative area, proximity, and preferential flow patterns, will be described in more detail below.

Justification of Presence and relative area as impact factors

As observed in the non-DRASTIC models, the presence and size of karst sinkhole are essential to increase the GWPP indices of karst containing distinct units. Within Delaware County and the state of Ohio, the work of identifying potential sinkholes has largely been completed by the ODNR DGS. They identified localized areas of low elevation, field-authenticated whether the depressions were karst driven, and visually inspected and quantified the area of surficial depressions from the most recent LiDAR dataset for the large fraction of these depressions. If a karst-driven sinkhole exists within a distinct unit, by definition; that unit will have higher GWPP.

Also, the area of the surficial depressions relative to the distinct unit area must be incorporated as the greater coverage of sinkholes within a distinct unit results in higher likelihood of contamination reaching a sinkhole. Because of the magnitude of difference between the sinkhole and distinct unit areas, this factor will be normalized by the square root of the distinct unit area to identify the relative sinkhole to distinct unit density.

Proximity and preferential flow pattern as impact factors

Proximity to other sinkholes and preferential surficial flow patterns are also correlated criteria for quantifying the effect of karst sinkholes on GWPP. When multiple sinkholes exist in close proximity to each other, the likelihood of subsurface connectivity and internal drainage is highest. Examples of this potential connectivity can be observed theoretically in Figure 3-2 and from imagery in Figure 3-3 and Figure 3-4. Thus, a factor associating the sinkholes relative closeness to each other ensured that potential connectivity is incorporated. Additionally, preferential flow patterns play a key role in pollution potential. Within Delaware County, Ohio, the basins of the Scioto and Olentangy rivers intersect the Western portion of the county within the identified potential karstified region lifted by the Cincinnati Arch. Because of this, the edge of the watersheds leading to each of the rivers form a ridge with corresponding valleys on either side. The surficial flow of water within the Western portion of Delaware County thus falls within one of these watersheds and is subject to accumulation from the highest elevation to lower elevations. Because of this, surficial flow distance and accumulation within these two watersheds must be considered. While this falls outside of the assumptions of the original model, preferential flow and accumulation is a key factor in identifying the potential of contamination for sinkholes within the region.

Combining these factors, the +K formula was established by considering a suite of possible test cases as presented in Figure 3-1.

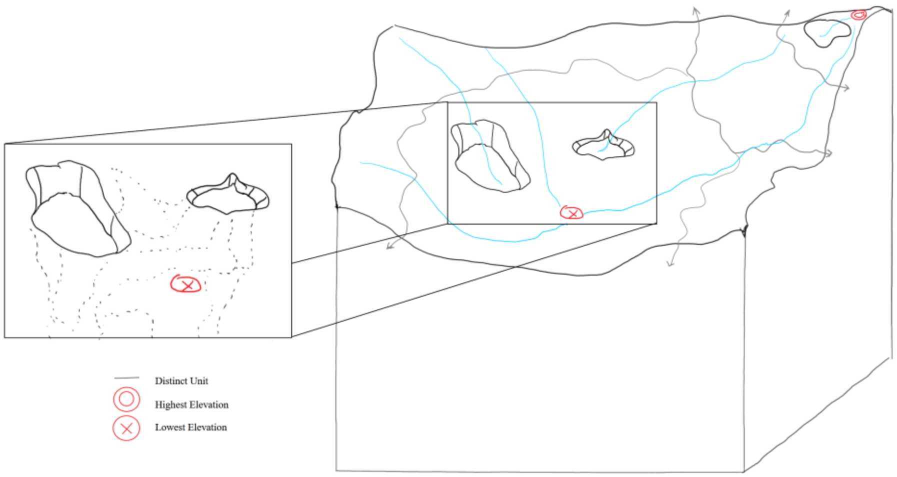


Figure 3-1: Sample cases representing sinkhole presence and spatial relationships for +K implementation

Potential sinkhole-distinct unit combinations are associated with having low elevation and contributions from up gradient regions or having high elevation and thus having few to no contributors. Another variable of importance is the percent slope of the region containing the sinkhole. Low slopes associated with sinkholes at high elevation and short flow accumulation result in low likelihood of flow contributing to other distinct units while low slopes at low elevations with high flow accumulation have high capture likelihood. Additionally, as the slope associated with any sinkhole increases the likelihood of capture within that sinkhole decreases. It must be noted that the nature of flow accumulation or distance across the landscape goes beyond the parameters of the

DRASTIC model but are necessary to accurately represent the catchment potential of sinkholes on the landscape.

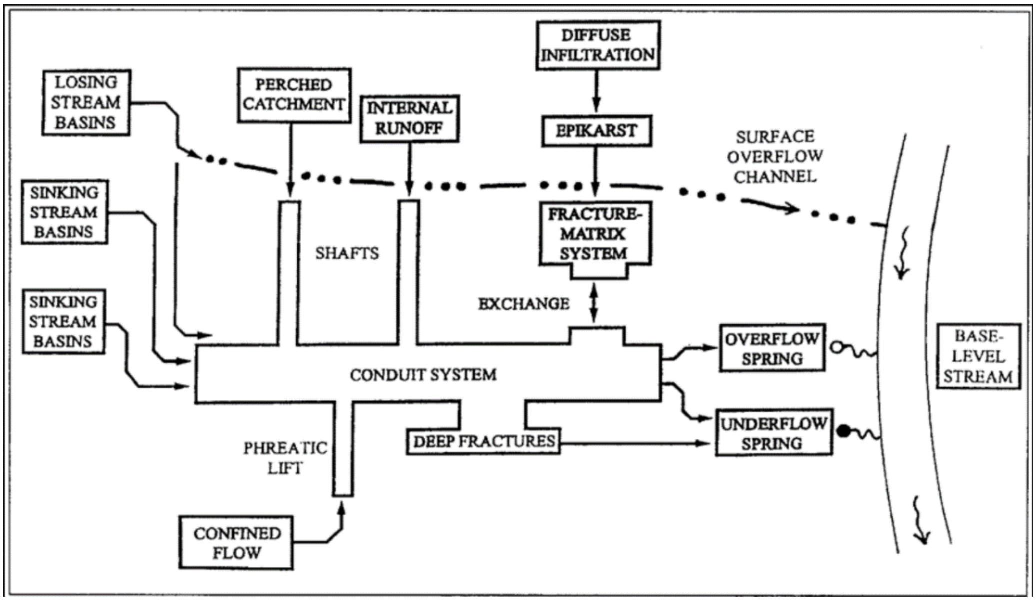


Figure 3-2: Conceptual model for a karstic aquifer. From White (1999) with modification by J. A. Ray. (White & White, 2001)

Figure 3-3: Internally drained sinkholes with pooling in Bellevue, Ohio

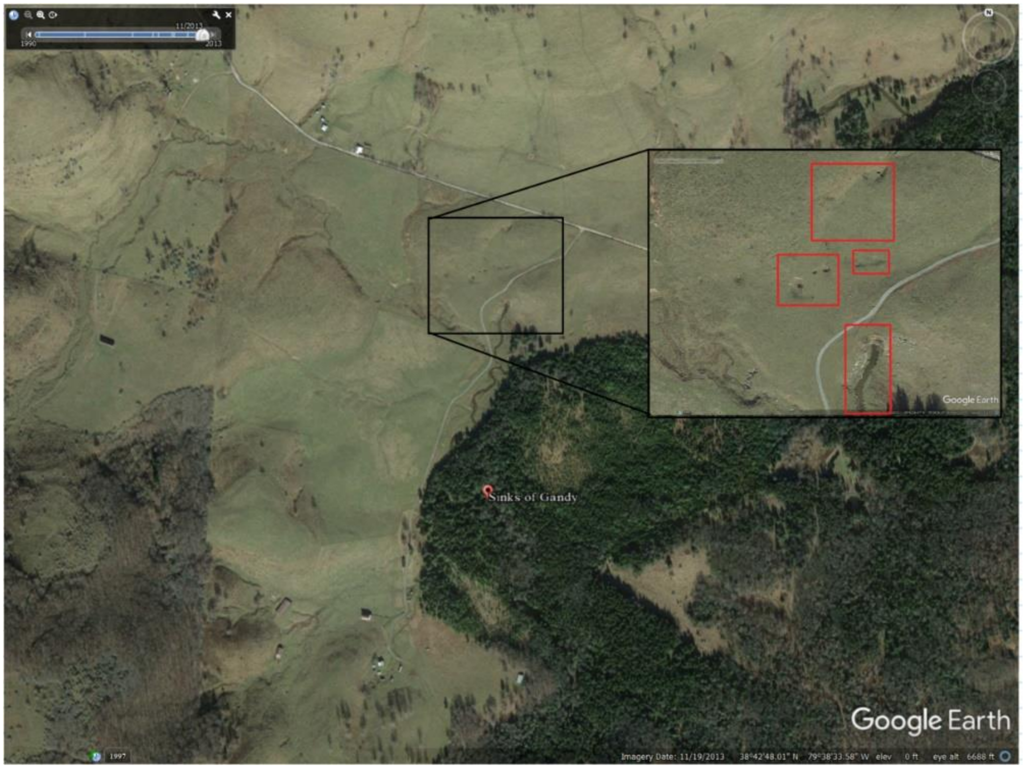


Figure 3-4: Sinks of Gandy in Dry Fork, West Virginia are a good representation of potential subsurface connectivity of both sinkholes and other karst features such as sinking streams.

Another key consideration is that units without karst sinkholes existing up gradient of karst containing distinct units are potential contributors to GWPP from overland flow. Even the largest karst sinkholes within the highest elevation regions in a distinct unit will have less impact than sinkholes situated in the lowest elevation regions and an identification of the steepest flow path for any given point within a distinct unit to another distinct unit having a karst sinkhole is necessary. The ‘Flow Direction Steepest Downslope Neighbor’ spatial analyst component is an ArcMAP spatial analysis tool and requisite addition to the model. This approach is limited to only the steepest flow paths, such that if more than one low lying karst sinkhole exists within an adjacent distinct unit, only one will be considered as the collection point for all overland flow. Considering topographic fluctuations, high slope and short distance between an upland distinct unit and a sinkhole at a lower elevation increases the likelihood of surface runoff.

Drift thickness incorporation justification and approach

The conditions of surficial karst geology and drift thickness must be specified within Delaware County. While glacial drift may be removed for unglaciated regions, because till materials sloughed off onto the landscape as glaciers retreated in Ohio are typically considered fine enough to form a seal over the karst sinkholes and offset the effect of the karst. Presumably 4 to 7 feet of overlying glacial till could not compensate for the increase in sensitivity from karst sinkholes, but a clear threshold thickness value has not been identified and must be assessed statistically.

The ODNR DGS drift thickness raster map was converted to a point feature class in order to utilize the ArcMAP select by location tool to identify the drift thickness at all known and suspected karst points. The raster resolution of 38,750 square feet was too high for our purposes and as a result the generated point grid did not coincide with the karst points feature class. To overcome this discrepancy, a search distance of 150 feet around each karst point was used to ensure that it could be paired with at least one nearby drift thickness point. The reason for 150 feet as opposed to the 196.85 foot raster cell length was because it represented the longest distance between a karst point and a drift thickness point. These data yielded a normal dataset confirmed with both q-q plot generation and the standard deviation requirements for normal distributions. Drift thickness values found within 150 feet of karst locations were assumed to represent the relative drift thickness near each karst driven sinkhole and indicated that 85% of known or suspect karst points exist in regions with up to 44.5 feet of drift thickness (Figure 3-5).

Two percent of the karst points feature class were found in regions with drift thickness of greater than 44 feet, yet these points were all surrounded by areas having a maximum of 55 feet of thickness, suggesting that the categorization of drift thickness within the raster file, due to its level of precision, could be the result of imprecise map creation. As such, these 10 sinkholes will still be considered as contributing to distinct unit GWPP (Figure 3-6).

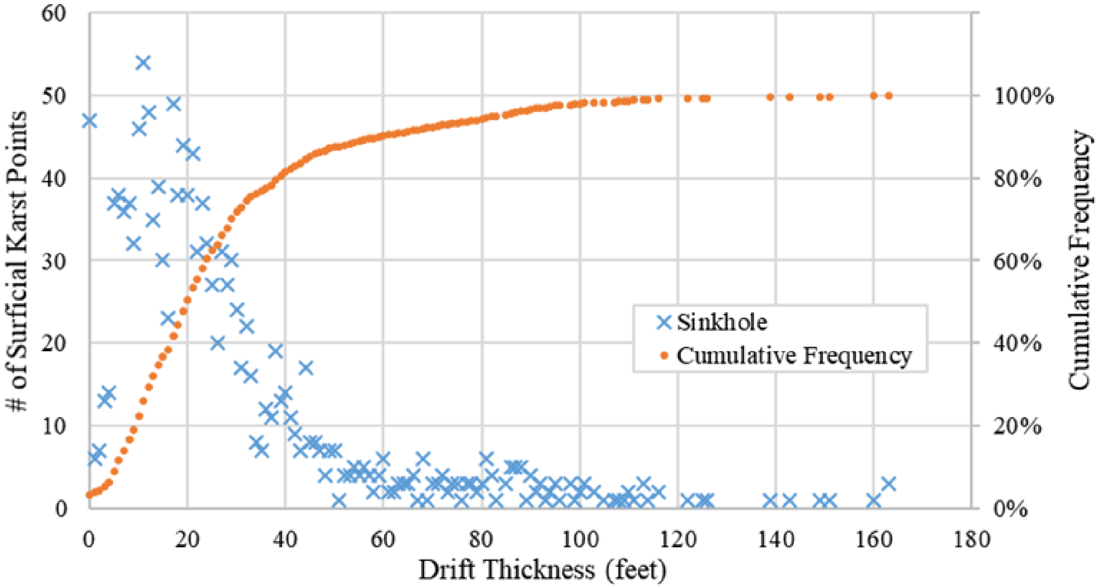


Figure 3-5: Average drift thickness at a distance 150 feet from karst point locations

This approach is appropriate because the Ohio state drift thickness, surficial geology, and aquifer maps were generated from inherently imprecise and or sparse datasets; such as well logs and utilities measurements, combined with the DEM. This hearkens back to the reasoning behind DRASTIC’s original assumption of using generalized datasets, as intensive surveys would be required to identify exact conditions at any location. The drift thickness raster was thus appended to the +K geodatabase and a model threshold of over 45 feet of glacial till between the ground surface and a susceptible aquifer was assumed to be sufficient to overcome any increased GWPP from karst sinkholes.

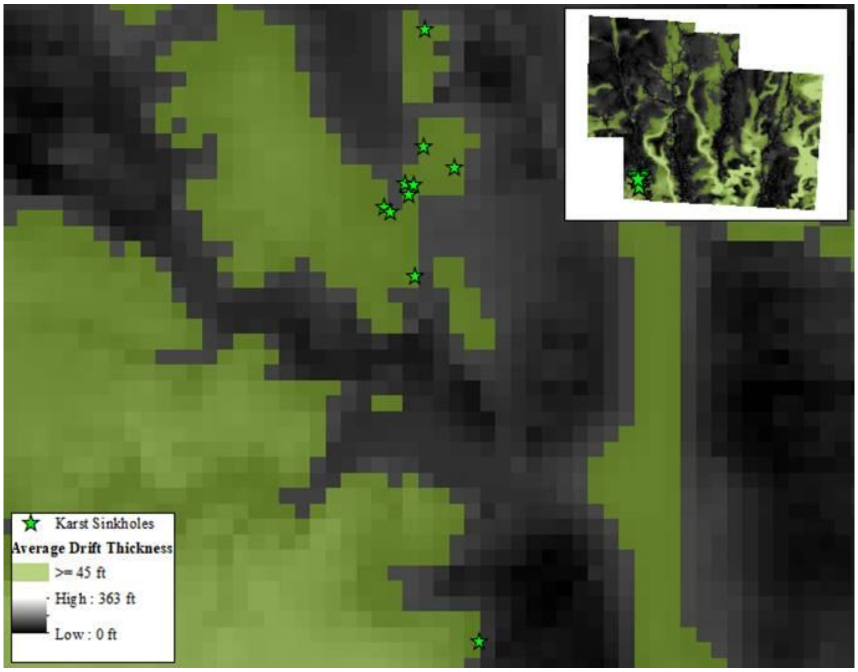


Figure 3-6: Sinkholes identified from DEM in regions having average drift thickness of greater than the presumed effective coverage thickness of 44.5 feet

One caution for use of sufficient drift thickness coverage as a removal criterion for potential karst sinkholes is that regardless of the amount of overlying geology, if karst hole reaches the static water table, there is a direct path for contamination to groundwater resources. A second consideration is that the state of Ohio only has at best semi-confined aquifers and all aquifers are leaky (ODNR DGS, personal communication, December 6, 2018). Thus, even if there is ‘deep karst’ with arbitrarily thick soil and geological coverage, the time it would take for contaminants to travel through an affected soil and geologic profile is closer to a scale of days to months than decades to centuries.

Issues with DGS sinkhole quantification polygon feature class coverage

Because the ODNR DGS work has been completed for the area of study, this analysis will retain these pre-established karst polygon feature classes as characteristic assumed karst sinkholes. The 29.7% (137 out of 478) of sinkholes point features missing depression extents (Figure 3-7) were assigned three foot buffers to represent the potential shape and extent of these small features (ODNR DGS, personal communication, April 16, 2019). Future DRASTIC +K analyses for regions lacking these polygon feature classes will require additional work to identify sinkholes, by either automated or manual analysis of DEMs and or LiDAR datasets (Doctor & Young, 2013; Green & Hartle, 2014; Kobal, Bertoncelj, Pirotti, Dakskobler, & Kutnar, 2015; Ladd, 2011; Launspach, 2013; Rahimi & Calvin Alexander Jr, 2013; Rajabi, 2018; Taylor, Nelson, Hileman, & Kaiser; Todd & Burden, 2015).

A second issue was that the sinkhole features were composites of the various depth extents for each sinkhole, leaving some sinkholes with several areas associated. To avoid this, a rasterized feature class generated from the ArcMAP Zonal Statistics tool output was used to ensure that each sinkhole only had one associated polygon shape associated with the maximum depth of the sinkhole. In order to ensure the maximum number of sinkholes was incorporated into the analysis, the polygon and zonal geometry feature classes were combined. The reason for this is that fifty additional features were present in the polygon feature class that were lacking in the zonal geometry raster class. Ultimately, the zonal geometry, polygon features, and three foot buffers were combined into a single feature class that is used in the +K formula.

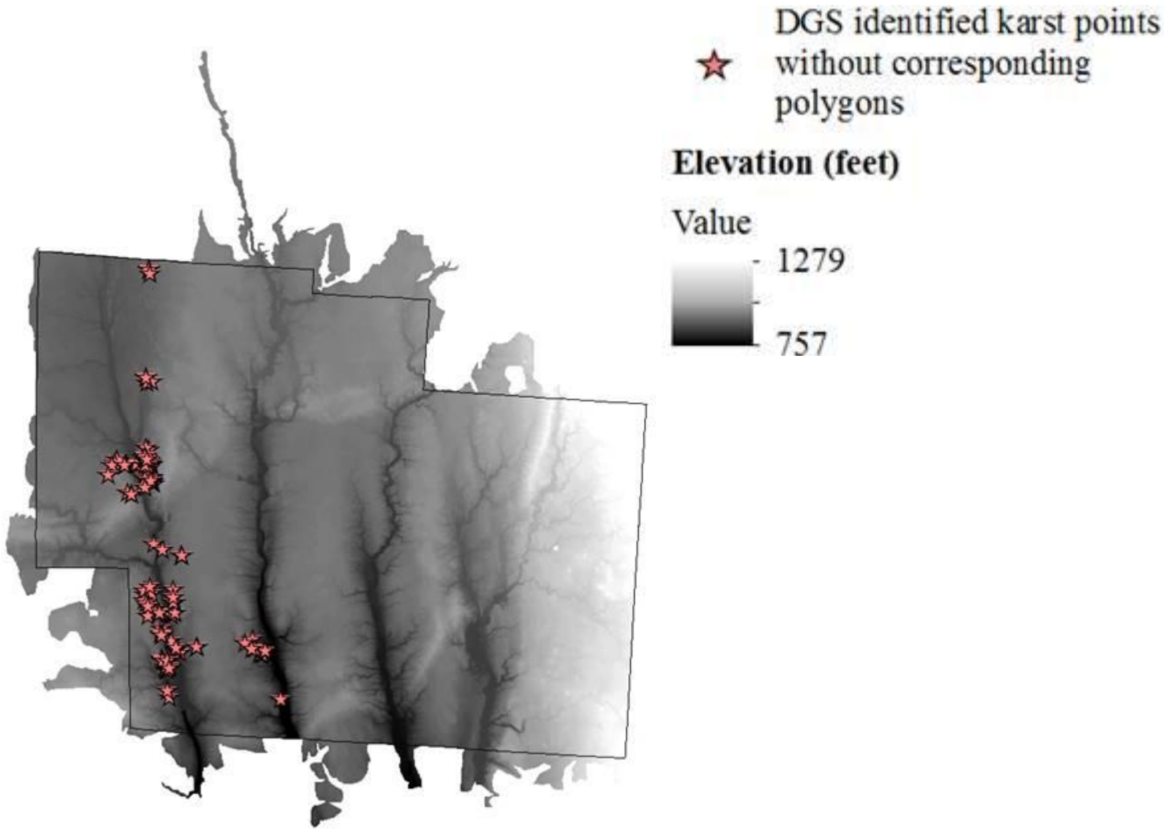


Figure 3-7: ODNR DGS identified sinkholes in Delaware County lacking manually identified extents.

Pre-processing of data layers for +K layer formula

A key limitation in creating this additional pollution potential parameter is that only the effect of hypothetical cumulative contaminated overland flow as a function of GWPP will be considered. This is because the complexity of subsurface water interaction in the landscape is far too intricate and would essentially require the development of a new arm of the DRASTIC model to represent this movement alongside more intensive on-site investigative efforts, i.e. dye or isotopic tracer testing (Raab, et al., 2009; Malík, Švasta, Michalko, & Gregor, 2016). There is precedent for the efficacy of these methods, however for DRASTIC + K, only the effect of surficial pooling will be incorporated. A second consideration for this approach is that it does not incorporate the impacts of rain intensity or average precipitation for the region. This aspect is simulated within the Flow Length and Flow Accumulation tools, but because variability in datasets from sources like the USGS National Hydrography Dataset, this aspect was not incorporated into the +K layer to retain alignment with DRASTIC's simple input datasets.

Spatial considerations that cause variations in the geology of the region include the impact of the Cincinnati Arch and the deposition of the Powell End Moraine. The Southeastern third of Delaware County was subject to minimal movement and weathering from the rise of the Cincinnati arch and became part of the Northwest limb of Appalachian basin. As such, there is likely sufficient thickness of rock formations overtopping the karst limestone to protect from subsidence. It must also be noted that the Southwest of Delaware County contains relatively thick bands (30 - 90 feet) of the Powell end moraine overlying karst limestone layers to a degree where the sensitivity of the region is no higher than anywhere else in the area (Figure 3-7, Figure 3-78). Though this region of the county is geologically fractured, the fine materials of the end moraine serve as a seal over the karst features and minimize pollution sensitivity. It is important to note that the extents of the moraine were identified in the 1979 ground water resources map. This resulted in an imprecision that can be seen in Figure 3-8, as the theorized extent of the moraine coincides with known karst points found later by field verification or within the LiDAR data. It is likely that the true extent of the moraine can be observed slightly south, as indicated by the region in Figure 3-8 along the Scioto River free of known and suspected sinkholes even though the Northern and Southern portions of the river have many sinkholes.

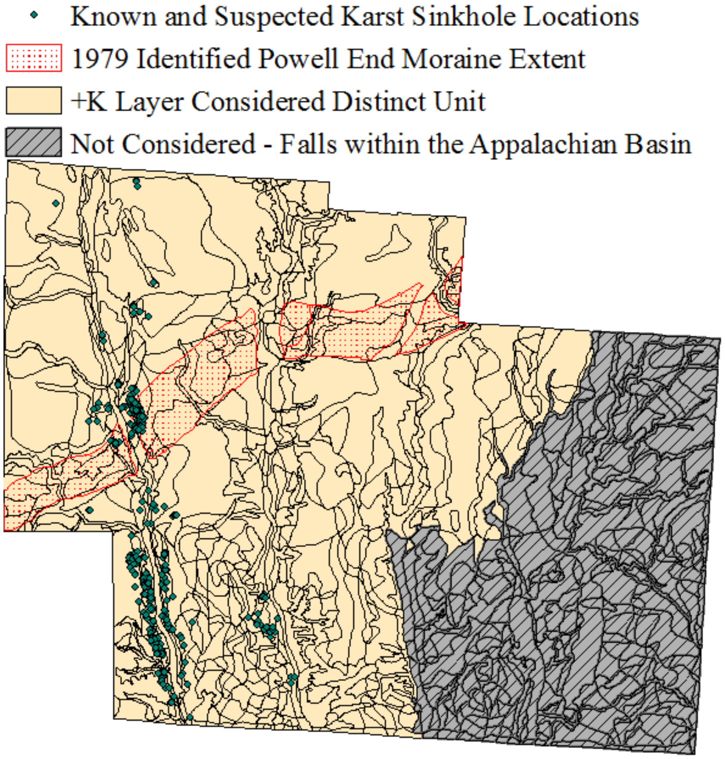


Figure 3-8: Exclusion of GWPP distinct units within the Appalachian Basin and the band of the Powell end moraine in Delaware County, Ohio

These parameters all combine in the below formula:

Equation 3-1: +K weight and rating formula for addition to DRASTIC

$$K_{weight} * \sum_{DUID=1}^{n} Rating_{DUID} = 5 * \sum_{DUID=1}^{n} \left(COU * \frac{1}{SCF}\right)^{ADT} + (\mathrm{ESD}) + (CONT * SCR)$$

Where:

DUID = Distinct Unit Unique Spatial Object ID

Count (COU) = Number of sinkholes within Distinct Unit

This parameter was applied all distinct units under consideration with the goal of incorporating count (COU), sinkhole connectivity factor (SCF), contributing areas (CONT), and sinkhole coverage ratio (SCR) for distinct units containing sinkholes, while distinct units lacking sinkholes but within the range of external sinkholes will be increased by the associated ESD value multiplied by the rating. This ensured that nearby distinct units' sensitivity could be increased even if those distinct units did not contain sinkholes themselves.

The average drift thickness component (ADT) was set as an exponent to the count and spacing parameter to allow for it to be ignored in areas lacking any drift thickness without fundamentally changing the outputs where the value equals 1 if there is less than 45 feet of glacial till, and 0 if more than 45 feet. SCF is the average distance between all sinkholes falling within a given distinct unit. SCR is the ratio of cumulative sinkhole area divided by the total distinct unit area for a given distinct unit where the impact of sinkholes increases with the area of sinkholes to distinct unit area. The SCR was calculated based on the full sinkhole and distinct unit area as the flow of water from any given unit will likely flow to the lowest elevation point based on the full area of each sinkhole; not the fraction of any given sinkhole falling within a distinct unit.

The combination of distinct units and sinkholes areal extents with flow lengths and identified topographic effect on surface flow and accumulation within sinkholes as a value of contribution to GWPP (CONT). This parameter is identified by four raster files, three of which are generated from the DEM:

- Elevation
- Flow Length
- Flow Accumulation
- Percent Slope

These data represent the relative amount of water accumulated along the landscape from pixels up gradient of any given pixel and the direct distance over the landscape that must be traversed to get to any given point. Flow Accumulation and Flow Length tool outputs are all relative to the lowest elevations within a given area of study; in Delaware County these are the basins of the Scioto and Olentangy Rivers. The watersheds of these rivers dictates the accumulation of flow and results in a minimization of the smaller elevation changes in the area of study. For this reason, it is necessary to include not only the length and accumulation raster files, but also the percent slope, to identify steepness (see Table 3-1) and relative elevation for all sinkholes. These data represent both the amount of contribution and the relative location of any sinkhole on the landscape. Sinkholes with the highest contribution to pollution potential are theorized to have low flow length (i.e. travel distance to reach the sinkhole) and high flow accumulation, whereas sinkholes contributing the least to pollution potential are theorized to have high flow length and low flow accumulation.

Table 3-1: Soil Survey Manual simple slope classes and lower boundaries (Schoeneberger, Wysocki, Busskohl, & Libohova, 2017)

Slope Type	Lower Bound (percent)
Nearly level	0
Gently Sloping	1
Strongly Sloping	4
Moderately Steep	10
Steep	20
Very Steep	> 45

Spatially, it is possible that sinkholes can exist at any elevation within the area of study, from low lying regions to the highest points and their location relative to the topography is relevant (i.e. whether they exist on flat ground or on a slope). Some of these theoretical cases can be observed in Figure 3-1. These layers have been combined into Equation 3-2:

Equation 3-2: Incorporating factors affecting preferential flow patterns with respect to karst sinkholes on the landscape

$$CONT = \left(\left(\frac{\text{Flow Accumulation}}{Flow\ Length}\right) * \text{Elevation}\right) + \text{Percent Slope}$$

A consideration for this component is that the precision of Flow Length, Percent Slope, and Flow Accumulation cannot exceed the precision of the DEM because these layers are all generated from the DEM; thus, the smaller the cell size of the DEM the more accurate the CONT variable.

External Sinkhole Distance (ESD) from any distinct unit was categorized to simulate likelihood of surficial flow exiting the distinct unit in question and entering the external sinkhole. The likelihood of sinkhole capture decreases with increasing distance to nearest sinkhole (Table 3-2). These nearest external sinkhole ranges have been assigned values from 5 to 1 to better fit the DRASTIC formulation. This incorporates the topography to account for cases such as where a sinkhole lies close to the edge of an external distinct unit, but low to no slope between the two features results in low capture likelihood, or that a giant sinkhole at the highest point in the distinct unit will have less impact than a sinkhole situated in the lowest region of the distinct unit.

Table 3-2: External Sinkhole Distance Categories and associated values for incorporation into the +K layer

Distance to Nearest External Sinkhole (feet)	Category Value
0 – 500	4
500 – 1,000	3
1,000 – 2,000	2
2,000 – 6,000	1
6,000 +	0

The range of outputs for the +K factor are likely to exceed the “extremely sensitive” index value of 200. This is the correct approach because sinkholes take all existing protections and remove them. Thus, the only accurate way to incorporate the increased sensitivity of a karst sinkhole is to consider all GWPP values from 200 to infinity as “extremely sensitive” and guarantee that the +K factor, when it comes into play will always increase the GWPP for a given distinct unit from any protective level to “extremely sensitive”. While Aller et al. (1987) postulated that the average range of DRASTIC indices would be from 65 to 223, it can be determined that all distinct units having values exceeding 223 are simply considered to have maximal GWPP.

Table 3-3 indicates the manipulation of data required to populate the +K layer. All raster files were gathered and clipped to the boundaries of distinct units within Delaware County, Ohio. The clipped elevation raster can be used as an input into the Flow Direction tool to identify the direction of a theoretical drop of water from pixel to pixel from the highest elevation points to the lowest points in the DEM which could be either streams or surficial depressions. Many ArcMAP spatial analyst slope-centric tools allow for increasingly complex flow regimes including D8 for identification of the steepest downslope neighbor from each pixel, Multiple Flow Direction (MFD) for cases having the potential for one pixel to contribute flow to all of its downslope neighbors, and D-Infinity which triangulates the steepest downward slope based on 8 facets formed by a 3x3 pixel region around any given pixel. MFD would not render properly, thus this analysis considered the D8 calculation.

Running the Flow Direction tool requires preparatory work to identify and fill in the low points (i.e., areas of unknown data values from the DEM) using the Fill tool. All pixels having more than 3 cells flowing into them are set as relative sinks where pooling could occur, while cells with fewer than 3 contributing pixels are set as null values to ensure that contributing pixels do not accidentally get considered as depressions in the landscape. The relative depth of these upland sinkholes may contribute directly to aquifers below the ground surface, but such interactions fall outside of the assumptions of the DRASTIC model and thus will not be considered (
Figure 3-9). The Flow Length tool is then generated using the Flow Direction output raster. Flow lengths identifies the downstream flow distance for any given pixel within the identified region.

Table 3-3: Pre-processing required to generate additional GWPP index values by data layer type

Karst points	• Buffered where polygon extents did not exist (137 points)
Karst polygons + karst point buffers from points missing polygons	• Generated additional shapes from DGS zonal statistics analysis • Merged buffered karst point polygons, DGS identified polygons, and zonal statistics polygons • Generated near table between all sinkholes and between sinkholes and distinct units ○ Use for proximity (i.e. potential for subsurface connectivity) calculations • Identified which were falling within ‘no data’ pixels (‘upland’ sinkholes) ○ These won’t have any contributors, only contributes potentially receiving flow ○ These may still be incorporated into the connectivity calculation based on near table
DEM and drift thickness clipped to Distinct Units around Delaware County	• DEM: FILL and CON tools to remove wrong sinks and delineate pixels contributing no flow • Ran FLOW DIRECTION, FLOW LENGTH, and FLOW ACCUMULATION tools ○ Flow Accumulation converted to 32 bit unsigned raster in order to generate an attribute table for the data that could be applied to the sinkholes feature class • Converted both drift thickness and DEM from raster to polygon
Spatial join karst polygons, Distinct units, Flow Length, Flow Accumulation, Drift thickness, near tables for sinkhole proximity and sinkhole distance to distinct unit	Used Select by Location tool to identify: • Which Distinct Units had Sinkholes (and count of how many) • Which Sinkholes fell within which Distinct Units by Unique ID (i.e. 1-813) • Which Sinkholes exist in insufficient drift thickness (all of them)

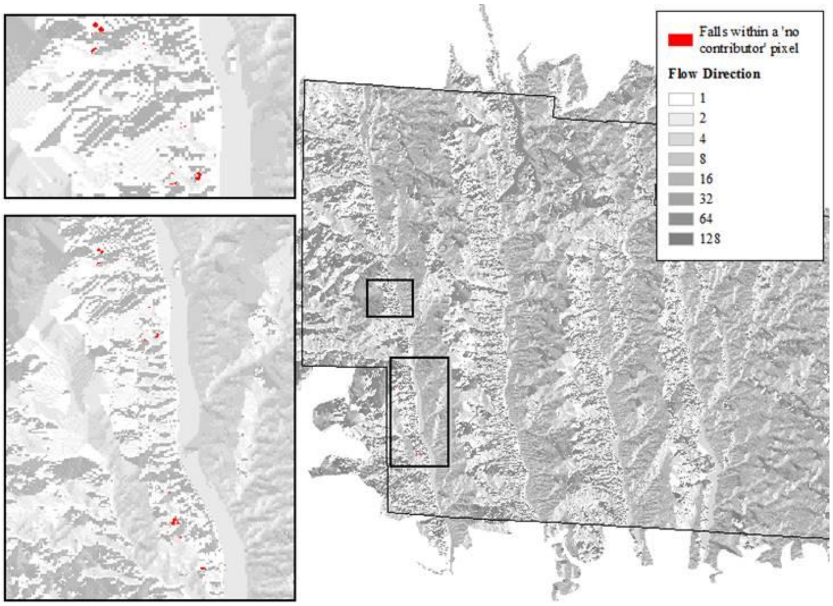
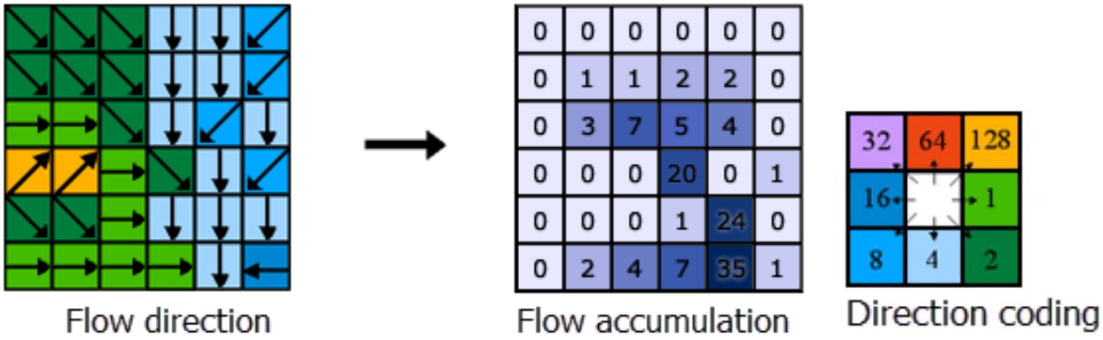


Figure 3-9: Sinkholes falling within upland regions having no direct pixel contributions. Note: Flow direction color scheme is the inverse of DEM

The process of incorporating Flow Length and Flow Accumulation into the sinkholes feature class was completed manually with the Select Features tool. The resulting selection from Flow Length and Accumulation were then appended to the sinkholes feature class, where the lowest Flow Length and highest Flow Accumulation polygons associated with any sinkhole were selected. The reasoning for this is that flow reaching the furthest extents of any sinkhole must first pass the shortest flow length value based on the determination of the ArcMAP tool. Similarly, because the Flow Accumulation tool identifies all contributors from the cardinal and intermediate directions around any given raster pixel or post-conversion polygon shape, it is essential that the highest accumulation value is used to account for potential accumulation from all direction into the cell (ESRI, How Flow Accumulation works—Help | ArcGIS Desktop, n.d.).



0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	1

Figure 3-10: ArcMAP Flow Accumulation Tool sample value determination (ESRI, How Flow Accumulation works—Help | ArcGIS Desktop, n.d.).

Once all input feature classes were prepared and spatially tied to distinct units, the data was converted from ArcMAP attribute tables to an excel spreadsheet and the components of the +K layer were calculated in Excel. Once the DRASTIC + K indices were generated, the indices were re-incorporated into ArcMAP so that a visual comparison of outputs against the 2005 DRASTIC map could be completed.

Results

The formula was applied to the five hundred and twenty seven distinct units as identified in Figure 3-8 and the resulting GWPP map is presented in Figure 3-11.

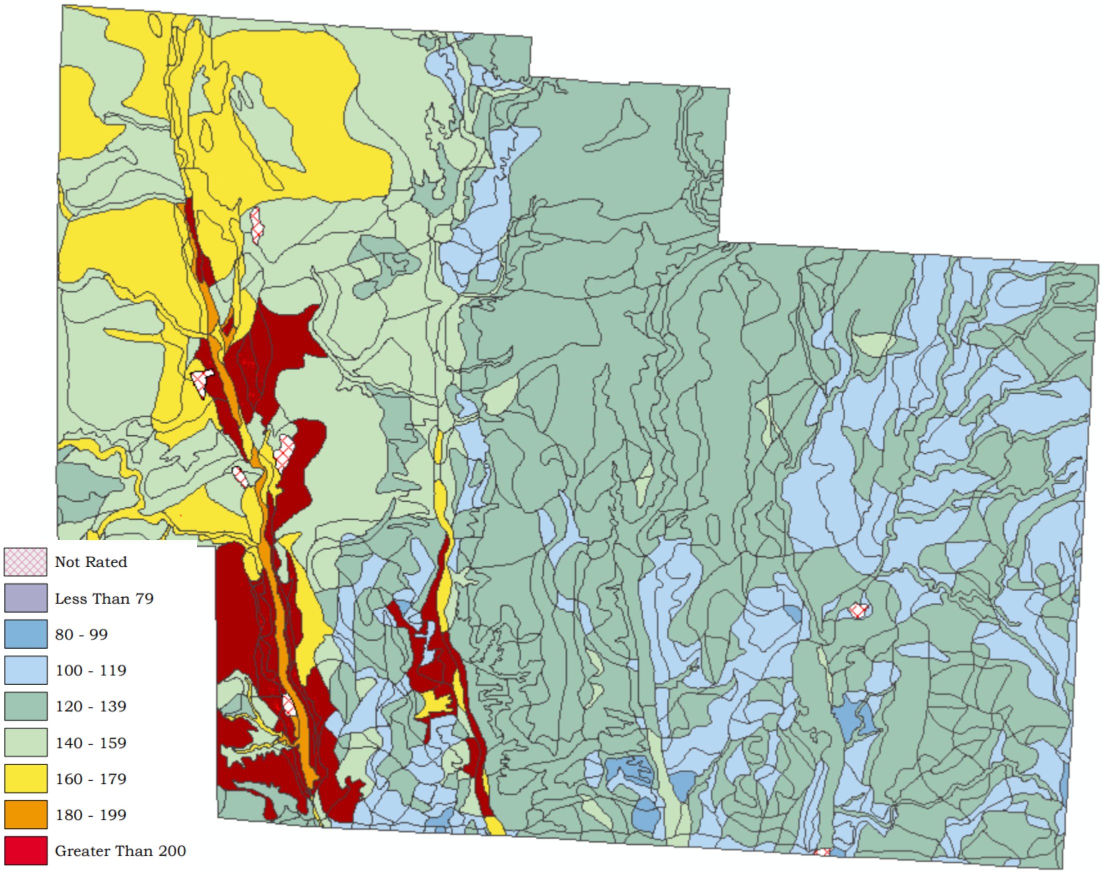


Figure 3-11: DRASTIC + K GWPP map showing increased sensitivity of both district units containing sinkholes and distinct units close to sinkholes

A confusion matrix was generated to identify the ability of the +K formula to correctly increase the GWPP sensitivity categories of sinkhole containing distinct units and units adjacent to those units. False negatives and positives were identified from the output dataset based on the presence of sinkhole and falling within the farthest external sinkhole distance category. An incorrectly maintained distinct unit index is one that either contains sinkholes or has an ESD value of greater than 0 that had an insufficient increase in GWPP needed to be considered part of the next highest sensitivity category. Similarly, an incorrectly increased distinct unit is a unit without sinkholes that fell in the farthest distance to external sinkhole category but was still increased enough to fall into the next highest sensitivity category.

Table 3-4: Confusion matrix results for the +K layer GWPP sensitivity categories

		Known Conditions	
		Positive	Negative
+ K Layer Results	Positive	Correctly Increased 178	Correctly Maintained 162
	Negative	Incorrectly Increased 156	Incorrectly Maintained 31

Discussion and Conclusions

Visually, the results of the +K layer show that the DRASTIC + K indices increased the sensitivity of the regions identified by ODNR DGS as containing karst driven sinkholes. Also, the composition of the +K formula does not allow for decreases in indices, unlike the outputs of other selected models identified in Chapter 2. A statistical determination of the +K layer’s success was observed in the results of the confusion matrix, where 65% of the distinct unit indices were either correctly increased or maintained.

Only one sinkhole containing distinct unit was incorrectly maintained (Figure 3-12). The likely reason for this unit not being increased is because of the relatively small size of the sinkhole as compared to the distinct unit (313 square feet of sinkhole to the 6,117,740 square foot distinct unit area).

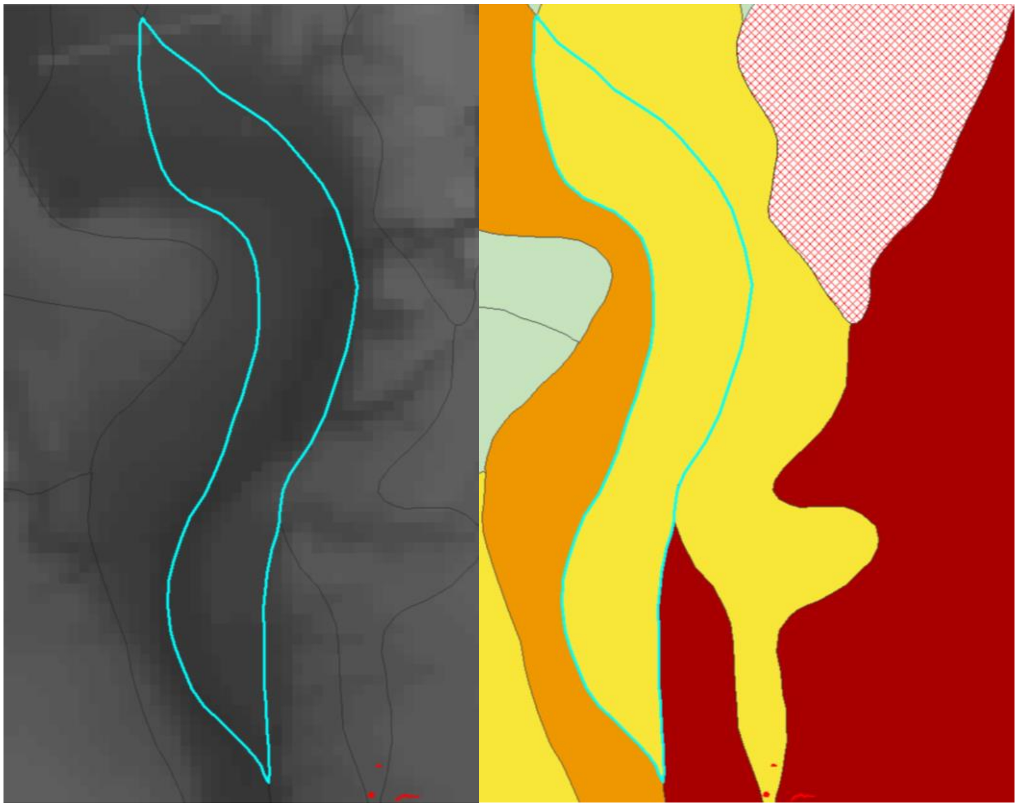


Figure 3-12: Case where sinkhole index remained within the original DRASTIC sensitivity range

These results suggest that while the +K layer is an improvement over DRASTIC alone, there are still areas of improvement for the formula associated with data precision. The formula could benefit from a verification test in a region that does not have pre-existing distinct units. The reason for this reflects that the Delaware County distinct units were generated in 2005 and; while created thoughtfully by experienced geologists, lack the precision that can be achieved with improved remote sensing technologies. Indeed, advancements in dataset precision would affect the area of distinct units generated, the DEM, and the Drift Thickness layers.

Chapter 4. Further DRASTIC-Karst Incorporation Methodology

Future work includes appending the Delaware County drainage easement layers, if accessible, to better identify what sinkholes are stream cuts as opposed to karst. Considering the nature and impact of anthropogenic voids in the geologic profile as the result of strip mining was not an issue for the Delaware County analysis because ODNR verified sinkhole locations, but it may be necessary to distinguish rock quarries, strip mines, and subsurface mining depressions from legitimate karst depressions in other regions of the state of Ohio or elsewhere. Overarching categories of future work can be broken down two categories: formula improvements and verification of results.

Formula accuracy could be enhanced by increasing the precision of the flow direction and accumulation input layers, accounting for regional precipitation and infiltration rates, improving the precision of the known and suspected sinkholes layer, and/or incorporating constants into the +K formula. First, the spatial analyst tool can be better utilized to represent the complex interactions between the land surface and karst sinkholes. Multiple low lying sinkholes spaced too far apart to be potentially connected may receive different volumes of water. This can be addressed with more exacting preferential infiltration consideration or by dividing total overland flow volume amongst all steepest downslope neighboring unit sinkholes instead of just the nearest sinkhole. This can be achieved with the Multiple Flow Dimension feature of the Flow Accumulation tool. This component allows for flow partitioning to all downslope neighbors instead of only the steepest downslope neighbor. Also, reprocessing all components of the +K layer on a machine with the ArcHydro extension would greatly expand the precision of the result due to iterative assessment built into ArcHydro extension tools (ESRI, Arc Hydro: GIS for Water Resources, 2013).

A second consideration is that the +K layer does not presently account for the known average rainfall quantities or intensities for given regions. The inclusion of these values for distinct units could be combined with flow accumulation values to identify the actual accumulation in the area of study. While rainfall is simulated within the Flow Length and Flow Accumulation tools, these should not be considered correct for a region of study without verification. Third, the case study region had distinct units generated based on the precision of available datasets in 2005, smaller distinct units would solve the issue of overly small sinkhole to distinct unit ratios. The + K layer’s ability to increase indices is tied to the presence of surficial sinkholes and thus can only be as precise as the input sinkhole layer. As such, precision can be improved by using automated methods to pull sinkhole locations from a LiDAR point cloud instead of relying on pre-existing raster files from older LiDAR datasets or manual determination.

Finally, parameter ranges for distinct units with karst presence could be increased to attain the same effect without potentially causing mismatches of GWPP values as compared to the rest of the state of Ohio by altering the fundamental nature of the equation. Fortunately, precedent exists for altering DRASTIC weights as found in the Pesticide-specific definition of DRASTIC without too much discrepancy in values (Aller et al., 1987).

As previously noted, DRASTIC requires review from an experienced individual to determine the accuracy of the GWPP map. After the model has been updated, verification of accurate results presents the biggest challenge and also a fundamental need as shown by the imprecision of existing GWPP maps. Because DRASTIC is limited to analyzing areas of 100 acres or more and because of the size and variable topography and ground cover of the selected area of study, a full field investigation of studied areas is prohibitively time consuming. Alternatives to field verification include the creation of a feature class to indicate regions where sinkholes should exist based on parent materials and topography or using radar or laser technology to gather data including ground penetrating radar and acoustic-seismic tools. Future research opportunities tied to model verification steps include hyperspectral satellite data analysis and verification of the DRASTIC + K outputs in Delaware County as compared to the original ratings.

The limitations of these techniques; relying on potentially imprecise datasets to formulate the verification feature class, shallow penetration capacity of ground penetrating radar into topsoil, and the installation requirements of seismic or acoustic equipment make these methods ineffective. Multispectral remote sensing laser techniques like LiDAR can overcome topographic issues, but these methods do not have the capacity to infiltrate beyond the soil layer. Hyperspectral satellite imaging on the other hand overcomes both issues with other verification devices and could be utilized in further investigation of this process.

Hyperspectral satellite verification becomes possible in regions with undisturbed topsoil, such as areas that have not yet been used for urban or agricultural purposes because the dataset allows for chemical compositional analysis and the topsoil has chemical ties to the underlying geology. It can be assumed that these data can be used to identify karst limestone overlain by susceptible sulfur shale or dissolved karst voids because of the unique reflection and absorption signatures of minerals (Magendran and Sanjeevi, 2013). These datasets can then be compared with the trained and field verified existing ODNR karst field depressions ArcMAP feature class to confirm the efficacy of this methodology to identify karstified regions and sinkholes. By identifying the percent identification efficiency of hyperspectral satellite data against counties with or without pre-existing DRASTIC GWPP maps it is possible to extrapolate the efficiency of the dataset for the selected case study which has no AVIRIS flight data gathered.

Because the 2005 GWPP map accounted somewhat for karst by selecting parameter ratings, a future verification step is to compare +K indices against the seven DRASTIC parameters to see if the considerations for incorporating karst initially utilized in the 2005 DRASTIC calculation coincide with the +K layer values. If +K increased distinct units coincide with karst limestone parameters in the 2005 map, it will prove that the formula serves the same purpose as the original adjustments to account for karst. This is necessary because any increased ratings within DRASTIC should be lowered so as not to count the effect of karst sinkholes twice.

The ability to accurately represent site conditions will continue to improve and allow land use planners and small communities to make better choices to avoid contaminating the groundwater resources they access. The presence of karst limestone plays a role in groundwater pollution resilience as it can be dissolved by acidic water and oxygen intrusion and leave voids in the soil and geologic profile that provide no protection to infiltrating water. From hand drawn maps and imprecise datasets to modeling software and satellite imaging with the capability to identify chemical signatures from machinery installed on planes, GWPP models have evolved and become much more complex and provide a better representation of areas of pollution sensitivity. There is more work that can be done including incorporating machine learning into coded GWPP models that incorporate all the experience and knowledge of hydrologists, geologists, and environmental consultants. In spite of this, the addition of the +K karst layer is an incremental change that will allow the outputs of DRASTIC to more accurately represent the true pollution sensitivity of regions containing karst limestone like Delaware County, Ohio.

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Appendix A Figures

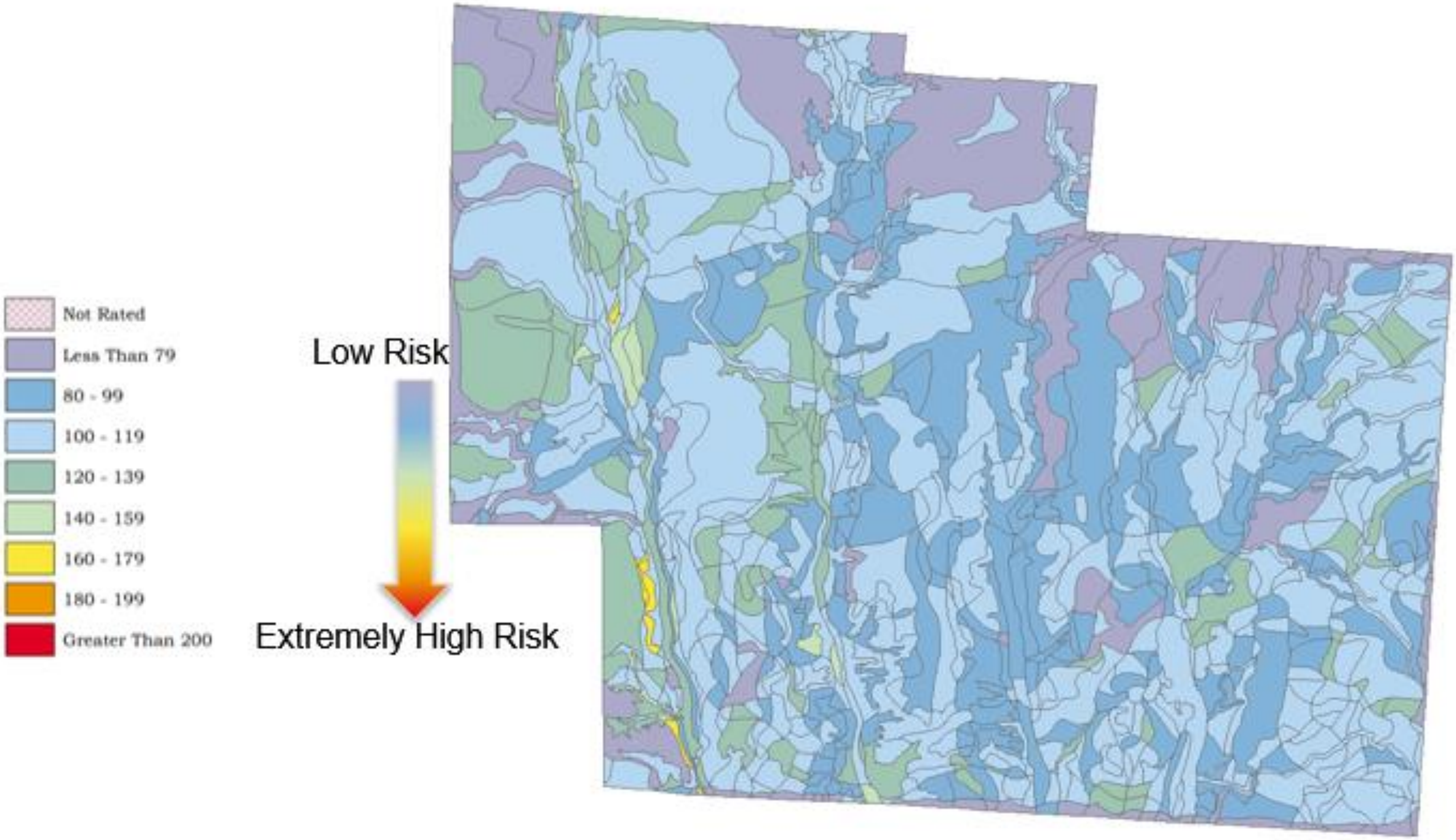


Figure A-1: MATLAB simulation output - KARSTIC

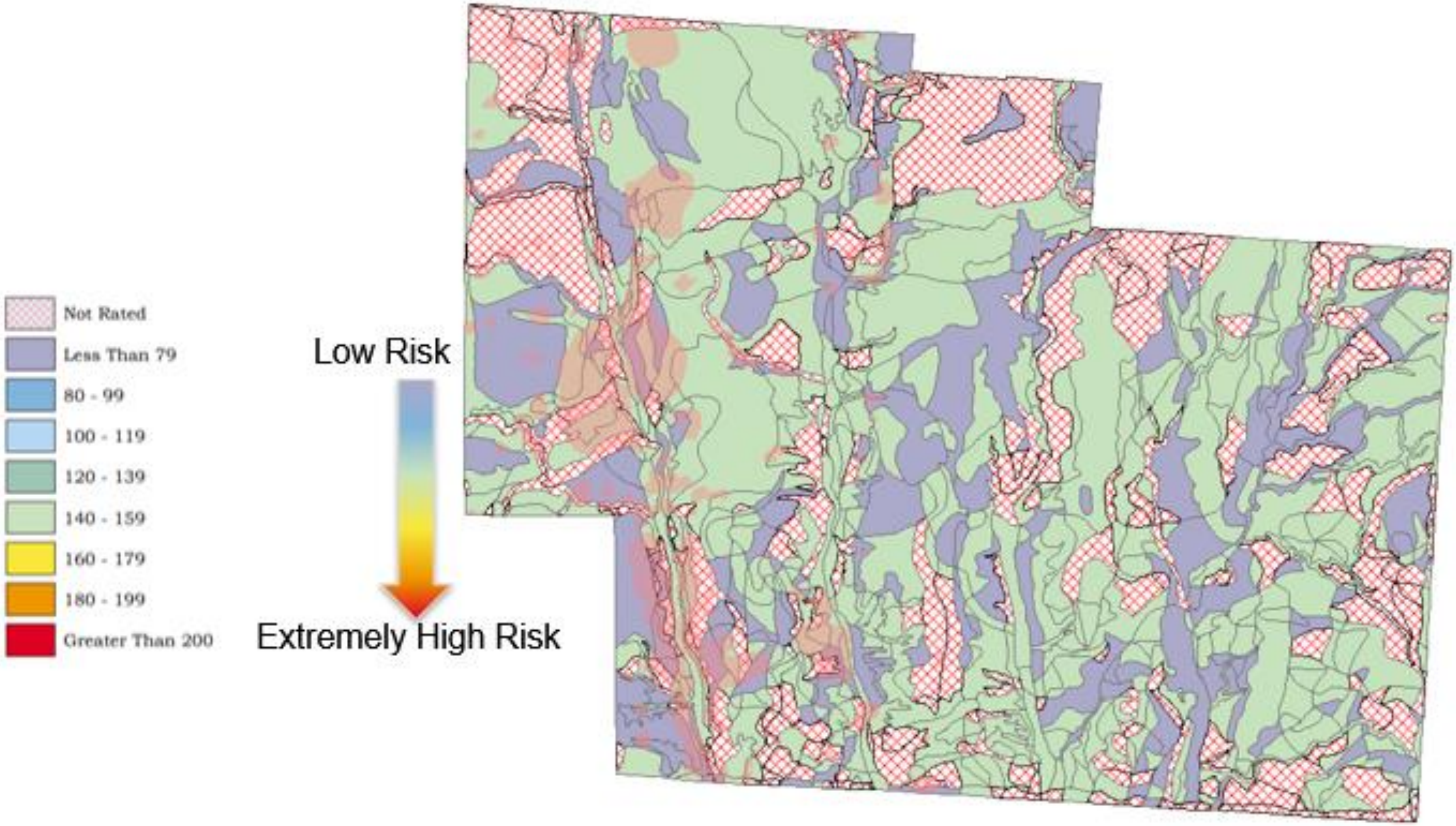


Figure A-2: MATLAB simulation output - SI

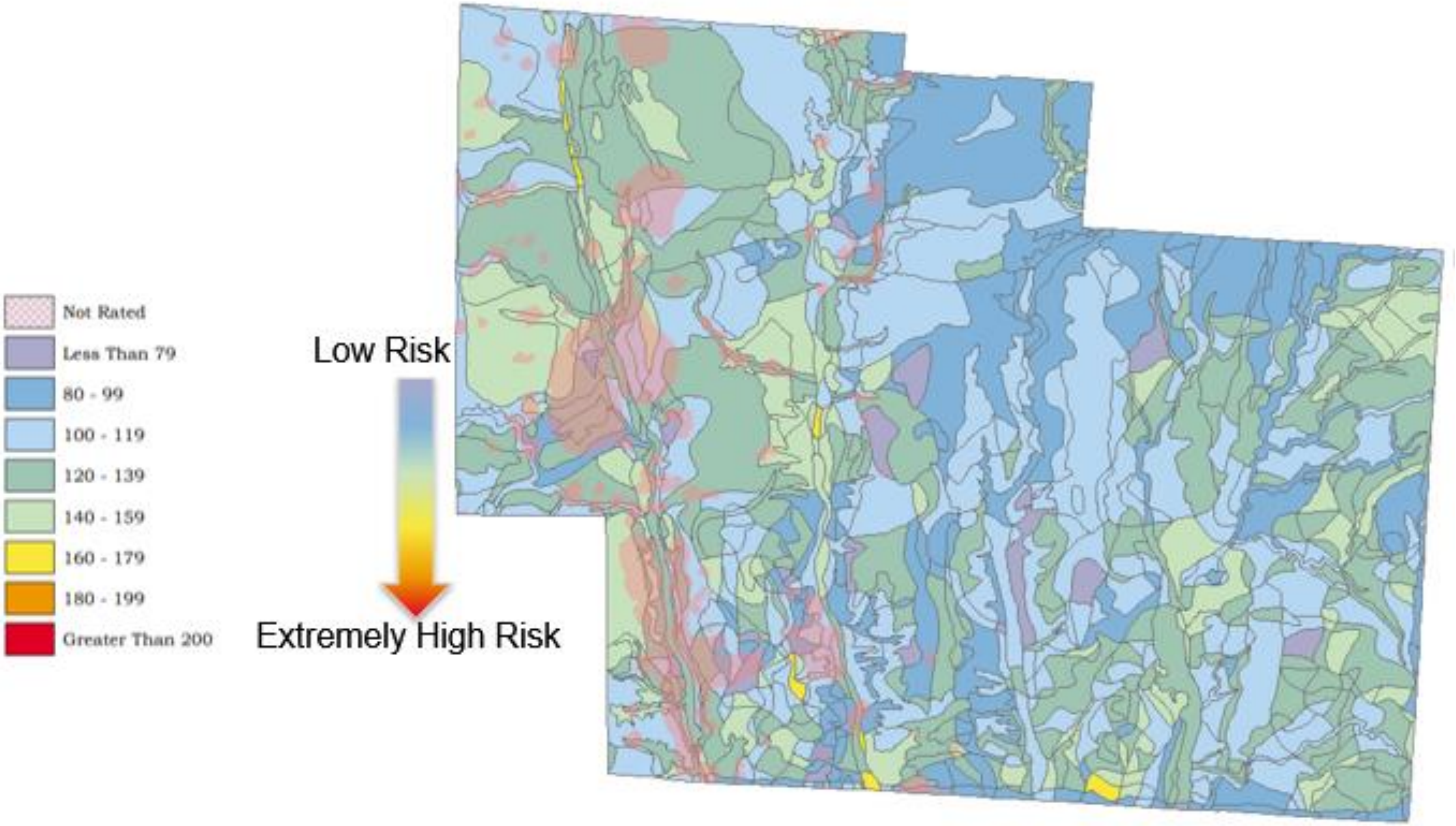


Figure A-3: MATLAB simulation output - Altered Weight DRASTIC

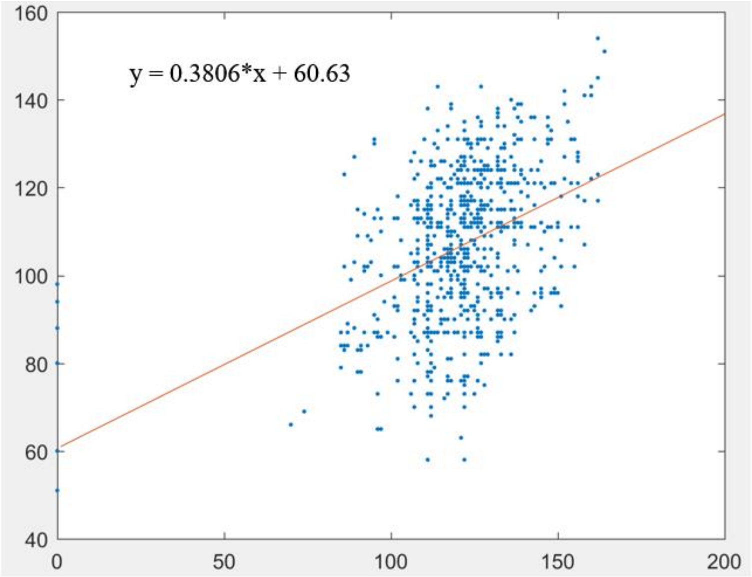


Figure A-4: Comparison of 2005 DRASTICGWPP Values and the MATLAB DRASTIC simulation

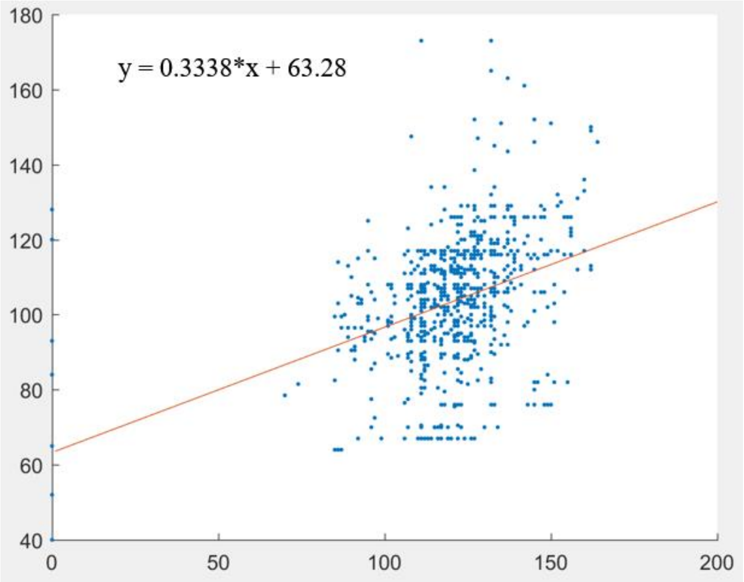


Figure A-5: Comparison of 2005 DRASTICGWPP Values and the MATLAB KARSTIC simulation

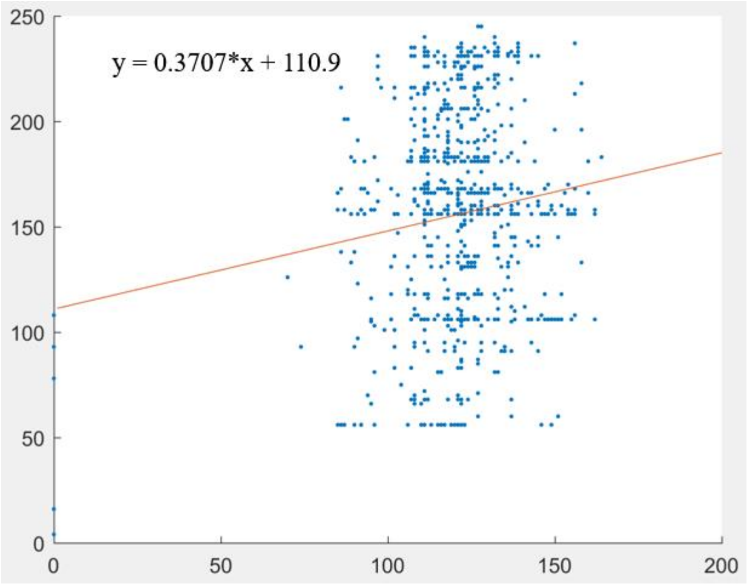


Figure A-6: Comparison of 2005 DRASTICGWPP Values and the MATLAB SIN-DRASTIC simulation

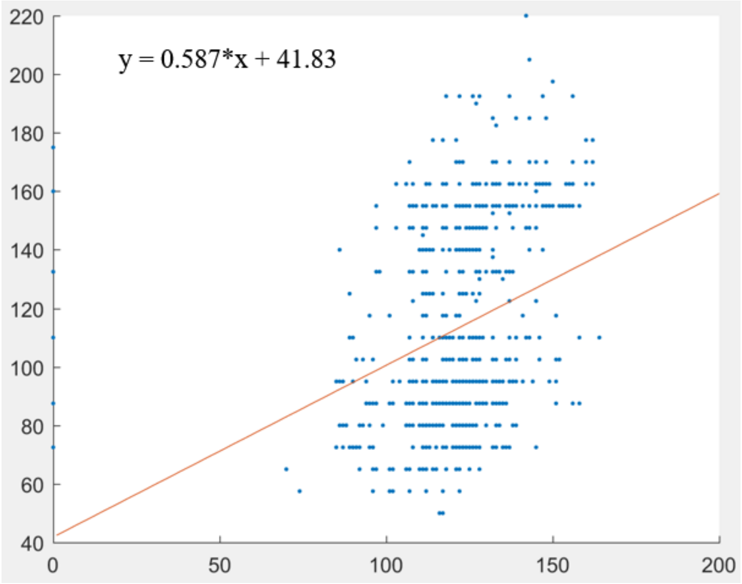


Figure A-7: Comparison of 2005 DRASTICGWPP Values and the MATLAB KAVI simulation

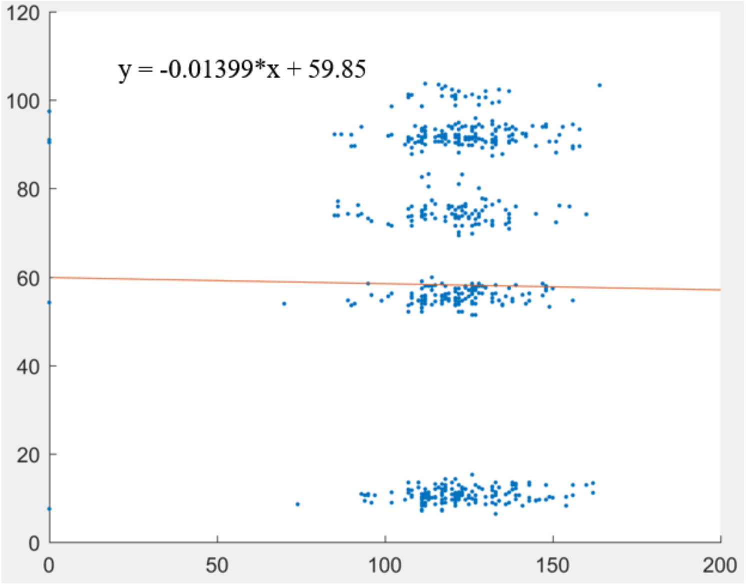


Figure A-8: Comparison of 2005 DRASTICGWPP Values and the MATLAB SI simulation

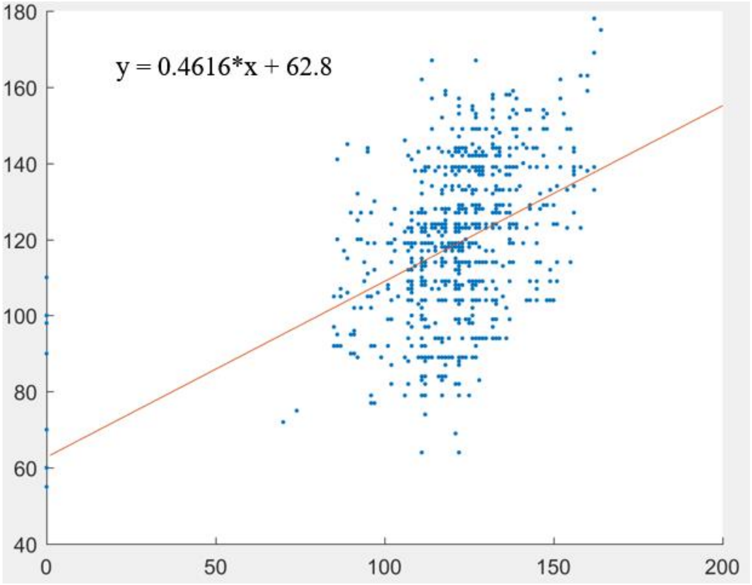


Figure A-9: Comparison of 2005 DRASTICGWPP Values and the MATLAB Altered Weight DRASTIC simulation

Appendix B Ground Water Induced Flooding in the Bellevue Ohio Area Spring and Summer 2008 Report (Appendix A)

APPENDIX A

Block diagrams showing the typical progression of karst geology.
Graphics used with permission from the Columbus Dispatch. Slightly modified.

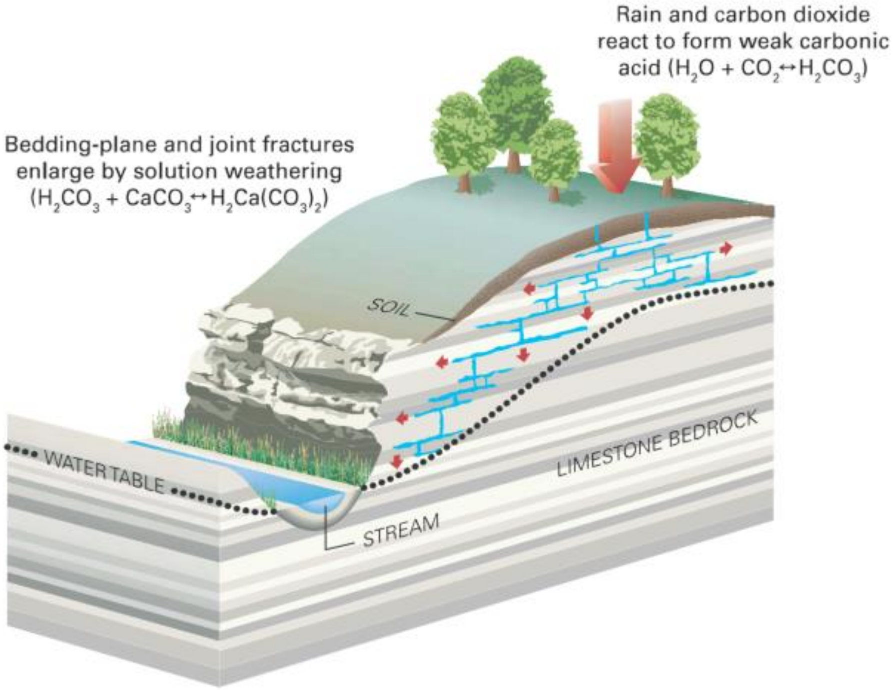


Figure A-1.—Rainwater falling through the air reacts with atmoshperic carbon dioxide to form carbonic acid ($H_2O + CO_2 \Leftrightarrow H_2CO_3$). Upon entering the soil, rainwater reacts with carbon dioxide released from decaying vegetation to form additional carbonic acid.As part of the ground-water environment, carbonic-acid-charged water continues to move downward under the force of gravity into underlying limestone bedrock. The water moves laterally along horizontal fractures (bedding planes) and downward along vertical fractures (joints) until it reaches a depth where all fractures and pore spaces within the rock are filled with water (the water table). As the water moves along fractures, both above and below the water table, small amounts of limestone are dissolved by carbonic acid ($H_2CO_3 + CaCO_3 \Leftrightarrow H_2Ca(CO_3)_2$). Additional limestone is mechanically abraded and removed by the movement of the water.

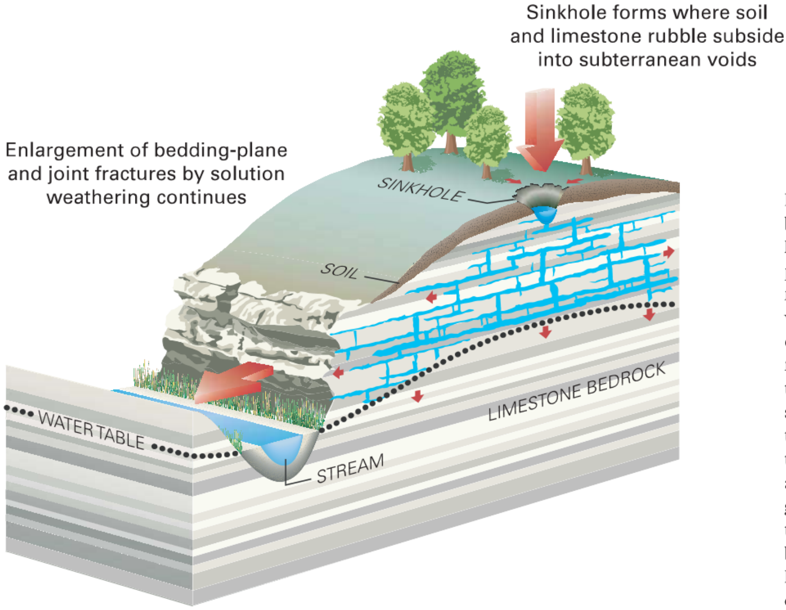


Figure A-2.—With the passing of time, bedrock fractures become greatly enlarged by the dissolution and abrasion process. Sinkholes (dolines) begin to form on the surface where enlarged vertical fractures allow soil and rock debris to collapse into the earth. Surface drainage is diverted directly into the ground-water environment where sinkholes intersect drainageways, thereby accelerating the rate of fracture enlargement through mechanical abrasion.The water table is lowered as ground water escapes to the surface through springs. The terrain created by the presence of numerous sinkholes and other solution features is called karst.

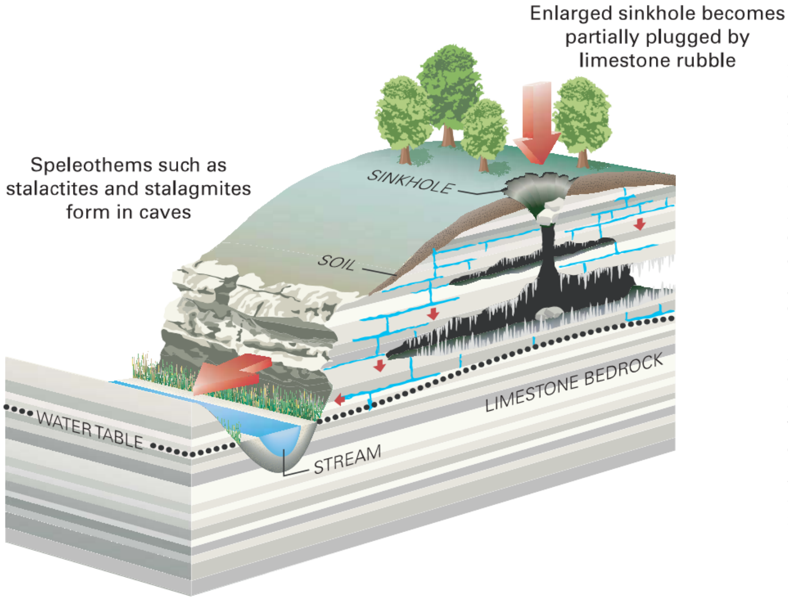
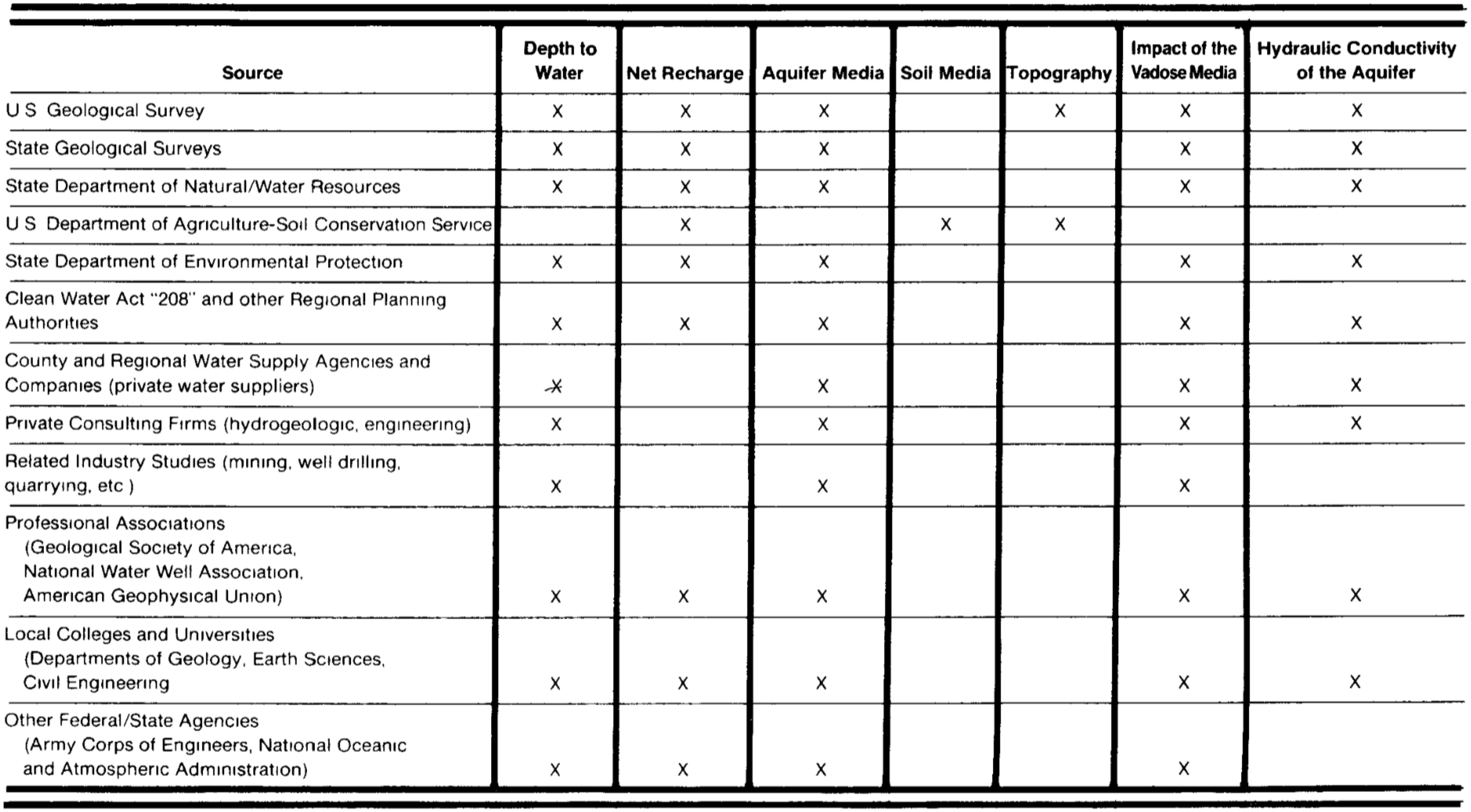


Figure A-3.—Over the course of many centuries, sinkholes continue to enlarge and coalesce with other sinkholes as underground voids collapse and ongoing abrasion and/or dissolution continue to remove bedrock. Horizontal and vertical fractures become enlarged to the extent that they can be classified as a cave (an underground passage large enough for a person to enter). The water table continues to drop in elevation as internal drainage networks within the cave system become more integrated and efficient in collecting and discharging ground water. Ground water saturated with calcium carbonate (calcite) and dripping from cave ceilings and walls or flowing along the cave floor evaporates, causing calcite to be deposited as cave formations (speleothems) such as stalactites, stalagmites, flowstone, and travertine.

Appendix C Tables

Table C-1: Examples of Sources of hydrogeological information to populate DRASTIC (Aller, et al., 1987)



Source	Depth to Water	Net Recharge	Aquifer Media	Soil Media	Topography	Impact of the Vadose Media	Hydraulic Conductivity of the Aquifer
U S Geological Survey	X	X	X		X	X	X
State Geological Surveys	X	X	X			X	X
State Department of Natural/Water Resources	X	X	X			X	X
U S Department of Agriculture-Soil Conservation Service		X		X	X		
State Department of Environmental Protection	X	X	X			X	X
Clean Water Act "208" and other Regional Planning Authorities	X	X	X			X	X
County and Regional Water Supply Agencies and Companies (private water suppliers)	X		X			X	X
Private Consulting Firms (hydrogeologic, engineering)	X		X			X	X
Related Industry Studies (mining, well drilling, quarrying, etc)	X		X			X	
Professional Associations (Geological Society of America, National Water Well Association, American Geophysical Union)	X	X	X			X	X
Local Colleges and Universities (Departments of Geology, Earth Sciences, Civil Engineering	X	X	X			X	X
Other Federal/State Agencies (Army Corps of Engineers, National Oceanic and Atmospheric Administration)	X	X	X			X	

Table C-2: Applications of modified or adapted DRASTIC models (Adapted from Kim, 2018)

Continents	Countries	References
Africa	Congo	Kihumba et al. (2017)
	Jordan	Al-Hanbali & Kondoh (2008)
	Kenya	Kuria et al. (2012)
	Morocco	Boughriba et al. (2010); Sinan & Razack (2009)
	Nigeria	Hamza et al.(2017); Majolagbe et al. (2016); Majolagbe et al. (2017)
	Tunisia	Chenini et al. (2015); Saidi et al. (2009); Allouche et al. (2017)
N. America	Canada	Denny et al. (2007); Lubianetzky et al. (2015)
	Mexico	Bojo´rquez-Tapia et al. (2009); Hernández-Espriú et al. (2014)
	Nicaragua	Johansson et al. (1999); Mendoza & Barmen (2006)
	USA	Devis et al. (2002); Dixon (2005); Evans & Myers (1990); Ehteshami et al. (1991); Halliday & Wolfe (1991); Fritch et al. (2000); Gomez del campo & Dickerson (2008); Klug (2009); Li & Merhcant (2013); Rupert (2001); Uddameri & Hommungar (2007) van Beynen et al. (2012); Weatherington-Rice et al. (2006 a & b)
S. America	Brazil	Nobre et al. (2007)
	Ecuador	Ribeiro et al. (2017)
Asia	China	Bai et al. (2011); Guo et al. (2007); Gou et al. (2006); Hailin et al. (2011); Huan et al. (2012); Li et al. (2016); Su et al. (2015); Wang et al. (2012); Wang et al. (2007); Wu et al. (2016); Zhou et al. (2010); Zhou et al. (2012)
	India	Brindha & Elango (2015); Ckakraborty et al. (2007); Iqbal et al. (2015); Khan et al. (2010); Khan et al. (2014); Sahoo et al. (2016); Singh et al. (2015); Sinha et al. (2016); Sophiya & Syed (2013); Thirumalaivasan et al. (2003)
	Iran	Mohammadi et al. (2009); Akhavan et al. (2011); Baghapour et al. (2016); Barzegar et al. (2016); Farjad et al. (2012); Fijani et al. (2013); Jafari & Nikoo (2016); Javadi et al. (2011a & b); Khodabakhshi et al. (2017); Neshat & Pradhan (2015); Neshat et al. (2014a, b, & c); Vaezihir & Tabarmayeh (2015) Neshat et al. (2015); Rezaei et al. (2016); Sadat-Noori & Ebrahimi (2016); Taheri et al. (2017)

Continued

Table C-2 Continued

	Iraq	Abdullah et al. (2015); Abdullah et al. (2016)
	Israel	Mimi et al. (2012); Secunda et al. (1998)
	Japan	Mishima et al. (2011)
	Jordan	Al-Adamat et al. (2003, 2010); Al-Farajat et al. (2016); Al Kuisi et al. (2006); Al-Rawabdeh et al. (2014); Awawdeh & Jaradat (2010); Awawdeh et al. (2015); Jasem & Alraggad (2010)
Asia Cont.	Malaysia	Shirazi et al. (2013); Mogaji et al. (2014)
	Nepal	Pathak et al. (2009); Shrestha et al. (2017)
	Pakistan	Hussain et al. (2017)
	Palestine	Baalousha (2006, 2011)
	South Korea	Lee (2003)
	Taiwan	Jang et al. (2016)
	Thailand	Seeboonruang (2016)
	Turkey	Sener & Davraz (2013); Sener & Sener (2015)
Europe	Belgium	Jiménez-Madrid et al. (2013)
	Germany	Berkhoff (2008)
	Greece	Antonakos & Lambrakis (2007); Asadi et al. (2017); Kazakis et al. (2015 a & b); Panagopouls et al. (2006)
	Italy	Bonfanti et al. (2016); Celico et al. (2007)
	Poland	Witkowski et al. (2003)
	Portugal	Barroso et al. (2015); Junior et al. (2015); Pacheco & Sanches Fernandes (2013); Stigter et al. (2006); Teixeira et al. (2015); Valle Junior et al. (2015)
	Spain	Jiménez-Madrid et al. (2013); Martínez-Bastida et al. (2010); Santos et al. (2015)
	United Kingdom	Yang & Wang (2008)
Oceania	New Zealand	Close (1993 a & b)

Table C-3: Hierarchy of GWPP models. Adapted from Ivan and Madl-Szonyi, 2017

<table>
<tr><td>*DRASTIC*
1985/87</td><td colspan="3" rowspan="2">*EPIK*
1996</td><td colspan="7">*GLA (+ EPIK)*
1995</td></tr>
<tr><td>KARSTIC
(2nd)
2002</td><td colspan="7">*PI*
(2nd)
*2000**</td></tr>
<tr><td>DRISTPI
(2nd)
2013</td><td>Reks
(2nd)
1998</td><td colspan="2">RISKE (2nd)
2000</td><td colspan="7">European Approach [A.] (3rd) 2002 (a comprehensive framework)</td></tr>
<tr><td>DAC
(2nd)
1996</td><td></td><td>PRESK
(3rd)
2011</td><td>RISKE 2
(3rd)
2005</td><td colspan="3">COP
(4th)
2006</td><td>VULK
(3rd)
2001*</td><td>Time-Input
(4th)
2003</td><td>Simplified M.
(4th)
2004</td><td>VURAAS
(4th)
2004</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">PaPRIKA
(5th)
2010</td><td>COP + K
(5th)
2009</td><td>Slovene A.
(5th)
2007</td><td>VI & C_v
(4th)
2008</td><td>Transit Time
(5th)
2008</td><td>Pan-European A.
(4th)
2006</td><td></td></tr>
</table>

Notes: * identifies a correlation between the identified models. *Italics* represent early or basic models. Right justification indicates that it is a sub-model of the above model

Table C-4: All selected model properties and parameters for MATLAB simulation

Model Function & Descriptions		Input 2	Input 3	Input 4	Input 5	Input 6	Input 7
DRASTIC	**Variable**	De	ReNet	AqMed	SoilMed	Topog	ImpV
	Definition	Depth to Groundwater	Net Recharge of Water	Aquifer Media	Soil Media	Topography	Impact of the Vadose Zone
	MATLAB Units	ft	in/yr	Nominal List of Options	Nominal List of Options	%	Nominal List of Options
KARSTIC	**Variable**	Ka	AqMed	ReNet	SoilMed	Topog	ImpV
	Definition	Karst Sinkholes with surface recharge	Aquifer Media	Net Recharge of Water	Soil Media	Topography	Impact of the Vadose Zone
	MATLAB Units	Nominal List of Options	Nominal List of Options	in/year	Nominal List of Options	%	Nominal List of Options
DRISTPI	**Variable**	D	R	I	S	T	PI
	Definition	Depth of water Scenario 1: high karstic development. Scenario 2: carbonated materials non-karstified and detritic materials.	Net Recharge	Impact of the vadose zone	Soil Media	Topography	Preferential Infiltration – Scenario 1: high karstic development. Scenario 2: carbonated materials non-karstified and detritic materials.
	MATLAB Units	Meters	mm/Yr	Nominal List of Options	Nominal List of Options	%	Nominal List of Options

Continued

Table C-4 Continued

SINDRASTIC	**Variable**	assess		PSink	GWleveldecline	De	ReNet	AqMed
	Definition	Hydrogeologic Setting Definition, Rated or Not Rated		Sinkhole Catchment Factor	Groundwater Level Decline	Depth to Water	Net Recharge	Aquifer Media
	MATLAB Units	Logical. 1 = Rated, anything else = Not Rated	Meters	Meters	Meters	Meters	mm/yr	Nominal List of Options
KAVI	**Variable**	assess	De	SoPer	CD	LndCov	Road	CondHy
	Definition	Hydrogeologic Setting Definition, Rated or Not Rated	Depth to Groundwater	Soil Permeability	Epikarst (Closed Topographic Depressions)	Land Use	Presence of Major Roadway	Hydraulic Conductivity of the Aquifer
	MATLAB Units	Logical. 1 = Rated, anything else = Not Rated	Meters	cm/hr	Nominal List of Options	Nominal List of Options	Logical. 1 = Rated, anything else = Not Rated	Meters/D
SI	**Variable**	assess	De	ReNet	AqMed	LndUse	Topog	
	Definition	% When Hydrogeologic Setting ~= NR	Depth to Groundwater	Net Recharge	Aquifer Media	Land Use	Topography	
	MATLAB Units	Logical. 1 = Rated, anything else = Not Rated	Meters	mm/yr	Nominal List of Options	Nominal List of Options	%	

Notes: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area (ft3/d)/ft2. In this report, the mathematically reduced form, feet per day (ft/d), is used for convenience

Aquifer Media, Soil Media, and Impact of Vadose Zone Nominal Lists **may not** be identical between Models.

DRISTPI, SINDRASTIC, KAVI, & SI - D Parameter has a conversion from Feet to Meters, so input table can be in feet.

DRISTPI, SINDRASTIC & SI - R Parameter has a conversion from in/yr to mm/yr, so input table can be in in/yr.

DRISTPI – I, S, and T Parameters have identical options to 1987 DRASTIC.

SINDRASTIC – SIN, Gwleveldecline, & Psink Parameters have conversions from feet to meters, input table in feet.

SINDRASTIC & KAVI - CondHy Parameter has a conversion from feet/day to meters/day input table in feet

KAVI - SoPer Parameter has a conversion from um/s to cm/hr, input table in μm/s

Appendix D Equations and MATLAB Code for Statistical Analysis

KARSTIC

$$Groundwater\ Pollution\ Potential = K_W * K_R + D_W * D_R + A_W * A_R + R_W * R_R + S_W * S_R + T_W * T_R + I_W * I_R + C_W * C_R$$

$$Where:$$

$$x_R = Rating\ of\ each\ Variable$$

$$x_W = Weight\ of\ each\ Variable$$

$$K = Karstic\ sinkholes\ (including\ surface\ recharge, geologic\ structure, and\ fractures)$$

$$D = Depth\ to\ Water\ Table$$

$$A = Aquifer\ media,$$

$$R = Net\ Recharge\ of\ water\ ,$$

$$S = Soil\ media,$$

$$T = Topography\ (\%\ slope),$$

$$I = Impact\ of\ the\ vadose\ zone\ (including\ depth\ to\ water),$$

$$C = Hydraulic\ Conductivity\ of\ the\ aquifer$$

DRISTPI

$$Groundwater\ Pollution\ Potential = D_W * D_R + R_W * R_R + I_W * I_R + S_W * S_R + T_W * T_R + PI_W * PI_R$$

$$Where:$$

$$x_R = Rating\ of\ each\ Variable$$

$$x_W = Weight\ of\ each\ Variable$$

$$D = Depth\ to\ groundwater\ (feet),$$

$$R = Net\ Recharge\ of\ water\ (inches),$$

$$I = Impact\ of\ the\ vadose\ zone,$$

$$S = Soil\ media,$$

$$T = Topography\ (\%\ slope),$$

$$PI = Preferential\ Infiltration\ to\ swallowholes,$$

SIN-DRASTIC

$$Groundwater\ Pollution\ Potential = P_{Sink} + SIN + D_W * D_R + R_W * R_R + A_W * A_R + S_W * S_R + T_W * T_R + I_W * I_R + C_W * C_R$$

$$Where:$$

$$Sinkhole\ pollution\ conveyance\ potential\ (P_{Sink}) = SCF * D_{Sinkhole} * d_{Sinkhole}$$

$$SCF = Sinkhole\ Catchment\ Factor,$$

$$D_{Sinkhole} = Major\ Axial\ Length\ of\ sinkhole\ (m\ or\ ft),$$

$$d_{Sinkhole} = depth\ of\ the\ sinkhole\ (m\ or\ ft)$$

$$SIN = Distance\ to\ closest\ Sinkhole\ (m\ or\ ft)$$

$$\textit{All other variables are the same as DRASTIC}$$

COP+K

$$\begin{aligned}
&\textit{Groundwater Pollution Potential for karstified areas}\\
&\qquad = [\textit{Distance to swallowhole} * \textit{Distance to sinking water body}\\
&\qquad * \textit{Slope and Vegetation} + \textit{Temporal Variability}]\\
&\qquad * [\textit{Soil Texture and Structure}\\
&\qquad + \{\textit{Lithology and Fracturation} * \textit{Layer Index}\\
&\qquad * \textit{Confined Conditions}\}] * [\textit{Rainy Days} * \textit{Storm Events}]\\
&\qquad + [\textit{Groundwater Travel Time} * \textit{Information on the Karst Network}\\
&\qquad * \textit{Connection and Contribution}]
\end{aligned}$$

$$\begin{aligned}
&\textit{GWPP for non} - \textit{karstified areas}\\
&\qquad = [\textit{Surface Morphologic Features} * \textit{Slope and Vegetation}]\\
&\qquad * [\textit{Soil Texture and Structure} + \{\textit{Lithology and Fracturation}\\
&\qquad * \textit{Layer Index} * \textit{Confined Conditions}\}]\\
&\qquad * [\textit{Rainy Days} * \textit{Storm Events}] + [\textit{Groundwater Travel Time}\\
&\qquad * \textit{Information on the Karst Network}\\
&\qquad * \textit{Connection and Contribution}]
\end{aligned}$$

KAVI

$$\textit{Groundwater Pollution Potential} = D_W * D_R + C_W * C_R + CD_W * CD_R + LU$$

$$\textit{Where}:$$

$$x_R = \textit{Rating of each Variable}$$

$$x_W = \textit{Weight of each Variable}$$

$$D = \textit{Depth to groundwater},$$

$$C = \textit{Aquifer Hydraulic Conductivity},$$

$$CD = \textit{Closed Depressions (Surficial Sinkholes)},$$

$$LU = \textit{Land Use}$$

SI

$\textit{Groundwater Pollution Potential} =$
$DW*DR+RW*RR+AW*AR+TW*TR\textit{Groundwater Pollution Potential} = D_W *$
$D_R + R_W * R_R + A_W * A_R + T_W * T_R + LU$

$$\textit{Where}:$$

$$x_R = \textit{Rating of each Variable}$$

$$x_W = \textit{Weight of each Variable}$$

$$D = \textit{Depth to groundwater},$$

$$R = \textit{Net Recharge of water},$$

$$A = \textit{Aquifer media},$$

$$T = \textit{Topography (\% slope)},$$

$$LU = Land\ Use$$

Matlab Code used to identify most appropriate other GWPP models for incorporation into DRASTIC

Data Scrub and analysis script file

```
%% Establishing Data Sources & File Save Locations and the Scrub
azc = fix(clock);
aBaseDir = pwd; % Note that leading a's and d's for variables are for categorizing the
workspace for 'beginning file determination' and 'data collection', respectively
AOCCityName = 'Delaware_County'; %Getting name of area for file saving later
AOCStateName = 'OH'; %Getting state info for file saving later
INIT = 'rw'; %Getting worker initials for filename
% Following If/If statement combination identifies location of excel table to be used for
analysis
% [aFileName, aFilePath] = uigetfile('*.xls', ...
%     'Please locate and choose the Excel file containing your compiled data', aBaseDir);
% if isequal(aFileName, 0)
%     fprintf('User aborted file choosing.')
% end
%zSaveLocation = uigetdir(aBaseDir,'Where do you want to save the outputs?');
zSaveLocation = 'C:\Users\Rachel\Desktop\MATLAB6220';
%aFile = fullfile(aFilePath, aFileName);
aFile = 'C:\Users\Rachel\Desktop\MATLAB6220\Input_Tables_6220.xls';

file_spec = 'C:\Users\Rachel\Desktop\MATLAB6220\Input_Tables_6220.xls';
exist( file_spec, 'file' ) ;
[ num, txt, raw ] = xlsread( file_spec );
dData = num;
dTextData = txt;
dTable = importdata(aFile);
dData = dTable.data.Scrubbedwheadings;
dColHeaders = dTable.colheaders;
dTextData = [dTable.textdata.Scrubbedwheadings];
dColDescriptions = dTable.textdata.Scrubbedwheadingswdescriptions(2,:);

NumMODELS = 8; %UPDATE! THESIS = 14, 6220 = 8

i = 1;
RUN = 1;
```

```
%RUN = [1,0,0,0,0,0,0,0,0]; %initializing a vector with the maximum number of columns
associated with all the models available. The first value must be one to initiate the while
loop to choose the number of models to analyze.
while RUN ~= 0
   NUMRUN = num2str(RUN);
   % Assigning Input Variables - from Inputs_6220.xls
   assess = dData(:,2);

   De = dData(:,17);
   ReNet = dData(:,10);
   AqMed = dTextData(2:end,18);
   SoilMed = dTextData(2:end,11);
   Topog = dData(:,8);
   ImpV = dTextData(2:end,29);
   CondHy = dData(:,20);

   Ka = dData(:,21);
   FracGeo = AqMed;
   D = De;

   R = ReNet;
   I = ImpV;
   S = SoilMed;
   T = Topog;
   PI = AqMed;
   KarstPotential = dData(:,24);

   SIN = dData(:,22);
   GWleveldecline = dData(:,16);
   PSink = dData(:,16);

   CN = dData(:,19);
   LT = dData(:,23);
   SoilTex = SoilMed;
   distswallow = SIN;
   LAY = AqMed;
   SoilThick = dData(:,14);
   rainfall = dData(:,7);
   raindays = dData(:,6);
   stormevents = raindays;
   swallowhole = dData(:,21);
   distsinkstrm = dData(:,30);
   Slope = Topog;
   Veg = dTextData(:,9);
```

```
    surflayer = dData(:,15);
    karstfeat = swallowhole;
    karstinfo = swallowhole;
    gwtravti = dData(:,20);
    karstinf = swallowhole;
    connection = ones(813,1);

    SoPer =  dData(:,15);
    LndCov = Veg;
    CD = swallowhole;
    Road = dData(:,28);

    LndUse = Veg;

    %% Selecting & Running the Chosen Scenario/s
    fprintf('AVAILABLE GWPP MODELS:\n')
    fprintf('Scenario 1: DRASTIC\n'); fprintf('Scenario 2: KARSTIC\n'); fprintf('Scenario
3: DRISTPI\n');fprintf('Scenario 4: SIN-DRASTIC\n'); fprintf('Scenario 10: COP+K\n');
fprintf('Scenario 11: KAVI\n'); fprintf('Scenario 14: SI from KAVI paper\n');
fprintf('Scenario 15: DRASTIC w/ Increased weight of 5 for parameters A and C to
account for karst presence.\n')
    zModSel = input('\nPlease choose your model with the corresponding number 1 - 15.
\n');
    if zModSel == 1 %Trigger GWPPModel1
        Sheet{RUN+1} = sprintf('%d_DRASTIC',RUN);
        ModData{RUN+1} = aDRASTIC(assess, De, ReNet, AqMed, SoilMed, Topog,
ImpV, CondHy);
        Headings{RUN+1} = ["OBJECTID", "Assess?", "Groundwater Pollution Potential
Index", "Depth to Water Rating", "Depth to Water Index","Net Recharge Rating", "Net
Recharge Index","Aquifer Media Rating", "Aquifer Media Index","Soil Media Rating",
"Soil Media Index","Topography Rating", "Topography Index","Impact of Vadose Zone
Rating", "Impact of Vadose Zone Index","Hydraulic Conductivity Rating", "Hydraulic
Conductivity Index"];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 2 %Trigger GWPPModel2
        Sheet{RUN+1} = sprintf('%d_KARSTIC',RUN);
        ModData{RUN+1} = bKARSTIC(assess, Ka, AqMed, ReNet, SoilMed, Topog,
ImpV, CondHy, FracGeo, D);
        Headings{RUN+1} = ["OBJECTID","Assess?","GWPP"," "," "," "," "," "," ","
"," "," "," "," "," "," "," "," "];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 3 %Trigger GWPPModel3
        Sheet{RUN+1} = sprintf('%d_DRISTPI',RUN);
        ModData{RUN+1} = cDRISTPI(assess, D,R,I,S,T,PI,KarstPotential);
```

```
        Headings{RUN+1} = ["OBJECTID","Assess?","GWPP"," "," "," "," "," "," "," ","
"," "," "," "," "," "," "," "," "," "];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 4 %Trigger GWPPModel4
        Sheet{RUN+1} = sprintf('%d_SINDRASTIC',RUN);
        ModData{RUN+1} = dSINDRASTIC(assess, SIN,PSink, GWleveldecline, De,
ReNet, AqMed, SoilMed, Topog, ImpV, CondHy);
        Headings{RUN+1} = ["OBJECTID", "Assess?", "Groundwater Pollution Potential
Index"," "," "," "," "," "," "," "," "," "," "," "," "," "," "," "," "," "," "," "," "];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 10 %Trigger GWPPModel10
        Sheet{RUN+1} = sprintf('%d_COPK_Method',RUN);
        ModData{RUN+1} = jCOPKMethod(assess, CN, LT, LAY, SoilTex, SoilThick,
rainfall, raindays, stormevents,swallowhole, distswallow, distsinkstrm, Slope, Veg,
surflayer,karstfeat, gwtravti, karstinfo,connection);
        Headings{RUN+1} = ["OBJECTID", "Assess?", "Groundwater Pollution Potential
Index"," "," "," "," "," "," "," "," "];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 11 %Trigger GWPPModel11
        Sheet{RUN+1} = sprintf('%d_KAVI',RUN);
        ModData{RUN+1} = kKAVI(assess, De, SoPer, CD, LndCov, Road, CondHy);
        Headings{RUN+1} = ["OBJECTID", "Assess?", "Groundwater Pollution Potential
Index"," "," "," "," "," "," "," "," "," "," "," "," "," "," "];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 14 %Trigger GWPPModel14
        Sheet{RUN+1} = sprintf('%d_SIfromKAVI',RUN);
        ModData{RUN+1} = nSI(assess, De, ReNet, AqMed, LndUse, Topog);
        Headings{RUN+1} = ["OBJECTID", "Assess?", "Groundwater Pollution Potential
Index"," "," "," "," "," "," "," "," "," "," "," "," "];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    elseif zModSel == 15 %Trigger GWPPModel15
        Sheet{RUN+1} = sprintf('%d_MODDRASTIC',RUN);
        ModData{RUN+1} = oMODDRASTIC(assess, De, ReNet, AqMed, SoilMed,
Topog, ImpV, CondHy);
        Headings{RUN+1} = ["OBJECTID", "Assess?", "Groundwater Pollution Potential
Index", "Depth to Water Rating", "Depth to Water Index","Net Recharge Rating", "Net
Recharge Index","Aquifer Media Rating", "Aquifer Media Index","Soil Media Rating",
"Soil Media Index","Topography Rating", "Topography Index","Impact of Vadose Zone
Rating", "Impact of Vadose Zone Index","Hydraulic Conductivity Rating", "Hydraulic
Conductivity Index"];
        Fulldata{RUN+1} = [Headings{RUN+1};ModData{RUN+1}];
    else
        while isstring(zModSel) || zModSel > length(NumMODELS) || ~isinteger(zModSel)
            zModSel = input('Entry Invalid: Please choose a valid scenario.\n');
```

```
        end
    end

    CHECK = input('\nContinue with another model? 1 = Yes, 0 = No. '); % Going back to the top of the code
    if CHECK == 1
        RUN(RUN) = RUN+1;
    elseif CHECK == 0
        RUN = 0;
    else
        CHECK = input('\nContinue with another model? 1 = Yes, 0 = No. ');
    end

    if size(RUN,2) > 1
        RUN = RUN(end)
    else
    end
    i = i+1;
end

%% SAVE OUTPUT/S TO AN EXCEL FILE IN THE SAME LOCATION AS THE ORIGINAL FILE WITH 'AOC Info_GWPPOutputs_areaname_datecreatedYYYY_MM_DD.xls' and each sheet associated with a given model run (with the exception of models that have more than one scenario to run.
OutputFileName = [zSaveLocation 'CIVILEN6220_Run_' num2str(i) '_' num2str(azc(1)) '_' num2str(azc(2)) '_' num2str(azc(3)) '_' num2str(azc(4)) '_' num2str(azc(5)) '_' num2str(azc(6)) '_' INIT '.xlsx'];
xlswrite(OutputFileName,Fulldata{2},Sheet{2})
xlswrite(OutputFileName,Fulldata{3},Sheet{3})
xlswrite(OutputFileName,Fulldata{4},Sheet{4})
xlswrite(OutputFileName,Fulldata{5},Sheet{5})
xlswrite(OutputFileName,Fulldata{6},Sheet{6})
xlswrite(OutputFileName,Fulldata{7},Sheet{7})
xlswrite(OutputFileName,Fulldata{8},Sheet{8})
xlswrite(OutputFileName,Fulldata{9},Sheet{9})

%% Basic Statistical analysis
Stats = importdata('C:\Users\Rachel\Desktop\MATLAB6220\COMP_6220.xls');
Statsdata = Stats.data;
SI = Statsdata(:,12);
SI(SI == -9999) = NaN;
SI = SI*3;
SIindexvalid = ~isnan(SI);
```

```
cODNR = (Statsdata(:,2));
c2018DRASTIC = (Statsdata(:,3));
cKARSTIC = (Statsdata(:,5));
cSINDRASTIC = (Statsdata(:,7));
cKAVISHIFT = (Statsdata(:,10)); %Shift refers to the multiplier of 50 applied to all outputs to ensure the range of indices are comparable.
cSI = (SI);
cALTDRASTIC = (Statsdata(:,14));

MeanODNR = mean(Statsdata(:,2))
Mean2018DRASTIC = mean(Statsdata(:,3))
MeanKARSTIC = mean(Statsdata(:,5))
MeanSINDRASTIC = mean(Statsdata(:,7))
MeanKAVISHIFT = mean(Statsdata(:,10))
MeanSI = mean(SI)
MeanALTDRASTIC = mean(Statsdata(:,14))

STDODNR = std(Statsdata(:,2))
STD2018DRASTIC = std(Statsdata(:,3))
STDKARSTIC = std(Statsdata(:,5))
STDSINDRASTIC = std(Statsdata(:,7))
STDKAVISHIFT = std(Statsdata(:,10))
STDSI = std(SI)
STDALTDRASTIC = std(Statsdata(:,14))

%% Root mean squared error value for models compared to actual
%Residual = actual minus predicted
ResidODNR2018DRASTIC = Statsdata(:,2) - Statsdata(:,3);
ResidODNRKARSTIC = Statsdata(:,2) - Statsdata(:,5);
ResidODNRSINDRASTIC = Statsdata(:,2) - Statsdata(:,7);
ResidODNRKAVISHIFT = Statsdata(:,2) - Statsdata(:,10);
ResidODNRSI = Statsdata(:,2) - SI;
ResidODNRALTDRASTIC = Statsdata(:,2) - Statsdata(:,14);

RMSE2018DRASTIC = sqrt((ResidODNR2018DRASTIC).^2);
RMSEKARSTIC = sqrt((ResidODNRKARSTIC).^2);
RMSESINDRASTIC = sqrt((ResidODNRSINDRASTIC).^2);
RMSEKAVISHIFT = sqrt((ResidODNRKAVISHIFT).^2);
RMSESI = sqrt((ResidODNRSI).^2);
RMSEALTDRASTIC = sqrt((ResidODNRALTDRASTIC).^2);

%% AICc Calculation - calculate for all models found best to identify karst and the 2018 DRASTIC with actual karst.
```

```
%residuals is the vector of residual values = (obs - model)
%k is the number of parameters

k2018DRASTIC = 7;
kKARSTIC = 10;
kSINDRASTIC = 11;
kKAVISHIFT = 6;
kSI = 5;
kALTDRASTIC = 7;

n=length(ResidODNR2018DRASTIC);
s = std(ResidODNR2018DRASTIC);
L = -n/2*log(2*pi)-n*log(s)-1/(2*s^2)*sum(ResidODNR2018DRASTIC.^2);
aic = 2*k2018DRASTIC-2*L;
aicc = aic+2*k2018DRASTIC*(k2018DRASTIC+1)/(n-k2018DRASTIC-1)

n=length(ResidODNRKARSTIC);
s = std(ResidODNRKARSTIC);
L = -n/2*log(2*pi)-n*log(s)-1/(2*s^2)*sum(ResidODNRKARSTIC.^2);
aic = 2*kKARSTIC-2*L;
aicc = aic+2*kKARSTIC*(kKARSTIC+1)/(n-kKARSTIC-1)

n=length(ResidODNRSINDRASTIC);
s = std(ResidODNRSINDRASTIC);
L = -n/2*log(2*pi)-n*log(s)-1/(2*s^2)*sum(ResidODNRSINDRASTIC.^2);
aic = 2*kSINDRASTIC-2*L;
aicc = aic+2*kSINDRASTIC*(kSINDRASTIC+1)/(n-kSINDRASTIC-1)

n=length(ResidODNRKAVISHIFT);
s = std(ResidODNRKAVISHIFT);
L = -n/2*log(2*pi)-n*log(s)-1/(2*s^2)*sum(ResidODNRKAVISHIFT.^2);
aic = 2*kKAVISHIFT-2*L;
aicc = aic+2*kKAVISHIFT*(kKAVISHIFT+1)/(n-kKAVISHIFT-1)

n=length(ResidODNRSI);
s = std(ResidODNRSI);
L = -n/2*log(2*pi)-n*log(s)-1/(2*s^2)*sum(ResidODNRSI.^2);
aic = 2*kSI-2*L;
aicc = aic+2*kSI*(kSI+1)/(n-kSI-1)

n=length(ResidODNRALTDRASTIC);
s = std(ResidODNRALTDRASTIC);
L = -n/2*log(2*pi)-n*log(s)-1/(2*s^2)*sum(ResidODNRALTDRASTIC.^2);
aic = 2*kALTDRASTIC-2*L;
```

```
aicc = aic+2*kALTDRASTIC*(kALTDRASTIC+1)/(n-kALTDRASTIC-1)

%% Polynomial fitting all models with x = 2005 DRASTIC values

evalint = [1:813];
%1st order
p12018DRASTIC =     [0.3806 60.6272];
p1KARSTIC   = [0.3338   63.2762];
p1SINDRASTIC=   [0.3707 110.9227];
p1KAVISHIFT=    [0.587  41.8279];
p1SI    = [13.7 -9778.3];
p1ALTDRASTIC    = [0.4616   62.8007];

% Fitting Equations to each comparison (2005 values to MATLAB model values)
ODNRDRASTIC = fitlm(cODNR, c2018DRASTIC,'poly1')
scatter(Statsdata(:,2),Statsdata(:,3),'.')
plot(Statsdata(:,2),Statsdata(:,3),'.')
hold on
plot(1:200,0.3806*(1:200)+60.63)
hold off

ODNRKARSTIC = fitlm(cODNR, cKARSTIC,'poly1')
figure
scatter(Statsdata(:,2),Statsdata(:,5),'.')
hold on
plot(1:200,0.3338*(1:200)+63.28)
hold off

ODNRSINDRASTIC = fitlm(cODNR, cSINDRASTIC,'poly1')
figure
scatter(Statsdata(:,2),Statsdata(:,7),'.')
hold on
plot(1:200,0.3707*(1:200)+110.9)
hold off

ODNRKAVISHIFT = fitlm(cODNR, cKAVISHIFT,'poly1')
figure
scatter(Statsdata(:,2),Statsdata(:,10),'.')
hold on
plot(1:200,0.587*(1:200)+41.83)
hold off

ODNRSI = fitlm(cODNR(SIindexvalid), cSI(SIindexvalid),'poly1')
figure
```

```
scatter(Statsdata(:,2),SI,'.')
hold on
plot(1:200,-0.01399*(1:200)+59.85)
hold off

ODNRALTDRASTIC = fitlm(cODNR, cALTDRASTIC,'poly1')
figure
scatter(Statsdata(:,2),Statsdata(:,14),'.')
hold on
plot(1:200,0.4616*(1:200)+62.8)
hold off

%% Scatter plot with the means of each of the models and error bars
% formulated from the standard deviation of each model to show the relative
% spread
xscatters = [1:11]; %Nominal categories of the models under examination
compxtitles = ["","","Current ODNR","Simulated DRASTIC","KARSTIC","SIN-DRASTIC","Normalized KAVI","Normalized SI","Altered Drastic","",""];
yscatters = [NaN,NaN,MeanODNR, Mean2018DRASTIC, MeanKARSTIC, MeanSINDRASTIC, MeanKAVISHIFT, MeanSI, MeanALTDRASTIC,NaN,NaN];
%set(gca,'XtickL',compxtitles)
yerrorbars = [NaN,NaN,STDODNR, STD2018DRASTIC, STDKARSTIC, STDSINDRASTIC, STDKAVISHIFT, STDSI, STDALTDRASTIC,NaN,NaN];;
errorbar(xscatters,yscatters,yerrorbars,'','o')
xticklabels(["Current DRASTIC","Simulated DRASTIC","KARSTIC","SIN-DRASTIC","Normalized KAVI","Normalized SI","Altered Drastic",""]);
xtickangle(45)
xlim([2 10])
ylabel('Mean of Output Dataset')
```

DRASTIC Function

```
function [GWPPTBL] = aDRASTIC(assess, De, ReNet, AqMed, SoilMed, Topog, ImpV, CondHy)
% Reference: Aller, L., Bennet, T., Lehr, J., Petty, R., Hackett, G., Applications, J., . . . Kerr, R. (n.d.). DRASTIC: A STANDARDIZED SYSTEM FOR EVALUATING GROUND WATER POLLUTION POTENTIAL USING HYDROGEOLOGIC SETTINGS.
%
%The EPA DRASTIC Model for identifying the groundwater pollution potential for distinct units.
%   User provides  Depth to groundwater (in feet), net Recharge of water
```

```
%   (in inches/year), Aquifer media, Soil media, Topography (in % slope), Impact
%   of the vadose zone, and hydraulic Conductivity of the aquifer (Gallons
%   Per Day per Square Foot).
%
% Model Assumptions -
% 1) Contamination occurs at the ground surface.
% 2) The contaminant enters the water table when rain falls on the surface and percolates
into the saturated zone.
% 3) The contaminant travels with water, at the same rate as water (Retardation Factor =
1).
% 4) The method will be applied to no smaller than 100 acres.
% 5) The aquifer is unconfined (the method can be modified for a confined aquifer).
% 6) The dominant pollutants are not pesticides (the method can be modified to include
pesticides).
%
%Parameter weight = importance of model factor compared to others from least
significant = 1 to most significant = 5.
% Dw = 5; Depth to water avg. weight
% Rw = 4; Net Recharge avg. weight
% Aw = 3; Aquifer Media avg. weight
% Sw = 2; Soil Media avg. weight
% Tw = 1; Topology avg. weight
% Iw = 5; Impact of the vadose zone avg. weight
% Cw = 3; Hydraulic Conductivity avg. weight
%
%Parameter Range = the breakdown of significance for each factor - uses the tables in
the model book.
%
% Parameter Rating = relevant importance of each factor's range with respect to the other
factors from low = 1 to high = 10.
% Ground Water Pollution Potential (GWPP) Variables and Standard Weights
% Dr: Depth to water rating
% Rr: Net Recharge rating
% Ar: Aquifer Media rating
% Sr: Soil Media rating
% Tr: Topology rating
% Ir: Impact of the vadose zone rating
% Cr: Hydraulic Conductivity rating

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),17);
Der = NaN(length(assess),1);
ReNetr = NaN(length(assess),1);
AqMedr = NaN(length(assess),1);
```

```
SoilMedr = NaN(length(assess),1);
Topogr = NaN(length(assess),1);
ImpVr = NaN(length(assess),1);
CondHyr = NaN(length(assess),1);

%% Identifying Ratings of each parameter from Published 1987 EPA Paper
for i = 1:length(assess)
   GWPPTBL(i,1) = i; % Initializing OBJECTID field
   if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
      GWPPTBL(i,2:end) = 0;
   else     %for cases where data exists and Hydrogeologic Setting = NR
      %% Assumed Weights of each parameter - from Published 1987 EPA Paper
      Dew = 5;
      ReNetw = 4;
      AqMedw = 3;
      SoilMedw = 2;
      Topogw = 1;
      ImpVw = 5;
      CondHyw = 3;
      % DEPTH TO WATER - ifelse Ranges in feet identify ratings
      if (De(i) >= 0 && De(i) <= 5)
         Der(i) = 10;
      elseif (De(i) > 5 && De(i) <= 15)
         Der(i) = 9;
      elseif (De(i) > 15 && De(i) <= 30)
         Der(i) = 7;
      elseif (De(i) > 30 && De(i) <= 50)
         Der(i) = 5;
      elseif (De(i) > 50 && De(i) <= 75)
         Der(i) = 3;
      elseif (De(i) > 75 && De(i) <= 100)
         Der(i) = 2;
      elseif (De(i) > 100)
         Der(i) = 1;
      else
         Der(i) = 0;
         fprintf('Error at Row %0.0f. Depth to Water cannot be negative. ', i)
      end

      % NET RECHARGE - ifelse Ranges in feet identify ratings
      if (ReNet(i) >= 0 && ReNet(i) <= 2)
         ReNetr(i) = 1;
      elseif (ReNet(i) > 2 && ReNet(i) <= 4)
         ReNetr(i) = 3;
```

```
    elseif (ReNet(i) > 4 && ReNet(i) <= 7)
       ReNetr(i) = 6;
    elseif (ReNet(i) > 7 && ReNet(i) <= 10)
       ReNetr(i) = 8;
    elseif ReNet(i) > 10
       ReNetr(i) = 9;
    else
       ReNetr(i) = 0;
       fprintf('Error at Row %0.0f. Net Recharge cannot be negative. ', i)
    end

    % AQUIFER MEDIA - An ifelse table - based on Type of Material; a range of
ratings or typical
    % rating may be used. Expert opinion can be used to override distinct unit values in
the final GWPP table.
    if contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true) || contains(AqMed(i),'SH','IgnoreCase',true)
       AqMedr(i) = 2;
    elseif contains(AqMed(i),'Metamorphic/Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true) ||
contains(AqMed(i),'Igneous','IgnoreCase',true)
       AqMedr(i) = 3;
    elseif contains(AqMed(i),'Weathered','IgnoreCase',true) &&
contains(AqMed(i),'Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true)
       AqMedr(i) = 4;
    elseif contains(AqMed(i),'Glacial','IgnoreCase',true) ||
contains(AqMed(i),'Till','IgnoreCase',true)
       AqMedr(i) = 5;
    elseif contains(AqMed(i),'Bed','IgnoreCase',true) &&
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true)|| contains(AqMed(i),'SH','IgnoreCase',true)||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
       AqMedr(i) = 6;
    elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Sandstone','IgnoreCase',true) ||
contains(AqMed(i),'SS','IgnoreCase',true)
       AqMedr(i) = 6;
    elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
       AqMedr(i) = 6;
```

```
    elseif contains(AqMed(i),'Sand','IgnoreCase',true) ||
contains(AqMed(i),'Gravel','IgnoreCase',true) ||
contains(AqMed(i),'GVL','IgnoreCase',true)
      AqMedr(i) = 8;
    elseif contains(AqMed(i),'Basalt','IgnoreCase',true)
      AqMedr(i) = 9;
    elseif  contains(AqMed(i),'Karst','IgnoreCase',true)
      AqMedr(i) = 10;
    else
      AqMedr(i) = 0;
      fprintf('Error at Row %0.0f. Aquifer media values must be strings matching the
naming convention of the 1987 EPA paper. ', i)
    end

    %SOIL MEDIA An ifelse table - based on type of soil media. Expert opinion can be
used to override distinct unit values in the final GWPP table.
    if contains(SoilMed(i),'Thin','IgnoreCase',true) ||
contains(SoilMed(i),'Absent','IgnoreCase',true)
      SoilMedr(i) = 10;
    elseif contains(SoilMed(i),'Gravel','IgnoreCase',true) ||
contains(SoilMed(i),'Gravel','IgnoreCase',true)
      SoilMedr(i) = 10;
    elseif contains(SoilMed(i),'Sand','IgnoreCase',true) ||
contains(SoilMed(i),'SD','IgnoreCase',true)
      SoilMedr(i) = 9;
    elseif contains(SoilMed(i),'Peat','IgnoreCase',true)
      SoilMedr(i) = 8;
    elseif contains(SoilMed(i),'Clay','IgnoreCase',true) &&
contains(SoilMed(i),'Shrinking','IgnoreCase',true) ||
contains(SoilMed(i),'Aggregate','IgnoreCase',true) ||
contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 7;
    elseif contains(SoilMed(i),'Sandy Loam','IgnoreCase',true) ||
contains(SoilMed(i),'SD','IgnoreCase',true)
      SoilMedr(i) = 6;
    elseif contains(SoilMed(i),'Loam','IgnoreCase',true)
      SoilMedr(i) = 5;
    elseif contains(SoilMed(i),'Silty Loam','IgnoreCase',true) ||
contains(SoilMed(i),'SL','IgnoreCase',true)
      SoilMedr(i) = 4;
    elseif contains(SoilMed(i),'Clay Loam','IgnoreCase',true) ||
contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 3;
    elseif contains(SoilMed(i),'Muck','IgnoreCase',true)
```

```
      SoilMedr(i) = 2;
    elseif contains(SoilMed(i),'Nonshrinking','IgnoreCase',true) &&
contains(SoilMed(i),'Nonaggregated','IgnoreCase',true) &&
contains(SoilMed(i),'Clay','IgnoreCase',true) || contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 1;
    else
      SoilMedr(i) = 0;
      fprintf('Error at Row %0.0f. Soil media values must be strings matching the
naming conventions of the 1987 EPA paper. ', i)
    end

    % TOPOGRAPHY ifelse Ranges in % slope identify rating
    if (Topog(i) >= 0 && Topog(i) <= 2)
      Topogr(i) = 10;
    elseif (Topog(i) > 2 && Topog(i) <= 6)
      Topogr(i) = 9;
    elseif (Topog(i) > 6 && Topog(i) <= 12)
      Topogr(i) = 5;
    elseif (Topog(i) > 12 && Topog(i) <= 18)
      Topogr(i) = 3;
    elseif Topog(i) > 18
      Topogr(i) = 1;
    else
      Topogr(i) = 0;
      fprintf('Error at Row %0.0f. Slope cannot be negative. ', i)
    end

    %IMPACT OF VADOSE ZONE An ifelse table - based on Type of Material;
typical ratings used. Expert opinion can be used to override distinct unit values in the
final GWPP table.
    if contains(ImpV(i),'Confin','IgnoreCase',true) &&
contains(ImpV(i),'Layer','IgnoreCase',true)
      ImpVr(i) = 1;
    elseif contains(ImpV(i),'Silt','IgnoreCase',true) ||
contains(ImpV(i),'Clay','IgnoreCase',true) || contains(ImpV(i),'CL','IgnoreCase',true)  ||
contains(ImpV(i),'SL','IgnoreCase',true) || contains(ImpV(i),'Till','IgnoreCase',true)
      ImpVr(i) = 3; %Range is 2 - 6
    elseif contains(ImpV(i),'Shale','IgnoreCase',true)  ||
contains(ImpV(i),'SH','IgnoreCase',true)
      ImpVr(i) = 3; %Range is 2 - 5
    elseif contains(ImpV(i),'Limestone','IgnoreCase',true)  ||
contains(ImpV(i),'LST','IgnoreCase',true)  || contains(ImpV(i),'LS','IgnoreCase',true)
      ImpVr(i) = 6; %Range is 2 - 7
```

```
        elseif contains(ImpV(i),'Sandstone','IgnoreCase',true)  ||
contains(ImpV(i),'SS','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 4 - 8
        elseif contains(ImpV(i),'Bed','IgnoreCase',true)  ||
contains(ImpV(i),'INT','IgnoreCase',true) &&
contains(ImpV(i),'Limestone','IgnoreCase',true) ||
contains(ImpV(i),'Sandstone','IgnoreCase',true) ||
contains(ImpV(i),'Shale','IgnoreCase',true)  || contains(ImpV(i),'LS','IgnoreCase',true)  ||
contains(ImpV(i),'LST','IgnoreCase',true)  || contains(ImpV(i),'SH','IgnoreCase',true)  ||
contains(ImpV(i),'SS','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 4 - 8
        elseif contains(ImpV(i),'Sand','IgnoreCase',true)  ||
contains(ImpV(i),'SD','IgnoreCase',true) && contains(ImpV(i),'Gravel','IgnoreCase',true)
|| contains(ImpV(i),'GVL','IgnoreCase',true) &&
contains(ImpV(i),'significant','IgnoreCase',true) || contains(ImpV(i),'w/','IgnoreCase',true)
|| contains(ImpV(i),'Silt','IgnoreCase',true) || contains(ImpV(i),'Clay','IgnoreCase',true)  ||
contains(ImpV(i),'CL','IgnoreCase',true)  || contains(ImpV(i),'SL','IgnoreCase',true) ||
contains(ImpV(i),'Till','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 4 - 8
        elseif contains(ImpV(i),'Metamorphic','IgnoreCase',true) ||
contains(ImpV(i),'Igneous','IgnoreCase',true) || contains(ImpV(i),'Till','IgnoreCase',true)
            ImpVr(i) = 4; %Range is 2 - 8
        elseif contains(ImpV(i),'Sand','IgnoreCase',true) &&
contains(ImpV(i),'Gravel','IgnoreCase',true)  || contains(ImpV(i),'SD','IgnoreCase',true)  ||
contains(ImpV(i),'GVL','IgnoreCase',true)
            ImpVr(i) = 8; %Range is 6 - 9
        elseif contains(ImpV(i),'Basalt','IgnoreCase',true)
            ImpVr(i) = 9; %Range is 2 - 10
        elseif  contains(ImpV(i),'Karst','IgnoreCase',true)
            ImpVr(i) = 10; %Range is 8 - 10
        else
            ImpVr(i)  = 0;
            fprintf('Error at Row %0.0f. Impact of Vadose Zone values must be strings
including the naming conventions of the 1987 EPA paper. ', i)
        end

        % HYDRAULIC CONDUCTIVITY
        if (CondHy(i) >= 1 && CondHy(i) <= 100)%  ifelse Ranges in ft/day identify rating
            CondHyr(i) = 1;
        elseif (CondHy(i) > 100 && CondHy(i) <= 300)
            CondHyr(i) = 2;
        elseif (CondHy(i) > 300 && CondHy(i) <= 700)
            CondHyr(i) = 4;
        elseif (CondHy(i) > 700 && CondHy(i) <= 1000)
```

```
      CondHyr(i) = 6;
    elseif (CondHy(i) > 1000 && CondHy(i) <= 2000)
      CondHyr(i) = 8;
    elseif CondHy(i) > 2000
      CondHyr(i) = 10;
    else
      CondHyr(i) = 0;
      fprintf('Error at Row %0.0f. Hydraulic Conductivity cannot be negative.\n', i)
    end

    %% Final Identification of GWPP for each distinct unit
    fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
    GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
    GWPPTBL(i,3) =
Der(i)*Dew+ReNetr(i)*ReNetw+AqMedr(i)*AqMedw+SoilMedr(i)*SoilMedw+Topogr(
i)*Topogw+ImpVr(i)*ImpVw+CondHyr(i)*CondHyw; %Total GWPP Value
    GWPPTBL(i,4) = Der(i);
    GWPPTBL(i,5) = Der(i)*Dew;
    GWPPTBL(i,6) = ReNetr(i);
    GWPPTBL(i,7) = ReNetr(i)*ReNetw;
    GWPPTBL(i,8) = AqMedr(i);
    GWPPTBL(i,9) = AqMedr(i)*AqMedw;
    GWPPTBL(i,10) = SoilMedr(i);
    GWPPTBL(i,11) = SoilMedr(i)*SoilMedw;
    GWPPTBL(i,12) = Topogr(i);
    GWPPTBL(i,13) = Topogr(i)*Topogw;
    GWPPTBL(i,14) = ImpVr(i);
    GWPPTBL(i,15) = ImpVr(i)*ImpVw;
    GWPPTBL(i,16) = CondHyr(i);
    GWPPTBL(i,17) = CondHyr(i)*CondHyw;
    fprintf('\nObjectID/Distinct Unit %0.0f entered to output table\n\n',i)
  end
end
```

KARSTIC Function

```
function [GWPPTBL] = bKARSTIC(assess, Ka, AqMed, ReNet, SoilMed, Topog, ImpV,
CondHy, FracGeo, D)
% Reference 1: Davis, A., Long, A., & Wireman, M. (2002). KARSTIC: A sensitivity
method for carbonate aquifers in karst terrain. Environmental Geology, 42(1), 65-72.
% Reference 2: Davis, A., Long, A., Nazir, M., & Xiaodan, T. (1994). Ground-Water
Vulnerability in the Rapid Creek Basin above Rapid City, South Dakota. 1-69. Rapid
City: US EPA.
%
```

```
%Parameter weight = importance of model factor compared to others from least
significant = 1 to most significant = 5.
% Kaw = 5; Karst Sinkholes with surface recharge avg. weight
% Aw = 3; Aquifer Media avg. weight
% Rw = 4; Net Recharge avg. weight
% Sw = 2; Soil Media avg. weight
% Tw = 1; Topology avg. weight
% Iw = 4; Impact of the vadose zone avg. weight
% Cw = 3; Hydraulic Conductivity avg. weight
% FracGeow = 2; Fractures and Geologic Structure
% Dw = 5; Depth to Water
%
%Parameter Range = the breakdown of significance for each factor - uses the tables in
the model book.
%
% Parameter Rating = relevant importance of each factor's range with respect to the other
factors from low = 1 to high = 10.
% Ground Water Pollution Potential (GWPP) Variables and Standard Weights
% Kar: Karst Sinkholes with surface recharge rating
% Ar: Aquifer Media rating
% Rr: Net Recharge rating
% Sr: Soil Media rating
% Tr: Topology rating
% Ir: Impact of the vadose zone rating
% Cr: Hydraulic Conductivity rating
% FracGeor: Fractures and Geologic Structure
% Dr: Depth to Water Rating

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),17);
Kar = NaN(length(assess),1);
AqMedr = NaN(length(assess),1);
ReNetr = NaN(length(assess),1);
SoilMedr = NaN(length(assess),1);
Topogr = NaN(length(assess),1);
ImpVr = NaN(length(assess),1);
CondHyr = NaN(length(assess),1);
FracGeor = NaN(length(assess),1);
Dr = NaN(length(assess),1);

%% Identifying Ratings of each parameter
for i = 1:length(assess)
   GWPPTBL(i,1) = i; % Initializing OBJECTID field
   if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
```

```
        GWPPTBL(i,2:end) = 0;
    else     %for cases where data exists and Hydrogeologic Setting = NR
        %% Assumed Weights of each parameter
        Kaw = 5;
        AqMedw = 3;
        ReNetw = 4;
        SoilMedw = 2;
        Topogw = 1;
        ImpVw = 5;
        CondHyw = 3;
        FracGeow = 2;
        Dw = 5;

        % Karst Sinkholes with surface recharge
        if  Ka(i) == 1 % contains(Ka(i),'Major','IgnoreCase',true) ||
            Kar(i) = 10;
%           elseif  contains(Ka(i),'Minor','IgnoreCase',true)
%               Kar(i) = 5;
        elseif Ka(i) == 0 % contains(Ka(i),'No Visible','IgnoreCase',true) ||
            Kar(i) = 1;
        else
            Kar(i) = 0;
            fprintf('Error at Row %0.0f. Sinkhole Value cannot be negative. ', i)
        end

        % Fractures and Geologic Structure
        if contains(FracGeo(i),'Major','IgnoreCase',true) ||
contains(FracGeo(i),'Limestone','IgnoreCase',true) ||
contains(FracGeo(i),'permeable','IgnoreCase',true)
            FracGeor(i) = 5;
        elseif  contains(FracGeo(i),'Minor','IgnoreCase',true) || contains(FracGeo(i),'lenses
of sand and gravel','IgnoreCase',true) || contains(FracGeo(i),'till','IgnoreCase',true)
            FracGeor(i) = 3;
        elseif contains(FracGeo(i),'No Significant','IgnoreCase',true) ||
contains(FracGeo(i),'im','IgnoreCase',true) || contains(FracGeo(i),'Clay','IgnoreCase',true)
|| contains(FracGeo(i),'meager','IgnoreCase',true) ||
contains(FracGeo(i),'minimal','IgnoreCase',true) ||
contains(FracGeo(i),'Sandstone','IgnoreCase',true)
            FracGeor(i) = 1;
        else
            FracGeor(i) = 0;
            fprintf('Error at Row %0.0f. Fractures and Geologic Structure cannot be negative.
', i)
        end
```

```
        % AQUIFER MEDIA - An ifelse table - based on Type of Material; a range of
ratings or typical
        % rating may be used. Expert opinion can be used to override distinct unit values in
the final GWPP table.
        if contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true) || contains(AqMed(i),'SH','IgnoreCase',true)
            AqMedr(i) = 2;
        elseif contains(AqMed(i),'Metamorphic/Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true) ||
contains(AqMed(i),'Igneous','IgnoreCase',true)
            AqMedr(i) = 3;
        elseif contains(AqMed(i),'Weathered','IgnoreCase',true) &&
contains(AqMed(i),'Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true)
            AqMedr(i) = 4;
        elseif contains(AqMed(i),'Glacial','IgnoreCase',true) ||
contains(AqMed(i),'Till','IgnoreCase',true)
            AqMedr(i) = 5;
        elseif contains(AqMed(i),'Bed','IgnoreCase',true) &&
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true)|| contains(AqMed(i),'SH','IgnoreCase',true)||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
            AqMedr(i) = 6;
        elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Sandstone','IgnoreCase',true) ||
contains(AqMed(i),'SS','IgnoreCase',true)
            AqMedr(i) = 6;
        elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
            AqMedr(i) = 6;
        elseif contains(AqMed(i),'Sand','IgnoreCase',true) ||
contains(AqMed(i),'Gravel','IgnoreCase',true) ||
contains(AqMed(i),'GVL','IgnoreCase',true)
            AqMedr(i) = 8;
        elseif contains(AqMed(i),'Basalt','IgnoreCase',true)
            AqMedr(i) = 9;
        elseif  contains(AqMed(i),'Karst','IgnoreCase',true)
            AqMedr(i) = 10;
        else
            AqMedr(i) = 0;
            fprintf('Error at Row %0.0f. Aquifer media values must be strings matching the
naming convention Davis paper. ', i)
```

```
    end

    % NET RECHARGE - ifelse Ranges in in/yr identify ratings
    if (ReNet(i) >= 0 && ReNet(i) <= 2)
      ReNetr(i) = 1;
    elseif (ReNet(i) > 2 && ReNet(i) <= 4)
      ReNetr(i) = 3;
    elseif (ReNet(i) > 4 && ReNet(i) <= 7)
      ReNetr(i) = 6;
    elseif (ReNet(i) > 7 && ReNet(i) <= 10)
      ReNetr(i) = 8;
    elseif ReNet(i) > 10
      ReNetr(i) = 9;
    else
      ReNetr(i) = 0;
      fprintf('Error at Row %0.0f. Net Recharge cannot be negative. ', i)
    end

    %SOIL MEDIA An ifelse table - based on type of soil media. Expert opinion can be
used to override distinct unit values in the final GWPP table.
    if contains(SoilMed(i),'Thin','IgnoreCase',true) ||
contains(SoilMed(i),'Absent','IgnoreCase',true)
      SoilMedr(i) = 10;
    elseif contains(SoilMed(i),'Gravel','IgnoreCase',true) ||
contains(SoilMed(i),'Gravel','IgnoreCase',true)
      SoilMedr(i) = 10;
    elseif contains(SoilMed(i),'Sand','IgnoreCase',true) ||
contains(SoilMed(i),'SD','IgnoreCase',true)
      SoilMedr(i) = 9;
    elseif contains(SoilMed(i),'Peat','IgnoreCase',true)
      SoilMedr(i) = 8;
    elseif contains(SoilMed(i),'Clay','IgnoreCase',true) &&
contains(SoilMed(i),'Shrinking','IgnoreCase',true) ||
contains(SoilMed(i),'Aggregate','IgnoreCase',true) ||
contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 7;
    elseif contains(SoilMed(i),'Sandy Loam','IgnoreCase',true) ||
contains(SoilMed(i),'SD','IgnoreCase',true)
      SoilMedr(i) = 6;
    elseif contains(SoilMed(i),'Loam','IgnoreCase',true)
      SoilMedr(i) = 5;
    elseif contains(SoilMed(i),'Silty Loam','IgnoreCase',true) ||
contains(SoilMed(i),'SL','IgnoreCase',true)
      SoilMedr(i) = 4;
```

```
    elseif contains(SoilMed(i),'Clay Loam','IgnoreCase',true) ||
contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 3;
    elseif contains(SoilMed(i),'Muck','IgnoreCase',true)
      SoilMedr(i) = 2;
    elseif contains(SoilMed(i),'Nonshrinking','IgnoreCase',true) &&
contains(SoilMed(i),'Nonaggregated','IgnoreCase',true) &&
contains(SoilMed(i),'Clay','IgnoreCase',true) || contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 1;
    else
      SoilMedr(i) = 0;
      fprintf('Error at Row %0.0f. Soil media values must be strings matching the
naming conventions of the Davis paper. ', i)
    end

    % TOPOGRAPHY ifelse Ranges in % slope identify rating
    if (Topog(i) >= 0 && Topog(i) <= 2)
      Topogr(i) = 10;
    elseif (Topog(i) > 2 && Topog(i) <= 6)
      Topogr(i) = 9;
    elseif (Topog(i) > 6 && Topog(i) <= 12)
      Topogr(i) = 5;
    elseif (Topog(i) > 12 && Topog(i) <= 18)
      Topogr(i) = 3;
    elseif Topog(i) > 18
      Topogr(i) = 1;
    else
      Topogr(i) = 0;
      fprintf('Error at Row %0.0f. Slope cannot be negative. ', i)
    end

    %IMPACT OF VADOSE ZONE An ifelse table - based on Type of Material;
typical ratings used. Expert opinion can be used to override distinct unit values in the
final GWPP table.
    if contains(ImpV(i),'Confin','IgnoreCase',true) &&
contains(ImpV(i),'Layer','IgnoreCase',true)
      ImpVr(i) = 1;
    elseif contains(ImpV(i),'Silt','IgnoreCase',true) ||
contains(ImpV(i),'Clay','IgnoreCase',true) || contains(ImpV(i),'CL','IgnoreCase',true)  ||
contains(ImpV(i),'SL','IgnoreCase',true) || contains(ImpV(i),'Till','IgnoreCase',true)
      ImpVr(i) = 3; %Range is 2 - 6
    elseif contains(ImpV(i),'Shale','IgnoreCase',true)  ||
contains(ImpV(i),'SH','IgnoreCase',true)
      ImpVr(i) = 3; %Range is 2 - 5
```

```
        elseif contains(ImpV(i),'Limestone','IgnoreCase',true)  ||
contains(ImpV(i),'LST','IgnoreCase',true)  || contains(ImpV(i),'LS','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 2 - 7
        elseif contains(ImpV(i),'Sandstone','IgnoreCase',true)  ||
contains(ImpV(i),'SS','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 4 - 8
        elseif contains(ImpV(i),'Bed','IgnoreCase',true)  ||
contains(ImpV(i),'INT','IgnoreCase',true) &&
contains(ImpV(i),'Limestone','IgnoreCase',true) ||
contains(ImpV(i),'Sandstone','IgnoreCase',true) ||
contains(ImpV(i),'Shale','IgnoreCase',true)  || contains(ImpV(i),'LS','IgnoreCase',true)  ||
contains(ImpV(i),'LST','IgnoreCase',true)  || contains(ImpV(i),'SH','IgnoreCase',true)  ||
contains(ImpV(i),'SS','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 4 - 8
        elseif contains(ImpV(i),'Sand','IgnoreCase',true)  ||
contains(ImpV(i),'SD','IgnoreCase',true) && contains(ImpV(i),'Gravel','IgnoreCase',true)
|| contains(ImpV(i),'GVL','IgnoreCase',true) &&
contains(ImpV(i),'significant','IgnoreCase',true) || contains(ImpV(i),'w/','IgnoreCase',true)
|| contains(ImpV(i),'Silt','IgnoreCase',true) || contains(ImpV(i),'Clay','IgnoreCase',true)  ||
contains(ImpV(i),'CL','IgnoreCase',true)  || contains(ImpV(i),'SL','IgnoreCase',true) ||
contains(ImpV(i),'Till','IgnoreCase',true)
            ImpVr(i) = 6; %Range is 4 - 8
        elseif contains(ImpV(i),'Metamorphic','IgnoreCase',true) ||
contains(ImpV(i),'Igneous','IgnoreCase',true) || contains(ImpV(i),'Till','IgnoreCase',true)
            ImpVr(i) = 4; %Range is 2 - 8
        elseif contains(ImpV(i),'Sand','IgnoreCase',true) &&
contains(ImpV(i),'Gravel','IgnoreCase',true)  || contains(ImpV(i),'SD','IgnoreCase',true)  ||
contains(ImpV(i),'GVL','IgnoreCase',true)
            ImpVr(i) = 8; %Range is 6 - 9
        elseif contains(ImpV(i),'Basalt','IgnoreCase',true)
            ImpVr(i) = 9; %Range is 2 - 10
        elseif  contains(ImpV(i),'Karst','IgnoreCase',true)
            ImpVr(i) = 10; %Range is 8 - 10
        else
            ImpVr(i)  = 0;
            fprintf('Error at Row %0.0f. Impact of Vadose Zone values must be strings
including the naming conventions of the Davis paper. ', i)
        end

        % HYDRAULIC CONDUCTIVITY
        if (CondHy(i) >= 1 && CondHy(i) <= 100)%  ifelse Ranges in ft/day identify rating
            CondHyr(i) = 1;
        elseif (CondHy(i) > 100 && CondHy(i) <= 300)
            CondHyr(i) = 2;
```

```
    elseif (CondHy(i) > 300 && CondHy(i) <= 700)
      CondHyr(i) = 4;
    elseif (CondHy(i) > 700 && CondHy(i) <= 1000)
      CondHyr(i) = 6;
    elseif (CondHy(i) > 1000 && CondHy(i) <= 2000)
      CondHyr(i) = 8;
    elseif CondHy(i) > 2000
      CondHyr(i) = 10;
    else
      CondHyr(i) = 0;
      fprintf('Error at Row %0.0f. Hydraulic Conductivity cannot be negative.\n', i)
    end

 % Depth to Water
if (D(i) >= 0 && D(i) <= 20)%  ifelse Ranges in ft identify rating
  Dr(i) = 5;
elseif (D(i) > 20 && D(i) <= 50)
  Dr(i) = 3;
elseif (D(i) > 50 && D(i) <= 100)
  Dr(i) = 1.5;
elseif D(i) > 100
  Dr(i) = 0.5;
else
  Dr(i) = 0;
  fprintf('Error at Row %0.0f. Depth To Water cannot be negative.\n', i)
end

    %% Final Identification of GWPP for each distinct unit
    fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
    GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
    GWPPTBL(i,3) = Kar(i)*Kaw+ReNetr(i)*ReNetw+AqMedr(i)*AqMedw+SoilMedr(i)*SoilMedw+Topogr(i)*Topogw+ImpVr(i)*ImpVw+CondHyr(i)*CondHyw+FracGeor(i)*FracGeow+Dr(i)*Dw; %Total GWPP Value
    GWPPTBL(i,4) = Kar(i);
    GWPPTBL(i,5) = Kar(i)*Kaw;
    GWPPTBL(i,6) = ReNetr(i);
    GWPPTBL(i,7) = ReNetr(i)*ReNetw;
    GWPPTBL(i,8) = AqMedr(i);
    GWPPTBL(i,9) = AqMedr(i)*AqMedw;
    GWPPTBL(i,10) = SoilMedr(i);
    GWPPTBL(i,11) = SoilMedr(i)*SoilMedw;
    GWPPTBL(i,12) = Topogr(i);
    GWPPTBL(i,13) = Topogr(i)*Topogw;
```

```
        GWPPTBL(i,14) = ImpVr(i);
        GWPPTBL(i,15) = ImpVr(i)*ImpVw;
        GWPPTBL(i,16) = CondHyr(i);
        GWPPTBL(i,17) = CondHyr(i)*CondHyw;
        GWPPTBL(i,18) = FracGeor(i)*FracGeow;
        GWPPTBL(i,19) = Dr(i)*Dw;
        fprintf('\nObjectID/Distinct Unit %0.0f entered to output table \n',i)
    end
end
```

DRISTPI Function

```
function [GWPPTBL] = cDRISTPI(assess, D,R,I,S,T,PI,KarstPotential)
%The Jimenez-Madrid Model for identifying the groundwater pollution potential for distinct units.
% Functions under two scenarios; one with karst development, one without. To avoid this distinction,
% this simulation will complete the outputs for both scenario 1 and scenario 2 and provide the
% outputs.
%
% Reference: Jimenez-Madrid, A., Carrasco, F., Martinez, C., & Gogu, R. (2013). DRISTPI, a new groundwater vulnerability mapping method for use in karstic and non-karstic aquifers. Quarterly Journal of Engineering Geology and Hydrogeology, 46(2), 245-255.
%
% Parameter weights = importance of model factor compared to others from least significant = 1 to most significant = 5.
% Dwone = 2; Depth of water for high karstic development avg. weight
% Dwtwo = 5; Depth of water for carbonated materials non-karstified and detritic materials avg. weight
% Rw = 4; Net Recharge avg. weight
% Iw = 5; Impact of the vadose zone avg. weight
% Sw = 2; Soil Media avg. weight
% Tw = 1; Topology avg. weight
% PIw = 5; Rapid Preferential Infiltration areas avg. weight

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),20);
Drone = NaN(length(assess),1);
Drtwo = NaN(length(assess),1);
Rr = NaN(length(assess),1);
```

```
Ir = NaN(length(assess),1);
Sr = NaN(length(assess),1);
Tr = NaN(length(assess),1);
PIrone = NaN(length(assess),1);
PIrtwo = NaN(length(assess),1);

%% Identifying Ratings of each parameter
for i = 1:length(assess)
    GWPPTBL(i,1) = i; % Initializing OBJECTID field
    if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
        GWPPTBL(i,2:end) = 0;
    else     %for cases where data exists and Hydrogeologic Setting = NR
        %% Assumed Weights of each parameter from Jimenez-Madrid et (2013)
        Rw = 4;
        Iw = 5;
        Sw = 2;
        Tw = 1;
        PIw = 5;

        if KarstPotential >= 15 %Within an expected highly karstic region "quantity of
Carbonate (CO3) in the soil expressed as CaCO3 and as a weight percentage of the less
than 2 mm size fraction."  according to SSURGO
            Dwone = 2;
             Dwtwo = 0; % Initializing cases where one situation exists and the other does
not.
            % DEPTH TO WATER for scenario one
            D(i) = D(i)*0.3048; %Converting from Depth to Water in feet to Depth to Water
in Meters
            if (D(i) >= 0 && D(i) <= 5)
                Drone(i) = 10;
            elseif (D(i) > 5 && D(i) <= 15)
                Drone(i) = 9;
            elseif (D(i) > 15 && D(i) <= 30)
                Drone(i) = 7;
            elseif (D(i) > 30 && D(i) <= 50)
                Drone(i) = 5;
            elseif (D(i) > 50 && D(i) <= 75)
                Drone(i) = 3;
            elseif (D(i) > 75 && D(i) <= 100)
                Drone(i) = 2;
            elseif (D(i) > 100)
                Drone(i) = 1;
            else
                Drone(i) = 0;
```

```
          fprintf('Error at Row %0.0f. Depth to Water for scenario 1 cannot be negative.
', i)
        end

        %Preferential Infiltration - Scenario 1
        if contains(PI(i),'Karstic','IgnoreCase',true) &&
contains(PI(i),'Swallow','IgnoreCase',true) || contains(PI(i),'Principal aquifer ist he
limestone bedrock','IgnoreCase',true) || contains(PI(i),'Wells cased through upper zones of
Shale and limestone seal off','IgnoreCase',true) || contains(PI(i),'Permeable layers of sand
and gravel deposited in buried valleys adjacent to','IgnoreCase',true)
          PIrone(i) = 10;
        elseif contains(PI(i),'Karstic','IgnoreCase',true) &&
contains(PI(i),'River','IgnoreCase',true)
          PIrone(i) = 10;
        elseif contains(PI(i),'Karstic','IgnoreCase',true) &&
contains(PI(i),'Artificial','IgnoreCase',true) && contains(PI(i),'Quarry','IgnoreCase',true)
          PIrone(i) = 9;
        elseif contains(PI(i),'Karstic','IgnoreCase',true) &&
contains(PI(i),'Canyon','IgnoreCase',true) || contains(PI(i),'Gorge','IgnoreCase',true) ||
contains(PI(i),'Narrow','IgnoreCase',true) || contains(PI(i),'Pass','IgnoreCase',true) ||
contains(PI(i),'Sand and gravel lenses interbedded in clay capable of higher
yield','IgnoreCase',true)
          PIrone(i) = 7;
        elseif contains(PI(i),'Not Karstic','IgnoreCase',true) && contains(PI(i),'Swallow
hole','IgnoreCase',true) || contains(PI(i),'recharge area','IgnoreCase',true)
          PIrone(i) = 10;
        elseif contains(PI(i),'Not Karstic','IgnoreCase',true) &&
contains(PI(i),'High','IgnoreCase',true) || contains(PI(i),'fissure zone','IgnoreCase',true) ||
contains(PI(i),'moraine','IgnoreCase',true) || contains(PI(i),'Principal aquifer is a
sandstone unit','IgnoreCase',true)
          PIrone(i) = 6;
        elseif contains(PI(i),'Not Karstic','IgnoreCase',true) &&
contains(PI(i),'Low','IgnoreCase',true) || contains(PI(i),'fissure zone','IgnoreCase',true) ||
contains(PI(i),'sandy Shale bedrock','IgnoreCase',true)
          PIrone(i) = 3;
        elseif contains(PI(i),'Not Karstic','IgnoreCase',true) ||
contains(PI(i),'impermeable','IgnoreCase',true) ||
contains(PI(i),'minimal','IgnoreCase',true) %anything else in the nonkarstic area
          PIrone(i) = 1;
        else
          PIrone(i) = 0;
          fprintf('Error at Row %0.0f. Scenario 1 Preferential Infiltration values must be
strings matching the naming conventions of the DRISTPI paper. ', i)
        end
```

```
        else % Scenario 2 - Carbonated Materials non-karstfied and detritic materials

            Dwtwo = 5;
            Dwone = 0; % Initializing cases where one situation exists and the other does not.
            % DEPTH TO WATER for scenario two
            if (D(i) >= 0 && D(i) <= 1.5)
                Drtwo(i) = 10;
            elseif (D(i) > 1.5 && D(i) <= 5)
                Drtwo(i) = 9;
            elseif (D(i) > 5 && D(i) <= 10)
                Drtwo(i) = 7;
            elseif (D(i) > 10 && D(i) <= 16.6)
                Drtwo(i) = 5;
            elseif (D(i) > 16.6 && D(i) <= 25)
                Drtwo(i) = 3;
            elseif (D(i) > 25 && D(i) <= 33.3)
                Drtwo(i) = 2;
            elseif (D(i) > 33.3)
                Drtwo(i) = 1;
            else
                Drtwo(i) = 0;
                fprintf('Error at Row %0.0f. Depth to Water for scenario 1 cannot be negative.
', i)
            end

            %Preferential Infiltration - Scenario 2
            if contains(PI(i),'Swallow','IgnoreCase',true) ||
contains(PI(i),'Hole','IgnoreCase',true) && contains(PI(i),'Recharge','IgnoreCase',true) ||
contains(PI(i),'Area','IgnoreCase',true)
                PIrtwo(i) = 10;
            elseif contains(PI(i),'River','IgnoreCase',true) ||
contains(PI(i),'Lake','IgnoreCase',true)
                PIrtwo(i) = 10;
            elseif contains(PI(i),'Artifical','IgnoreCase',true) &&
contains(PI(i),'Quarry','IgnoreCase',true)
                PIrtwo(i) = 7;
            elseif contains(PI(i),'Lagoon','IgnoreCase',true)
                PIrtwo(i) = 5;
            elseif contains(PI(i),'Not','IgnoreCase',true) &&
contains(PI(i),'Infiltration','IgnoreCase',true) || contains(PI(i),'Zone','IgnoreCase',true)
                PIrtwo(i) = 1;
            else
                PIrtwo(i) = 0;
```

```
        fprintf('Error at Row %0.0f. Scenario 2 Preferential Infiltration  values must be
strings matching the naming conventions of the DRISTPI paper. ', i)
      end
    end

    % NET RECHARGE - ifelse Ranges in feet identify ratings (mm/year)
    R(i) = R(i)*25.4; %Converting from inches/yr to mm/yr
    if (R(i) >= 0 && R(i) <= 20)
      Rr(i) = 1;
    elseif (R(i) > 20 && R(i) <= 50)
      Rr(i) = 2;
    elseif (R(i) > 50 && R(i) <= 100)
      Rr(i) = 4;
    elseif (R(i) > 100 && R(i) <= 150)
      Rr(i) = 6;
    elseif (R(i) > 150 && R(i) <= 200)
      Rr(i) = 7;
    elseif (R(i) > 200 && R(i) <= 250)
      Rr(i) = 8;
    elseif (R(i) > 250 && R(i) <= 300)
      Rr(i) = 9;
    elseif R(i) > 300
      Rr(i) = 10;
    else
      Rr(i) = 0;
      fprintf('Error at Row %0.0f. Net Recharge cannot be negative. ', i)
    end

    %IMPACT OF VADOSE ZONE - identical to DRASTIC
    if contains(I(i),'Confin','IgnoreCase',true) && contains(I(i),'Layer','IgnoreCase',true)
      Ir(i) = 1;
    elseif contains(I(i),'Silt','IgnoreCase',true) || contains(I(i),'Clay','IgnoreCase',true) ||
contains(I(i),'CL','IgnoreCase',true)  || contains(I(i),'SL','IgnoreCase',true) ||
contains(I(i),'Till','IgnoreCase',true)
      Ir(i) = 3; %Range is 2 - 6
    elseif contains(I(i),'Shale','IgnoreCase',true)  || contains(I(i),'SH','IgnoreCase',true)
      Ir(i) = 3; %Range is 2 - 5
    elseif contains(I(i),'Limestone','IgnoreCase',true)  ||
contains(I(i),'LST','IgnoreCase',true)  || contains(I(i),'LS','IgnoreCase',true)
      Ir(i) = 6; %Range is 2 - 7
    elseif contains(I(i),'Sandstone','IgnoreCase',true)  ||
contains(I(i),'SS','IgnoreCase',true)
      Ir(i) = 6; %Range is 4 - 8
```

```
    elseif contains(I(i),'Bed','IgnoreCase',true)  || contains(I(i),'INT','IgnoreCase',true)
&& contains(I(i),'Limestone','IgnoreCase',true) ||
contains(I(i),'Sandstone','IgnoreCase',true) || contains(I(i),'Shale','IgnoreCase',true)  ||
contains(I(i),'LS','IgnoreCase',true)  || contains(I(i),'LST','IgnoreCase',true)  ||
contains(I(i),'SH','IgnoreCase',true)  || contains(I(i),'SS','IgnoreCase',true)
       Ir(i) = 6; %Range is 4 - 8
    elseif contains(I(i),'Sand','IgnoreCase',true)  || contains(I(i),'SD','IgnoreCase',true)
&& contains(I(i),'Gravel','IgnoreCase',true)  || contains(I(i),'GVL','IgnoreCase',true) &&
contains(I(i),'significant','IgnoreCase',true) || contains(I(i),'w/','IgnoreCase',true) ||
contains(I(i),'Silt','IgnoreCase',true) || contains(I(i),'Clay','IgnoreCase',true)  ||
contains(I(i),'CL','IgnoreCase',true)  || contains(I(i),'SL','IgnoreCase',true) ||
contains(I(i),'Till','IgnoreCase',true)
       Ir(i) = 6; %Range is 4 - 8
    elseif contains(I(i),'Metamorphic','IgnoreCase',true) ||
contains(I(i),'Igneous','IgnoreCase',true) || contains(I(i),'Till','IgnoreCase',true)
       Ir(i) = 4; %Range is 2 - 8
    elseif contains(I(i),'Sand','IgnoreCase',true) &&
contains(I(i),'Gravel','IgnoreCase',true)  || contains(I(i),'SD','IgnoreCase',true)  ||
contains(I(i),'GVL','IgnoreCase',true)
       Ir(i) = 8; %Range is 6 - 9
    elseif contains(I(i),'Basalt','IgnoreCase',true)
       Ir(i) = 9; %Range is 2 - 10
    elseif  contains(I(i),'Karst','IgnoreCase',true)
       Ir(i) = 10; %Range is 8 - 10
    else
       Ir(i)  = 0;
       fprintf('Error at Row %0.0f. Impact of Vadose Zone values must be strings
including the naming conventions of the DRISTPI paper. ', i)
    end

    %SOIL MEDIA - identical to DRASTIC
    if contains(S(i),'Thin','IgnoreCase',true) || contains(S(i),'Absent','IgnoreCase',true)
       Sr(i) = 10;
    elseif contains(S(i),'Gravel','IgnoreCase',true) ||
contains(S(i),'Gravel','IgnoreCase',true)
       Sr(i) = 10;
    elseif contains(S(i),'Sand','IgnoreCase',true) || contains(S(i),'SD','IgnoreCase',true)
       Sr(i) = 9;
    elseif contains(S(i),'Peat','IgnoreCase',true)
       Sr(i) = 8;
    elseif contains(S(i),'Clay','IgnoreCase',true) &&
contains(S(i),'Shrinking','IgnoreCase',true) || contains(S(i),'Aggregate','IgnoreCase',true) ||
contains(S(i),'CL','IgnoreCase',true)
       Sr(i) = 7;
```

```
        elseif contains(S(i),'Sandy Loam','IgnoreCase',true) ||
contains(S(i),'SD','IgnoreCase',true)
            Sr(i) = 6;
        elseif contains(S(i),'Loam','IgnoreCase',true)
            Sr(i) = 5;
        elseif contains(S(i),'Silty Loam','IgnoreCase',true) ||
contains(S(i),'SL','IgnoreCase',true)
            Sr(i) = 4;
        elseif contains(S(i),'Clay Loam','IgnoreCase',true) ||
contains(S(i),'CL','IgnoreCase',true)
            Sr(i) = 3;
        elseif contains(S(i),'Muck','IgnoreCase',true)
            Sr(i) = 2;
        elseif contains(S(i),'Nonshrinking','IgnoreCase',true) &&
contains(S(i),'Nonaggregated','IgnoreCase',true) &&
contains(S(i),'Clay','IgnoreCase',true) || contains(S(i),'CL','IgnoreCase',true)
            Sr(i) = 1;
        else
            Sr(i) = 0;
            fprintf('Error at Row %0.0f. Soil media values must be strings matching the
naming conventions of the DRISTPI paper. ', i)
        end

        % TOPOGRAPHY  - identical to DRASTIC
        if (T(i) >= 0 && T(i) <= 2)
            Tr(i) = 10;
        elseif (T(i) > 2 && T(i) <= 6)
            Tr(i) = 9;
        elseif (T(i) > 6 && T(i) <= 12)
            Tr(i) = 5;
        elseif (T(i) > 12 && T(i) <= 18)
            Tr(i) = 3;
        elseif T(i) > 18
            Tr(i) = 1;
        else
            Tr(i) = 0;
            fprintf('Error at Row %0.0f. Slope cannot be negative. ', i)
        end

        %% Final Identification of GWPP for each distinct unit
        fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
        GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
        GWPPTBL(i,3) = Drone(i)*Dwone + Rr(i)*Rw + Ir(i)*Iw+Sr(i)*Sw + Tr(i)*Tw +
PIrone(i)*PIw; %Total GWPP Value for scenario 1
```

```
        GWPPTBL(i,4) = Drtwo(i)*Dwtwo + Rr(i)*Rw + Ir(i)*Iw+Sr(i)*Sw + Tr(i)*Tw + PIrtwo(i)*PIw; %Total GWPP Value for scenario 2
        GWPPTBL(i,5) = Drone(i);
        GWPPTBL(i,6) = Drone(i)*Dwone;
        GWPPTBL(i,7) = Drtwo(i);
        GWPPTBL(i,8) = Drtwo(i)*Dwtwo;
        GWPPTBL(i,9) = Rr(i);
        GWPPTBL(i,10) = Rr(i)*Rw;
        GWPPTBL(i,11) = Ir(i);
        GWPPTBL(i,12) = Ir(i)*Iw;
        GWPPTBL(i,13) = Sr(i);
        GWPPTBL(i,14) = Sr(i)*Sw;
        GWPPTBL(i,15) = Tr(i);
        GWPPTBL(i,16) = Tr(i)*Tw;
        GWPPTBL(i,17) = PIrone(i);
        GWPPTBL(i,18) = PIrone(i)*PIw;
        GWPPTBL(i,19) = PIrtwo(i);
        GWPPTBL(i,20) = PIrtwo(i)*PIw;
        fprintf('\nObjectID/Distinct Unit %0.0f entered to output table\n\n',i)
    end
end
```

SIN-DRASTIC Function

```
function [GWPPTBL] = dSINDRASTIC(assess, SIN,PSink, GWleveldecline, De, ReNet, AqMed, SoilMed, Topog, ImpV, CondHy)
%% YO IMPORTANT QUESTIONS COME FIRST!!!!
%IS THE RANGE FOR TOPOGRAPHY & HYDRAULIC CONDUCTIVITY BACKWARDS?????
% Reference: Taheri, K., Taheri, M., & Mohsenipour, F. (2015). LEPT, A Simplified Approach for Karst Assessing Vulnerability in Regions with Sparse Data; A Case Study From Kermanshah Province, Iran. Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the Fourteenth Multidisciplinary Conference(1968), 483-492.
%
%Parameter weight = importance of model factor compared to others from least significant = 1 to most significant = 5.
% Dw = 5; Depth to water avg. weight
% PSinkw = 3; Sinkhole Catchment Factor avg. weight
% GWleveldeclinew = 4; 'Dynamic Approach Groundwater Level Design'
% Rw = 4; Net Recharge avg. weight
% Aw = 3; Aquifer Media avg. weight
% Sw = 2; Soil Media avg. weight
% Tw = 1; Topology avg. weight
```

```
% Iw = 5; Impact of the vadose zone avg. weight
% Cw = 3; Hydraulic Conductivity avg. weight
%
%Parameter Range = the breakdown of significance for each factor - uses the tables in
the model book.
% Parameter Rating = relevant importance of each factor's range with respect to the other
factors from low = 1 to high = 10.
% Ground Water Pollution Potential (GWPP) Variables and Standard Weights
% SINr = Sinkholes factor rating
% PSinkr = Sinkhole Catchment Factor rating (Which must be generated with
% thiessen polygons and determinations BEFORE running this model.)
% Dr: Depth to water rating
% Rr: Net Recharge rating
% Ar: Aquifer Media rating
% Sr: Soil Media rating
% Tr: Topology rating
% Ir: Impact of the vadose zone rating
% Cr: Hydraulic Conductivity rating

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),23);
SINr = NaN(length(assess),1);
PSinkr = NaN(length(assess),1);
GWleveldecliner = NaN(length(assess),1);
Der = NaN(length(assess),1);
ReNetr = NaN(length(assess),1);
AqMedr = NaN(length(assess),1);
SoilMedr = NaN(length(assess),1);
Topogr = NaN(length(assess),1);
ImpVr = NaN(length(assess),1);
CondHyr = NaN(length(assess),1);

% Converting Data from english units to metric
SIN = SIN*0.3048; %Distance from Sinkhole converted from feet to meters
De = De*0.3048; %Depth to Water converted from feet to meters
ReNet = ReNet*25.4; %Net Recharge converted from inches/year to mm/year
CondHy = CondHy*0.3048; %Converted from ft/day to m/day.
GWleveldecline = GWleveldecline*0.3048; %Groundwater Level Decline Value
converted from feet to meters
PSink = PSink*0.3048; %Sinkhole Catchment Factor converted from feet to meters.

% Identifying Ratings of each parameter
for i = 1:length(assess)
   GWPPTBL(i,1) = i; % Initializing OBJECTID field
```

```
if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
   GWPPTBL(i,2:end) = 0;
else     %for cases where data exists and Hydrogeologic Setting = NR
   % Assumed Weights of each parameter
   SINw = 5;
   Dew = 5;
   ReNetw = 4;
   AqMedw = 3;
   SoilMedw = 2;
   Topogw = 1;
   ImpVw = 5;
   CondHyw = 3;
   PSinkw = 3;
   GWleveldeclinew = 4;

   % Distance to Sinkhole - ranges in meters generated by the
   % Arc-Hydro  tool in ArcMAP
   if (SIN(i) >= 0 && SIN(i) <= 500)
      SINr(i) = 10;
   elseif (SIN(i) > 500 && SIN(i) <= 1000)
      SINr(i) = 9;
   elseif (SIN(i) > 1000 && SIN(i) <= 2000)
      SINr(i) = 7;
   elseif (SIN(i) > 2000 && SIN(i) <= 3000)
      SINr(i) = 5;
   elseif (SIN(i) > 3000)
      SINr(i) = 1;
   else
      SINr(i) = 0;
      fprintf('Error at Row %0.0f. Distance to Sinkhole cannot be negative. ', i)
   end

   % PSink, Sinkhole Catchment Factor
   if (PSink(i) >= 0 && PSink(i) <= 11)
      PSinkr(i) = 1;
   elseif (PSink(i) > 11 && PSink(i) <= 27)
      PSinkr(i) = 2;
   elseif (PSink(i) > 27 && PSink(i) <= 46)
      PSinkr(i) = 3;
   elseif (PSink(i) > 46 && PSink(i) <= 77)
      PSinkr(i) = 7;
   elseif (PSink(i) > 77)
      PSinkr(i) = 10;
   else
```

```
   PSinkr(i) = 0;
   fprintf('Error at Row %0.0f. PSink Factor cannot be negative. ', i)
end

% Groundwater Level Decline, Sinkhole Catchment Factor
if (GWleveldecline(i) >= -70 && GWleveldecline(i) <= -50)
   GWleveldecliner(i) = 10;
elseif (GWleveldecline(i) > -50 && GWleveldecline(i) <= -40)
   GWleveldecliner(i) = 7;
elseif (GWleveldecline(i) > -40 && GWleveldecline(i) <= -30)
   GWleveldecliner(i) = 5;
elseif (GWleveldecline(i) > -30 && GWleveldecline(i) <= -20)
   GWleveldecliner(i) = 3;
elseif (GWleveldecline(i) > -20  && GWleveldecline(i) <-0)
   GWleveldecliner(i) = 1;
else
   GWleveldecliner(i) = 0;
end

% DEPTH TO WATER - ifelse Ranges in meters identify ratings
if (De(i) >= 2 && De(i) < 10)
   Der(i) = 10;
elseif (De(i) >= 10 && De(i) < 20)
   Der(i) = 7;
elseif (De(i) >= 20 && De(i) < 40)
   Der(i) = 5;
elseif (De(i) >= 40 && De(i) < 60)
   Der(i) = 3;
elseif (De(i) >= 60)
   Der(i) = 1;
else
   Der(i) = 0;
   fprintf('Error at Row %0.0f. Depth to Water cannot be negative. ', i)
end

% NET RECHARGE - ifelse Ranges in feet identify ratings
%May be simplified using Net Recharge = Mean Annual Precipitation *
%Percent of Recharge.
if (ReNet(i) >= 0 && ReNet(i) < 28)
   ReNetr(i) = 1;
elseif (ReNet(i) >= 28 && ReNet(i) < 30)
   ReNetr(i) = 3;
elseif (ReNet(i) >= 30 && ReNet(i) < 32)
   ReNetr(i) = 5;
```

```
    elseif (ReNet(i) >= 32 && ReNet(i) < 35)
      ReNetr(i) = 6;
    elseif (ReNet(i) >= 35 && ReNet(i) < 37)
      ReNetr(i) = 8;
    elseif ReNet(i) >= 37
      ReNetr(i) = 10;
    else
      ReNetr(i) = 0;
      fprintf('Error at Row %0.0f. Net Recharge cannot be negative. ', i)
    end

    % AQUIFER MEDIA - An ifelse table - based on Type of Material; a range of
ratings or typical
    % rating may be used. Expert opinion can be used to override distinct unit values in
the final GWPP table.
    if contains(AqMed(i),'Gravel','IgnoreCase',true)
      AqMedr(i) = 10;
    elseif contains(AqMed(i),'Gravel','IgnoreCase',true) &&
contains(AqMed(i),'Sand','IgnoreCase',true)
      AqMedr(i) = 7;
    elseif contains(AqMed(i),'Sand','IgnoreCase',true)
      AqMedr(i) = 5;
    elseif contains(AqMed(i),'Sand','IgnoreCase',true) &&
contains(AqMed(i),'Clay','IgnoreCase',true)
      AqMedr(i) = 3;
    elseif  contains(AqMed(i),'Silt','IgnoreCase',true) &&
contains(AqMed(i),'Clay','IgnoreCase',true)
      AqMedr(i) = 1;
    else
      AqMedr(i) = 0;
      fprintf('Error at Row %0.0f. Aquifer media values must be strings matching the
naming convention of the 2017 Taheri, Taheri, and Komail paper. ', i)
    end

    %SOIL MEDIA An ifelse table - based on type of soil media. Expert opinion can be
used to override distinct unit values in the final GWPP table.
    if contains(SoilMed(i),'Inceptisol','IgnoreCase',true)
      SoilMedr(i) = 7;
    elseif contains(SoilMed(i),'Aridisol','IgnoreCase',true)
      SoilMedr(i) = 3;
    elseif contains(SoilMed(i),'Rock','IgnoreCase',true) ||
contains(SoilMed(i),'Outcrop','IgnoreCase',true)  &&
contains(SoilMed(i),'Entisol','IgnoreCase',true)  ||
contains(SoilMed(i),'Inceptisol','IgnoreCase',true)
```

```
           SoilMedr(i) = 1;
        else
           SoilMedr(i) = 0;
           fprintf('Error at Row %0.0f. Soil media values must be strings matching the
naming conventions of the 2017 Taheri, Taheri, and Komail paper. ', i)
        end

        % TOPOGRAPHY ifelse Ranges in % slope identify rating
        if (Topog(i) >= 0 && Topog(i) < 3)
           Topogr(i) = 1;
        elseif (Topog(i) >= 3 && Topog(i) < 7)
           Topogr(i) = 3;
        elseif (Topog(i) >= 7 && Topog(i) < 12)
           Topogr(i) = 5;
        elseif (Topog(i) >= 12 && Topog(i) < 20)
           Topogr(i) = 7;
        elseif Topog(i) >= 20
           Topogr(i) = 10;
        else
           Topogr(i) = 0;
           fprintf('Error at Row %0.0f. Slope cannot be negative. ', i)
        end

        %IMPACT OF VADOSE ZONE An ifelse table - based on Type of Material;
typical ratings used. Expert opinion can be used to override distinct unit values in the
final GWPP table.
        if contains(ImpV(i),'Gravel','IgnoreCase',true) &&
contains(ImpV(i),'Sand','IgnoreCase',true)
           ImpVr(i) = 9;
        elseif contains(ImpV(i),'Sand','IgnoreCase',true)
           ImpVr(i) = 7;
        elseif contains(ImpV(i),'Clay','IgnoreCase',true)  &&
contains(ImpV(i),'Sand','IgnoreCase',true)
           ImpVr(i) = 5;
        elseif contains(ImpV(i),'Clay','IgnoreCase',true)
           ImpVr(i) = 2;
        elseif  contains(ImpV(i),'Silt','IgnoreCase',true) &&
contains(ImpV(i),'Clay','IgnoreCase',true)
           ImpVr(i) = 1;
        else
           ImpVr(i)  = 0;
           fprintf('Error at Row %0.0f. Impact of Vadose Zone values must be strings
including the naming conventions of the 2017 Taheri, Taheri, and Komail paper. ', i)
        end
```

```
    % HYDRAULIC CONDUCTIVITY
    if (CondHy(i) >= 0 && CondHy(i) < 5)%  ifelse Ranges in ft/day identify rating
       CondHyr(i) = 10;
    elseif (CondHy(i) >= 5 && CondHy(i) < 10)
       CondHyr(i) = 8;
    elseif (CondHy(i) >= 10 && CondHy(i) < 13)
       CondHyr(i) = 6;
    elseif (CondHy(i) >= 13 && CondHy(i) < 17)
       CondHyr(i) = 4;
    elseif (CondHy(i) >= 17)
       CondHyr(i) = 4;
    else
       CondHyr(i) = 0;
       fprintf('Error at Row %0.0f. Hydraulic Conductivity cannot be negative.\n', i)
    end

    %% Final Identification of GWPP for each distinct unit
    fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
    GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
    GWPPTBL(i,3) =
SINr(i)*SINw+PSinkr(i)*PSinkw+GWleveldecliner(i)*GWleveldeclinew+Der(i)*Dew+
ReNetr(i)*ReNetw+AqMedr(i)*AqMedw+SoilMedr(i)*SoilMedw+Topogr(i)*Topogw+I
mpVr(i)*ImpVw+CondHyr(i)*CondHyw; %Total GWPP Value
    GWPPTBL(i,4) = SINr(i);
    GWPPTBL(i,5) = SINr(i)*SINw;
    GWPPTBL(i,6) = PSinkr(i);
    GWPPTBL(i,7) = PSinkr(i)*PSinkw;
    GWPPTBL(i,8) = GWleveldecliner(i);
    GWPPTBL(i,9) = GWleveldecliner(i)*GWleveldeclinew;
    GWPPTBL(i,10) = Der(i);
    GWPPTBL(i,11) = Der(i)*Dew;
    GWPPTBL(i,12) = ReNetr(i);
    GWPPTBL(i,13) = ReNetr(i)*ReNetw;
    GWPPTBL(i,14) = AqMedr(i);
    GWPPTBL(i,15) = AqMedr(i)*AqMedw;
    GWPPTBL(i,16) = SoilMedr(i);
    GWPPTBL(i,17) = SoilMedr(i)*SoilMedw;
    GWPPTBL(i,18) = Topogr(i);
    GWPPTBL(i,19) = Topogr(i)*Topogw;
    GWPPTBL(i,20) = ImpVr(i);
    GWPPTBL(i,21) = ImpVr(i)*ImpVw;
    GWPPTBL(i,22) = CondHyr(i);
    GWPPTBL(i,23) = CondHyr(i)*CondHyw;
```

```
        fprintf('\nObjectID/Distinct Unit %0.0f entered to output table \n\n',i)
    end
end
```

KAVI Function

```
function [GWPPTBL] = kKAVI(assess, De, SoPer, CD, LndCov, Road, CondHy)
% Reference: van Beynen, P., Niedzielski, M., Bialkowska-Jelinska, E., Alsharif, K., &
Matusick, J. (2012). Comparative study of specific groundwater vulnerability of a karst
aquifer in central Florida. Applied Geography, 32(2), 868-877.
%"karst aquifer vulnerability index (KAVI), incorporates both physical
%(including a karst specific parameter) and human components."
%   User provides  Depth to groundwater (in m), Soil Permeability of water
%   (in cm/hr), Epikarst depression density, Land use, Presence or Absence of a major
highway, and hydraulic Conductivity of the aquifer (m/day).
%
%Parameter Range = the breakdown of significance for each factor - uses the tables in
the model book.
%
% Parameter Rating = relevant importance of each factor's range with respect to the other
factors from low = 1 to high = 10.
% Ground Water Pollution Potential (GWPP) Variables and Standard Weights
% Dr: Depth to water rating
% SoPerr: Soil Permeability rating
% CDr: Epikarst (Closed Topographic Depressions) rating
% LndCovr: Land Use rating
% Roadr: Presence or Absence of a major highway rating
% Cr: Aquifer Hydraulic Conductivity rating

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),15);
Der = NaN(length(assess),1);
SoPerr = NaN(length(assess),1);
CDr = NaN(length(assess),1);
LndCovr = NaN(length(assess),1);
Roadr = NaN(length(assess),1);
CondHyr = NaN(length(assess),1);

%% Conversions to metric units
De = De*0.3048; %Converting from ft to m
CondHy = CondHy*0.3048; %Converting from ft/d to m/d
SoPer = (SoPer/10000)*3600; %Converting from to um/s to  cm/hr
```

```
%% Identifying Ratings of each parameter
for i = 1:length(assess)
   GWPPTBL(i,1) = i; % Initializing OBJECTID field
   if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
      GWPPTBL(i,2:end) = 0;
   else     %for cases where data exists and Hydrogeologic Setting = NR
      %% Assumed Weights of each parameter
      Dew = 0.15;
      SoPerw = 0.15;
      CDw = 0.25;
      LndCovw = 0.3;
      Roadw = 0.3;
      CondHyw = 0.15;

      % DEPTH TO WATER - ifelse Ranges in m identify ratings
      if De(i) == 0
         Der(i) = 5;
      elseif (De(i) > 0 && De(i) <= 4.7)
         Der(i) = 4;
      elseif (De(i) > 4.7 && De(i) <= 7.7)
         Der(i) = 3;
      elseif (De(i) > 7.7 && De(i) <= 10.7)
         Der(i) = 5;
      elseif (De(i) > 10.7)
         Der(i) = 1;
      else
         Der(i) = 0;
         fprintf('Error at Row %0.0f. Depth to Water cannot be negative. ', i)
      end

      % Soil Permeability - ifelse Ranges in m identify ratings
      if SoPer(i) == 0
         SoPerr(i) = 1;
      elseif (SoPer(i) <= 1.5)
         SoPerr(i) = 2;
      elseif (SoPer(i) > 1.5 && SoPer(i) <= 15.2)
         SoPerr(i) = 3;
      elseif (SoPer(i) > 15.2 && SoPer(i) <= 50.5)
         SoPerr(i) = 4;
      elseif SoPer(i) > 50.5
         SoPerr(i) = 5;
      else
         SoPerr(i) = 0;
         fprintf('Error at Row %0.0f. Soil Permeability cannot be negative. ', i)
```

```
    end

    % Epikarst Closed Depressions (Density of sinkholes) - An ifelse table - based on
Type of Material; a range of ratings or typical
    % rating may be used. Expert opinion can be used to override distinct unit values in
the final GWPP table.
    if CD(i) == 0 %contains(CD(i),'No ','IgnoreCase',true) ||
contains(CD(i),'None','IgnoreCase',true)
      CDr(i) = 1;
%     elseif contains(CD(i),'Moderate','IgnoreCase',true)
%       CDr(i) = 3;
    elseif CD(i) == 1 %contains(CD(i),'High','IgnoreCase',true)
      CDr(i) = 5;
    else
      CDr(i) = 0;
      fprintf('Error at Row %0.0f. Epikarst Closed Depression values must be strings
matching the naming convention of the 2012 van Beynen paper. ', i)
    end

    %Land Use An ifelse table - Expert opinion can be used to override distinct unit
values in the final GWPP table.
    if contains(LndCov(i),'Natural','IgnoreCase',true) ||
contains(LndCov(i),'Protected','IgnoreCase',true)
      LndCovr(i) = 1;
    elseif contains(LndCov(i),'Pasture','IgnoreCase',true)
      LndCovr(i) = 2;
    elseif contains(LndCov(i),'High','IgnoreCase',true) &&
contains(LndCov(i),'Intensity','IgnoreCase',true) ||
contains(LndCov(i),'Ag','IgnoreCase',true)
      LndCovr(i) = 3;
    elseif contains(LndCov(i),'Residential','IgnoreCase',true) ||
contains(LndCov(i),'Industrial','IgnoreCase',true)
      LndCovr(i) = 4;
        elseif contains(LndCov(i),'Mine','IgnoreCase',true) ||
contains(LndCov(i),'Mining','IgnoreCase',true)
      LndCovr(i) = 5;
    else
      LndCovr(i) = 0;
      fprintf('Error at Row %0.0f. Land Use values must be strings matching the
naming conventions of the 2012 van Beynen paper. ', i)
    end


    %Roadways - An ifelse table
```

```
    if Road(i) == 0 %contains(Road(i),'No','IgnoreCase',true) || contains(Road(i),'No
Highway','IgnoreCase',true)
      Roadr(i) = 1;
    elseif  Road(i) == 1 %contains(Road(i),'Major','IgnoreCase',true)
      Roadr(i) = 5;
    else
      Roadr(i)  = 0;
      fprintf('Error at Row %0.0f. Roadway values must be strings matching the
naming conventions of the 2012 van Beynen paper. ', i)
    end

    % Aquifer HYDRAULIC CONDUCTIVITY
    if (CondHy(i) >= 1 && CondHy(i) <= 30)%  ifelse Ranges in m/day identify rating
      CondHyr(i) = 1;
    elseif (CondHy(i) > 30 && CondHy(i) <= 100)
      CondHyr(i) = 2;
    elseif (CondHy(i) > 100 && CondHy(i) <= 210)
      CondHyr(i) = 3;
    elseif (CondHy(i) > 210 && CondHy(i) <= 300)
      CondHyr(i) = 4;
    elseif CondHy(i) > 300
      CondHyr(i) = 5;
    else
      CondHyr(i) = 0;
      fprintf('Error at Row %0.0f. Hydraulic Conductivity cannot be negative.\n', i)
    end

    %% Final Identification of GWPP for each distinct unit
    fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
    GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
    GWPPTBL(i,3) =
Der(i)*Dew+SoPerr(i)*SoPerw+CDr(i)*CDw+LndCovr(i)*LndCovw+
Roadr(i)*Roadw+CondHyr(i)*CondHyw; %Total GWPP Value
    GWPPTBL(i,4) = Der(i);
    GWPPTBL(i,5) = Der(i)*Dew;
    GWPPTBL(i,6) = SoPerr(i);
    GWPPTBL(i,7) = SoPerr(i)*SoPerw;
    GWPPTBL(i,8) = CDr(i);
    GWPPTBL(i,9) = CDr(i)*CDw;
    GWPPTBL(i,10) = LndCovr(i);
    GWPPTBL(i,11) = LndCovr(i)*LndCovw;
    GWPPTBL(i,14) = Roadr(i);
    GWPPTBL(i,15) = Roadr(i)*Roadw;
    GWPPTBL(i,16) = CondHyr(i);
```

```
        GWPPTBL(i,17) = CondHyr(i)*CondHyw;
        fprintf('\nObjectID/Distinct Unit %0.0f entered to output table \n',i)
    end
end
```

SI Function

```
function [GWPPTBL] = nSI(assess, De, ReNet, AqMed, LndUse, Topog)
%
% Reference: van Beynen, P., Niedzielski, M., Bialkowska-Jelinska, E., Alsharif, K., &
Matusick, J. (2012). Comparative study of specific groundwater vulnerability of a karst
aquifer in central Florida. Applied Geography, 32(2), 868-877.
%"karst aquifer vulnerability index (KAVI), incorporates both physical
%(including a karst specific parameter) and human components."
%   User provides  Depth to groundwater (in m), Soil Permeability of water
%   (in cm/hr), Epikarst depression density, Land use, Impact
%   of the vadose zone, and hydraulic Conductivity of the aquifer (m/day).
%
%Parameter Range = the breakdown of significance for each factor - uses the tables in
the model book.
%
% Parameter Rating = relevant importance of each factor's range with respect to the other
factors from low = 1 to high = 10.
% Ground Water Pollution Potential (GWPP) Variables and Standard Weights
% Der: Depth to water rating
% ReNetr: Net Recharge avg. weight
% AqMedr: Aquifer Media avg. weight
% LndUser: Land Use rating
% Topogw = 1; Topology avg. weight
% CondHyr: Aquifer Hydraulic Conductivity rating

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),15);
Der = NaN(length(assess),1);
ReNetr = NaN(length(assess),1);
AqMedr = NaN(length(assess),1);
LndUser = NaN(length(assess),1);
Topogr = NaN(length(assess),1);

%% Conversions to metric units
De = De*0.3048; %Converting from ft to m
ReNet = ReNet*25.4; %Converting from inches/yr to mm/yr

%% Identifying Ratings of each parameter
```

```
for i = 1:length(assess)
    GWPPTBL(i,1) = i; % Initializing OBJECTID field
    if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
        GWPPTBL(i,2:end) = 0;
    else     %for cases where data exists and Hydrogeologic Setting = NR
        %% Assumed Weights of each parameter - from Stigter Et. Al 2006 (Not saved yet)
        Dew = 0.186;
        ReNetw = 0.212;
        AqMedw = 0.259;
        LndUsew = 0.3;
        Topogw = 0.121;

        % DEPTH TO WATER - ifelse Ranges in m identify ratings
        if De(i) == 0
            Der(i) = 5;
        elseif (De(i) > 0 && De(i) <= 4.7)
            Der(i) = 4;
        elseif (De(i) > 4.7 && De(i) <= 7.7)
            Der(i) = 3;
        elseif (De(i) > 7.7 && De(i) <= 10.7)
            Der(i) = 5;
        elseif (De(i) > 10.7)
            Der(i) = 1;
        else
            Der(i) = 0;
            fprintf('Error at Row %0.0f. Depth to Water cannot be negative. ', i)
        end

        % Net Recharge - mm/yr
        if ReNet(i) == 0
            ReNetr(i) = 1;
        elseif (ReNet(i) <= 1.5)
            ReNetr(i) = 2;
        elseif (ReNet(i) > 1.5 && ReNet(i) <= 15.2)
            ReNetr(i) = 3;
        elseif (ReNet(i) > 15.2 && ReNet(i) <= 50.5)
            ReNetr(i) = 4;
        elseif ReNet(i) > 50.5
            ReNetr(i) = 5;
        else
            ReNetr(i) = 0;
            fprintf('Error at Row %0.0f. Soil Permeability cannot be negative. ', i)
        end
```

```
    % AQUIFER MEDIA - An ifelse table - based on Type of Material; a range of
ratings or typical
    % rating may be used. Expert opinion can be used to override distinct unit values in
the final GWPP table.
    if contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true) || contains(AqMed(i),'SH','IgnoreCase',true)
        AqMedr(i) = 2;
    elseif contains(AqMed(i),'Metamorphic/Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true) ||
contains(AqMed(i),'Igneous','IgnoreCase',true)
        AqMedr(i) = 3;
    elseif contains(AqMed(i),'Weathered','IgnoreCase',true) &&
contains(AqMed(i),'Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true)
        AqMedr(i) = 4;
    elseif contains(AqMed(i),'Glacial','IgnoreCase',true) ||
contains(AqMed(i),'Till','IgnoreCase',true)
        AqMedr(i) = 5;
    elseif contains(AqMed(i),'Bed','IgnoreCase',true) &&
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true)|| contains(AqMed(i),'SH','IgnoreCase',true)||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
        AqMedr(i) = 6;
    elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Sandstone','IgnoreCase',true) ||
contains(AqMed(i),'SS','IgnoreCase',true)
        AqMedr(i) = 6;
    elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
        AqMedr(i) = 6;
    elseif contains(AqMed(i),'Sand','IgnoreCase',true) ||
contains(AqMed(i),'Gravel','IgnoreCase',true) ||
contains(AqMed(i),'GVL','IgnoreCase',true)
        AqMedr(i) = 8;
    elseif contains(AqMed(i),'Basalt','IgnoreCase',true)
        AqMedr(i) = 9;
    elseif  contains(AqMed(i),'Karst','IgnoreCase',true)
        AqMedr(i) = 10;
    else
        AqMedr(i) = 0;
        fprintf('Error at Row %0.0f. Aquifer media values must be strings matching the
naming convention KAVI. ', i)
    end
```

```
	%Land Use An ifelse table - Expert opinion can be used to override distinct unit
values in the final GWPP table.
	if contains(LndUse(i),'Irrigation','IgnoreCase',true) ||
contains(LndUse(i),'Cultivated','IgnoreCase',true)  ||
contains(LndUse(i),'Herbaceous','IgnoreCase',true)
	    LndUser(i) = 90;
%	    elseif contains(LndUse(i),'Permanent','IgnoreCase',true) ||
contains(LndUse(i),'Permanent','IgnoreCase',true) ||
contains(LndUse(i),'Orchard','IgnoreCase',true) ||
contains(LndUse(i),'Vineyard','IgnoreCase',true)
%	        LndUser(i) = 70;
	elseif contains(LndUse(i),'Heterogeneous','IgnoreCase',true) ||
contains(LndUse(i),'Pasture','IgnoreCase',true) || contains(LndUse(i),'agro-
forest','IgnoreCase',true)
	    LndUser(i) = 50;
	elseif contains(LndUse(i),'Medium Intensity','IgnoreCase',true) ||
contains(LndUse(i),'Landfill','IgnoreCase',true) || contains(LndUse(i),'Waste
Discharge','IgnoreCase',true) || contains(LndUse(i),'Industrial','IgnoreCase',true)
	    LndUser(i) = 100;
	elseif contains(LndUse(i),'Barren','IgnoreCase',true) ||
contains(LndUse(i),'Quarr','IgnoreCase',true) ||
contains(LndUse(i),'Shipyard','IgnoreCase',true)|| contains(LndUse(i),'Open Air
Min','IgnoreCase',true)
	    LndUser(i) = 80;
	elseif contains(LndUse(i),'High Intensity','IgnoreCase',true) ||
contains(LndUse(i),'Continuous Urban','IgnoreCase',true) ||
contains(LndUse(i),'airport','IgnoreCase',true) ||
contains(LndUse(i),'harb','IgnoreCase',true) || contains(LndUse(i),'rail','IgnoreCase',true)
|| contains(LndUse(i),'road','IgnoreCase',true)  || contains(LndUse(i),'industrial
activity','IgnoreCase',true)  || contains(LndUse(i),'commercial activity','IgnoreCase',true)
|| contains(LndUse(i),'green space','IgnoreCase',true)
	    LndUser(i) = 75;
	elseif contains(LndUse(i),'Low Intensity','IgnoreCase',true) ||
contains(LndUse(i),'Dis','IgnoreCase',true) || contains(LndUse(i),'urban','IgnoreCase',true)
	    LndUser(i) = 70;
	elseif contains(LndUse(i),'Water','IgnoreCase',true) ||
contains(LndUse(i),'Aquatic','IgnoreCase',true) || contains(LndUse(i),'salt
marsh','IgnoreCase',true) ||contains(LndUse(i),'salina','IgnoreCase',true) ||
contains(LndUse(i),'intertidal','IgnoreCase',true)
	    LndUser(i) = 50;
	elseif contains(LndUse(i),'Forest','IgnoreCase',true) ||
contains(LndUse(i),'Seminatural','IgnoreCase',true)
||contains(LndUse(i),'Shrub','IgnoreCase',true)
```

```
            LndUser(i) = 0;
        else
            fprintf('Error at Row %0.0f. Land Use values must be strings matching the
naming conventions of the 2012 van Beynen paper. ', i)
        end

        % TOPOGRAPHY ifelse Ranges in % slope identify rating (Assumed same
asDRASTIC- no info in
        % the 2012 van Beynen paper to show otherwise)
        if (Topog(i) >= 0 && Topog(i) <= 2)
            Topogr(i) = 10;
        elseif (Topog(i) > 2 && Topog(i) <= 6)
            Topogr(i) = 9;
        elseif (Topog(i) > 6 && Topog(i) <= 12)
            Topogr(i) = 5;
        elseif (Topog(i) > 12 && Topog(i) <= 18)
            Topogr(i) = 3;
        elseif Topog(i) > 18
            Topogr(i) = 1;
        else
            Topogr(i) = 0;
            fprintf('Error at Row %0.0f. Slope cannot be negative. ', i)
        end

        %% Final Identification of GWPP for each distinct unit
        fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
        GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
        GWPPTBL(i,3) =
Der(i)*Dew+ReNetr(i)*ReNetw+AqMedr(i)*AqMedw+LndUser(i)*LndUsew+
Topogr(i)*Topogw; %Total GWPP Value
        GWPPTBL(i,4) = Der(i);
        GWPPTBL(i,5) = Der(i)*Dew;
        GWPPTBL(i,6) = ReNetr(i);
        GWPPTBL(i,7) = ReNetr(i)*ReNetw;
        GWPPTBL(i,8) = AqMedr(i);
        GWPPTBL(i,9) = AqMedr(i)*AqMedw;
        GWPPTBL(i,10) = LndUser(i);
        GWPPTBL(i,11) = LndUser(i)*LndUsew;
        GWPPTBL(i,14) = Topogr(i);
        GWPPTBL(i,15) = Topogr(i)*Topogw;
        fprintf('\nObjectID/Distinct Unit %0.0f entered to output table \n',i)
    end
end
```

Altered Weight DRASTIC Function

```
function [GWPPTBL] = oMODDRASTIC(assess, De, ReNet, AqMed, SoilMed, Topog,
ImpV, CondHy)
%The EPA DRASTIC Model for identifying the groundwater pollution potential for
distinct units.
%   User provides  Depth to groundwater (in feet), net Recharge of water
%   (in inches/year), Aquifer media, Soil media, Topography (in % slope), Impact
%   of the vadose zone, and hydraulic Conductivity of the aquifer (Gallons
%   Per Day per Square Foot).
%
% Model Assumptions -
% 1) Contamination occurs at the ground surface.
% 2) The contaminant enters the water table when rain falls on the surface and percolates
into the saturated zone.
% 3) The contaminant travels with water, at the same rate as water (Retardation Factor =
1).
% 4) The method will be applied to no smaller than 100 acres.
% 5) The aquifer is unconfined (the method can be modified for a confined aquifer).
% 6) The dominant pollutants are not pesticides (the method can be modified to include
pesticides).
%
%Parameter weight = importance of model factor compared to others from least
significant = 1 to most significant = 5.
% Dw = 5; Depth to water avg. weight
% Rw = 4; Net Recharge avg. weight
% Aw = 5; Aquifer Media avg. weight
% Sw = 2; Soil Media avg. weight
% Tw = 1; Topology avg. weight
% Iw = 5; Impact of the vadose zone avg. weight
% Cw = 5; Hydraulic Conductivity avg. weight
%
%Parameter Range = the breakdown of significance for each factor - uses the tables in
the model book.
%
% Parameter Rating = relevant importance of each factor's range with respect to the other
factors from low = 1 to high = 10.
% Ground Water Pollution Potential (GWPP) Variables and Standard Weights
% Dr: Depth to water rating
% Rr: Net Recharge rating
% Ar: Aquifer Media rating
% Sr: Soil Media rating
% Tr: Topology rating
% Ir: Impact of the vadose zone rating
```

```
% Cr: Hydraulic Conductivity rating

%% Initializing the tables and vectors for output values
GWPPTBL = NaN(length(assess),17);
Der = NaN(length(assess),1);
ReNetr = NaN(length(assess),1);
AqMedr = NaN(length(assess),1);
SoilMedr = NaN(length(assess),1);
Topogr = NaN(length(assess),1);
ImpVr = NaN(length(assess),1);
CondHyr = NaN(length(assess),1);

%% Identifying Ratings of each parameter from Published 1987 EPA Paper
for i = 1:length(assess)
   GWPPTBL(i,1) = i; % Initializing OBJECTID field
   if assess(i) ~= 1 % When Hydrogeologic Setting ~= NR
      GWPPTBL(i,2:end) = 0;
   else     %for cases where data exists and Hydrogeologic Setting = NR
      %% Assumed Weights of each parameter - from Published 1987 EPA Paper
      Dew = 5;
      ReNetw = 4;
      AqMedw = 5;
      SoilMedw = 2;
      Topogw = 1;
      ImpVw = 5;
      CondHyw = 5;
      % DEPTH TO WATER - ifelse Ranges in feet identify ratings
      if (De(i) >= 0 && De(i) <= 5)
         Der(i) = 10;
      elseif (De(i) > 5 && De(i) <= 15)
         Der(i) = 9;
      elseif (De(i) > 15 && De(i) <= 30)
         Der(i) = 7;
      elseif (De(i) > 30 && De(i) <= 50)
         Der(i) = 5;
      elseif (De(i) > 50 && De(i) <= 75)
         Der(i) = 3;
      elseif (De(i) > 75 && De(i) <= 100)
         Der(i) = 2;
      elseif (De(i) > 100)
         Der(i) = 1;
      else
         Der(i) = 0;
         fprintf('Error at Row %0.0f. Depth to Water cannot be negative. ', i)
```

```
    end

    % NET RECHARGE - ifelse Ranges in feet identify ratings
    if (ReNet(i) >= 0 && ReNet(i) <= 2)
      ReNetr(i) = 1;
    elseif (ReNet(i) > 2 && ReNet(i) <= 4)
      ReNetr(i) = 3;
    elseif (ReNet(i) > 4 && ReNet(i) <= 7)
      ReNetr(i) = 6;
    elseif (ReNet(i) > 7 && ReNet(i) <= 10)
      ReNetr(i) = 8;
    elseif ReNet(i) > 10
      ReNetr(i) = 9;
    else
      ReNetr(i) = 0;
      fprintf('Error at Row %0.0f. Net Recharge cannot be negative. ', i)
    end

    % AQUIFER MEDIA - An ifelse table - based on Type of Material; a range of
ratings or typical
    % rating may be used. Expert opinion can be used to override distinct unit values in
the final GWPP table.
    if contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true) || contains(AqMed(i),'SH','IgnoreCase',true)
      AqMedr(i) = 2;
    elseif contains(AqMed(i),'Metamorphic/Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true) ||
contains(AqMed(i),'Igneous','IgnoreCase',true)
      AqMedr(i) = 3;
    elseif contains(AqMed(i),'Weathered','IgnoreCase',true) &&
contains(AqMed(i),'Igneous','IgnoreCase',true) ||
contains(AqMed(i),'Metamorphic','IgnoreCase',true)
      AqMedr(i) = 4;
    elseif contains(AqMed(i),'Glacial','IgnoreCase',true) ||
contains(AqMed(i),'Till','IgnoreCase',true)
      AqMedr(i) = 5;
    elseif contains(AqMed(i),'Bed','IgnoreCase',true) &&
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'Shale','IgnoreCase',true)|| contains(AqMed(i),'SH','IgnoreCase',true)||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
      AqMedr(i) = 6;
    elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Sandstone','IgnoreCase',true) ||
contains(AqMed(i),'SS','IgnoreCase',true)
```

```
      AqMedr(i) = 6;
    elseif contains(AqMed(i),'Massive','IgnoreCase',true) ||
contains(AqMed(i),'Limestone','IgnoreCase',true) ||
contains(AqMed(i),'LS','IgnoreCase',true)  || contains(AqMed(i),'LST','IgnoreCase',true)
      AqMedr(i) = 6;
    elseif contains(AqMed(i),'Sand','IgnoreCase',true) ||
contains(AqMed(i),'Gravel','IgnoreCase',true) ||
contains(AqMed(i),'GVL','IgnoreCase',true)
      AqMedr(i) = 8;
    elseif contains(AqMed(i),'Basalt','IgnoreCase',true)
      AqMedr(i) = 9;
    elseif  contains(AqMed(i),'Karst','IgnoreCase',true)
      AqMedr(i) = 10;
    else
      AqMedr(i) = 0;
      fprintf('Error at Row %0.0f. Aquifer media values must be strings matching the
naming convention of the 1987 EPA paper. ', i)
    end

    %SOIL MEDIA An ifelse table - based on type of soil media. Expert opinion can be
used to override distinct unit values in the final GWPP table.
    if contains(SoilMed(i),'Thin','IgnoreCase',true) ||
contains(SoilMed(i),'Absent','IgnoreCase',true)
      SoilMedr(i) = 10;
    elseif contains(SoilMed(i),'Gravel','IgnoreCase',true) ||
contains(SoilMed(i),'Gravel','IgnoreCase',true)
      SoilMedr(i) = 10;
    elseif contains(SoilMed(i),'Sand','IgnoreCase',true) ||
contains(SoilMed(i),'SD','IgnoreCase',true)
      SoilMedr(i) = 9;
    elseif contains(SoilMed(i),'Peat','IgnoreCase',true)
      SoilMedr(i) = 8;
    elseif contains(SoilMed(i),'Clay','IgnoreCase',true) &&
contains(SoilMed(i),'Shrinking','IgnoreCase',true) ||
contains(SoilMed(i),'Aggregate','IgnoreCase',true) ||
contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 7;
    elseif contains(SoilMed(i),'Sandy Loam','IgnoreCase',true) ||
contains(SoilMed(i),'SD','IgnoreCase',true)
      SoilMedr(i) = 6;
    elseif contains(SoilMed(i),'Loam','IgnoreCase',true)
      SoilMedr(i) = 5;
    elseif contains(SoilMed(i),'Silty Loam','IgnoreCase',true) ||
contains(SoilMed(i),'SL','IgnoreCase',true)
```

```
      SoilMedr(i) = 4;
    elseif contains(SoilMed(i),'Clay Loam','IgnoreCase',true) ||
contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 3;
    elseif contains(SoilMed(i),'Muck','IgnoreCase',true)
      SoilMedr(i) = 2;
    elseif contains(SoilMed(i),'Nonshrinking','IgnoreCase',true) &&
contains(SoilMed(i),'Nonaggregated','IgnoreCase',true) &&
contains(SoilMed(i),'Clay','IgnoreCase',true) || contains(SoilMed(i),'CL','IgnoreCase',true)
      SoilMedr(i) = 1;
    else
      SoilMedr(i) = 0;
      fprintf('Error at Row %0.0f. Soil media values must be strings matching the
naming conventions of the 1987 EPA paper. ', i)
    end

    % TOPOGRAPHY ifelse Ranges in % slope identify rating
    if (Topog(i) >= 0 && Topog(i) <= 2)
      Topogr(i) = 10;
    elseif (Topog(i) > 2 && Topog(i) <= 6)
      Topogr(i) = 9;
    elseif (Topog(i) > 6 && Topog(i) <= 12)
      Topogr(i) = 5;
    elseif (Topog(i) > 12 && Topog(i) <= 18)
      Topogr(i) = 3;
    elseif Topog(i) > 18
      Topogr(i) = 1;
    else
      Topogr(i) = 0;
      fprintf('Error at Row %0.0f. Slope cannot be negative. ', i)
    end

    %IMPACT OF VADOSE ZONE An ifelse table - based on Type of Material;
typical ratings used. Expert opinion can be used to override distinct unit values in the
final GWPP table.
    if contains(ImpV(i),'Confin','IgnoreCase',true) &&
contains(ImpV(i),'Layer','IgnoreCase',true)
      ImpVr(i) = 1;
    elseif contains(ImpV(i),'Silt','IgnoreCase',true) ||
contains(ImpV(i),'Clay','IgnoreCase',true) || contains(ImpV(i),'CL','IgnoreCase',true)  ||
contains(ImpV(i),'SL','IgnoreCase',true) || contains(ImpV(i),'Till','IgnoreCase',true)
      ImpVr(i) = 3; %Range is 2 - 6
    elseif contains(ImpV(i),'Shale','IgnoreCase',true)  ||
contains(ImpV(i),'SH','IgnoreCase',true)
```

```
      ImpVr(i) = 3; %Range is 2 - 5
    elseif contains(ImpV(i),'Limestone','IgnoreCase',true)  ||
contains(ImpV(i),'LST','IgnoreCase',true)  || contains(ImpV(i),'LS','IgnoreCase',true)
      ImpVr(i) = 6; %Range is 2 - 7
    elseif contains(ImpV(i),'Sandstone','IgnoreCase',true)  ||
contains(ImpV(i),'SS','IgnoreCase',true)
      ImpVr(i) = 6; %Range is 4 - 8
    elseif contains(ImpV(i),'Bed','IgnoreCase',true)  ||
contains(ImpV(i),'INT','IgnoreCase',true) &&
contains(ImpV(i),'Limestone','IgnoreCase',true) ||
contains(ImpV(i),'Sandstone','IgnoreCase',true) ||
contains(ImpV(i),'Shale','IgnoreCase',true)  || contains(ImpV(i),'LS','IgnoreCase',true)  ||
contains(ImpV(i),'LST','IgnoreCase',true)  || contains(ImpV(i),'SH','IgnoreCase',true)  ||
contains(ImpV(i),'SS','IgnoreCase',true)
      ImpVr(i) = 6; %Range is 4 - 8
    elseif contains(ImpV(i),'Sand','IgnoreCase',true)  ||
contains(ImpV(i),'SD','IgnoreCase',true) && contains(ImpV(i),'Gravel','IgnoreCase',true)
|| contains(ImpV(i),'GVL','IgnoreCase',true) &&
contains(ImpV(i),'significant','IgnoreCase',true) || contains(ImpV(i),'w/','IgnoreCase',true)
|| contains(ImpV(i),'Silt','IgnoreCase',true) || contains(ImpV(i),'Clay','IgnoreCase',true)  ||
contains(ImpV(i),'CL','IgnoreCase',true)  || contains(ImpV(i),'SL','IgnoreCase',true) ||
contains(ImpV(i),'Till','IgnoreCase',true)
      ImpVr(i) = 6; %Range is 4 - 8
    elseif contains(ImpV(i),'Metamorphic','IgnoreCase',true) ||
contains(ImpV(i),'Igneous','IgnoreCase',true) || contains(ImpV(i),'Till','IgnoreCase',true)
      ImpVr(i) = 4; %Range is 2 - 8
    elseif contains(ImpV(i),'Sand','IgnoreCase',true) &&
contains(ImpV(i),'Gravel','IgnoreCase',true)  || contains(ImpV(i),'SD','IgnoreCase',true)  ||
contains(ImpV(i),'GVL','IgnoreCase',true)
      ImpVr(i) = 8; %Range is 6 - 9
    elseif contains(ImpV(i),'Basalt','IgnoreCase',true)
      ImpVr(i) = 9; %Range is 2 - 10
    elseif  contains(ImpV(i),'Karst','IgnoreCase',true)
      ImpVr(i) = 10; %Range is 8 - 10
    else
      ImpVr(i)  = 0;
      fprintf('Error at Row %0.0f. Impact of Vadose Zone values must be strings
including the naming conventions of the 1987 EPA paper. ', i)
    end

    % HYDRAULIC CONDUCTIVITY
    if (CondHy(i) >= 1 && CondHy(i) <= 100)%  ifelse Ranges in ft/day identify rating
      CondHyr(i) = 1;
    elseif (CondHy(i) > 100 && CondHy(i) <= 300)
```

```
      CondHyr(i) = 2;
    elseif (CondHy(i) > 300 && CondHy(i) <= 700)
      CondHyr(i) = 4;
    elseif (CondHy(i) > 700 && CondHy(i) <= 1000)
      CondHyr(i) = 6;
    elseif (CondHy(i) > 1000 && CondHy(i) <= 2000)
      CondHyr(i) = 8;
    elseif CondHy(i) > 2000
      CondHyr(i) = 10;
    else
      CondHyr(i) = 0;
      fprintf('Error at Row %0.0f. Hydraulic Conductivity cannot be negative.\n', i)
    end

    %% Final Identification of GWPP for each distinct unit
    fprintf('ObjectID/Distinct Unit %0.0f GWPP calculated',i)
    GWPPTBL(i,2) = assess(i); %Whether the cell was counted or not
    GWPPTBL(i,3) =
Der(i)*Dew+ReNetr(i)*ReNetw+AqMedr(i)*AqMedw+SoilMedr(i)*SoilMedw+Topogr(
i)*Topogw+ImpVr(i)*ImpVw+CondHyr(i)*CondHyw; %Total GWPP Value
    GWPPTBL(i,4) = Der(i);
    GWPPTBL(i,5) = Der(i)*Dew;
    GWPPTBL(i,6) = ReNetr(i);
    GWPPTBL(i,7) = ReNetr(i)*ReNetw;
    GWPPTBL(i,8) = AqMedr(i);
    GWPPTBL(i,9) = AqMedr(i)*AqMedw;
    GWPPTBL(i,10) = SoilMedr(i);
    GWPPTBL(i,11) = SoilMedr(i)*SoilMedw;
    GWPPTBL(i,12) = Topogr(i);
    GWPPTBL(i,13) = Topogr(i)*Topogw;
    GWPPTBL(i,14) = ImpVr(i);
    GWPPTBL(i,15) = ImpVr(i)*ImpVw;
    GWPPTBL(i,16) = CondHyr(i);
    GWPPTBL(i,17) = CondHyr(i)*CondHyw;
    fprintf('\nObjectID/Distinct Unit %0.0f entered to output table \n',i)
  end
end
```