DELINEATING CRITICAL RECHARGE AREAS IN KARST TERRAIN:
SPRING CREEK WATERSHED CASE STUDY

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by
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ABSTRACT

A local source of readily available drinking water is necessary for any sustainable society. In many areas, groundwater is the common source of drinking water for individual residences and small communities. Identification of the source of groundwater is imperative for the protection of drinking water. By identifying areas of groundwater recharge on the surface, actions can be taken to protect the quality of water that becomes groundwater.

This study focused on identifying critical recharge areas in the Spring Creek watershed in Centre County, Pennsylvania using geographic information systems (GIS). Previous GIS studies concerning recharge have focused on groundwater resource development and exploitation and focused on deep geologic features. The Spring Creek watershed is karstic and prone to sinkhole development. The goal of this study was to identify surface areas that are most likely to provide infiltrated water that could become groundwater recharge.

Two different modeling approaches were used to address the research goal. A previously published modeling technique was used to incorporate several thematic layers into a groundwater recharge map. Among the published GIS-based models for identifying groundwater recharge zones, the model developed by Yeh et al. (2009) was selected for this work because it provided a detailed methodological description. This model identified and weighted five factors affecting groundwater recharge potential: geology (lithology), land use, lineaments, drainage, and slope. These data layers were combined to produce a resultant groundwater recharge potential zone map.
A second approach used the techniques described in Technical Release 55 (TR-55) by the Natural Resources Conservation Service (NRCS) for evaluating runoff in small, urbanized watersheds. The infiltration potential model was used to estimate runoff as a function of a twenty-four hour storm over five different return periods. In this research, rainfall that did not become runoff was considered as infiltration water. The infiltration potential model results were combined with datasets describing tributary areas to sinks and sinkholes and impervious surfaces to develop a set of composite maps delineating potential surface runoff areas that most directly contribute to recharge.

Using the Yeh et al. (2009) approach, a composite recharge area map of the Spring Creek watershed was developed. While the resultant map generally identified areas of high recharge potential, it did not incorporate known karstic features such as sinks and sinkholes. The Yeh et al. (2009) approach also heavily relied upon lineament data that was not fully digitized across the Spring Creek watershed. This study revealed limitations in directly using a model developed for a different geographical setting. For instance, in the karstic Spring Creek watershed, consideration needs to be given to sinks and sinkholes. The major limitation is the need to customize, for the specific area under consideration, the factor weighting values and scores used to characterize the relative influence of data layers on recharge potential. Additionally, the large variability in the quality and quantity of the available supporting data can potentially compromise the accuracy or completeness of specific data layers.

The developed composite maps from the infiltration potential model more reasonably identified surface infiltration potential areas in the Spring Creek watershed primarily because of the inclusion of surface features and the exclusion of features that
are associated with deep recharge such as geology and fractured bedrock. Subsurface features were excluded to create surface infiltration potential mapping intended to be used as part of a larger recharge model. The model also considered sinks and sinkholes which are primary features of the karstic nature of the Spring Creek watershed. One disadvantage of this approach is that it treats all non-runoff water as recharge/infiltration and effectively ignores evapotranspiration losses, which can be large in forested areas.

A major outcome of this study is model composite maps that indicate the source of infiltrated water across the Spring Creek watershed. A valuable observation made through conducting this study is the importance of distinguishing deep recharge models (e.g. the Yeh model) from infiltration potential models, and the necessity of selecting an appropriate model for the watershed to be evaluated. The model composite maps produced by this study may be used to inform decisions on wellhead protection, water quality, and emergency response plans in local municipalities.

The infiltration potential model composite maps produced by this study are intended to be used as part of a more complex potential groundwater recharge model. The composite maps are to be used as infiltration potential mapping, which assumes that water infiltrates beyond the soil horizon. Combining these surface infiltration potential areas and areas tributary to sinks/sinkholes with deep recharge models through the use of groundwater contours would allow for the delineation of surface features to points of interest below the surface and vice versa. Combining the mapping in this manner would provide a three-dimensional mapping that provides specific source areas, allows for accurate volume calculations, and gives more detailed information related to groundwater protection.
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“Oh, Eeyore, you are wet!” said Piglet, feeling him. Eeyore shook himself, and asked somebody to explain to Piglet what happened when you had been inside a river for quite a long time.’

-A.A. Milne
Chapter 1. INTRODUCTION

Readily available water resources are necessary for the presence of a society. According to the United States Geologic Survey (USGS, 2011a), in the United States in 2005, 20% of all water used came from groundwater sources and 82.6 billion gallons of water were withdrawn on a daily basis. Close to 99% of groundwater used in the country comes from freshwater aquifers. Groundwater has a major impact in people’s daily lives, as 98% of self-supplied domestic water comes from groundwater sources (USGS, 2011a).

Groundwater is often the primary source of drinking water to the population of a karst region. Karst geology exists in areas where there is an abundance of carbonate rocks (such as limestone and dolomite). While karst formations often provide readily available groundwater resources to the region, the nature of the formations does leave them vulnerable to contamination. One vulnerability of these areas is the susceptibility of the aquifer, a large water bearing strata beneath earth’s surface, to contamination due to bypass processes such as sinkholes that allow water to reach the groundwater without filtration of any kind. Development of critical recharge areas can result in reduced groundwater recharge and increased surface runoff by eliminating their natural infiltration capabilities (Bakalowicz, 2005).

It is estimated that about 12% of the planet’s dry, ice-free land is underlain by carbonate rock (Bakalowicz, 2005). Karst formations initially form when carbonate rocks are broken down by dissolved carbon dioxide in solution, which makes the solution acidic. In turn, this acidic solution moving through the geologic features breaks down the carbonate rock. Climate is active in the process of creating karst formations (known as karstification) due to the effects of pressure and temperature on the concentration of dissolved carbon dioxide. Water flow from the surface
to groundwater, as well as movement of groundwater in the aquifer, causes the dissolution of the carbonate rocks to occur. The shape of karst formations is primarily caused by varying hydrological gradients, and any variation of these flows and gradients has an effect on the structure of the karst (Bakalowicz, 2005).

Within the karst formations, aquifers receive, store, and discharge large amounts of percolated water. Often appearing as sinkholes on the surface, vertical conduits can prove to be direct lines to these aquifers. The aquifers are interconnected by a network of horizontal and vertical conduits that are often discharged at a spring. Often, in communities that exist in a karst environment, either karst aquifers are the groundwater source to the area, or their presence influences the effectiveness of wells by influencing the water table elevation (Bakalowicz, 2005).

Aquifers within karst regions provide a vital resource to society by providing a source of usable water to communities. For example, the Great Valley aquifer stretches through the I-81 corridor from Tennessee to Pennsylvania, and provides a water resource for towns and cities in the area (USGS, 2011b). Aquifers offer large storage capacities and can reduce the need for water storage infrastructure such as water towers or reservoirs. Due to the network of conduits feeding an aquifer and the high rate of movement through those conduits, aquifers are highly susceptible to contamination (Bakalowicz, 2005).

Due to the vulnerabilities to contamination within karst topography it is important to identify surface areas/regions that are responsible for the highest recharge rates. These areas within karst terrain are known as critical recharge areas. Critical recharge areas are vital to the karst system because of their role in providing fast and large amounts of recharge to the underlying aquifers. If the critical recharge areas are lost through development, additional
surface runoff will occur, reducing the net recharge to the aquifers and contributing to increased potential for contamination of surface waters. In communities that utilize these aquifers as a water source, loss of recharge could prove disastrous to the community’s water supply by limiting the water available from groundwater sources.

Development within and close to recharge areas adds impervious surfaces, thereby eliminating or reducing vertical conduits that provide recharge to aquifers. Additionally impervious strata, layers, or geology within the recharge area impedes the recharge rate of the aquifer. As a result, over time, the supply of water available from groundwater to a community is reduced. Additionally, more surface runoff occurs and flooding risks increase. Further, impervious surfaces can speed the process by which a contaminant would reach an aquifer if the impervious surfaces are tributary to a recharge area. Contamination of an aquifer could cause nearby land to be undevelopable in the future (Bakalowicz, 2005).

Human development and urbanization can affect the sustainability of groundwater as a pure and reliable source of drinking water. To better protect reliable underground water sources in a karst topography, it is important to identify and protect critical recharge areas. This research will focus on developing a geographic information system (GIS)-based process to delineate critical recharge areas for a case study watershed, Spring Creek, within the karst region of Centre County, PA.
Chapter 2. LITERATURE REVIEW

This literature review describes the unique characteristics related to karst areas and documents the current state of research and understanding of groundwater recharge mapping in karst topography. The review will focus first on groundwater recharge and then cover the interaction between groundwater and surface water, characteristics of karst, the importance of aquifers, responsible use of aquifers, responsibility in land development, and conclude with a discussion of research and practice in mapping recharge areas. Since this research is focused on frequently studied Spring Creek watershed containing Penn State University’s main campus, information on previous research conducted in the Spring Creek watershed was included, when relevant, under each section of this literature review. For the purposes of this study, the word ‘watershed’ refers to both the surface and subsurface Spring Creek watershed, and will consider the land area that contributes surface and subsurface flow to Spring Creek.

2.1 Groundwater Resources and Usage

The ready availability of ample (quantity) and suitable (quality) freshwater supply is necessary to form and sustain societies around the world. Groundwater is often used as a supply due to a wide availability of groundwater as a freshwater source throughout the world. The proper use of groundwater is vital to urban, industrial and agricultural needs in societies where it is relied upon. Groundwater plays a major role in economic development, as a ready supply of freshwater is important to individual households, businesses and industries (de Vries and Simmers, 2002).

Groundwater use throughout the world stands at about 1,000 km³/year, which is nearly 1.5% of renewable water resources. The United States alone uses 110 km³ of groundwater per year. With improved water extraction technologies, the use of groundwater has increased
dramatically worldwide since 1950. Greater reliance on groundwater makes the protection of the resource more important to societies (Shah, 2004).

Contamination of groundwater is an important societal issue due to the reliance on groundwater as a potable water supply. Most of the northeastern United States is underlain by fractured bedrock, giving the entire vertical soil and geologic profile high hydraulic conductivity; the speed at which water can move through a profile to groundwater. In karst areas groundwater exchanges back and forth with surface water. Due to the fractured topography in karst, often water will move from the surface to an aquifer quickly and directly, not allowing for filtration through the soil media and increasing the likelihood of groundwater contamination (Gburek and Folmar, 1999).

The risk of groundwater pollution is much larger in karst areas than in areas with greater protective cover. Protective cover includes the soil profile, which is often diminished in karst areas due to soil passing through cracks in the bedrock. The fractured nature of karst bedrock also increases the hydraulic conductivity of the aquifer, resulting in velocities up to hundreds times larger than in alluvial aquifers. In alluvial groundwater systems, longer holding times allow for additional purification of water. The shorter holding times exhibited by karst aquifers inhibits the time for purification to occur. These characteristics increase the need for protection and responsible management of karst aquifers (Kacaroglu, 1996).

Section 7.4 of the Pennsylvania Stormwater Best Management Practices (BMP) Manual (the Pennsylvania Department of Environmental Protection (DEP)’s Bureau of Watershed Management) is devoted to the management of stormwater in a karst terrain. The manual states
potential causes for new sinkhole development include creation of new concentrated sources of water, leaky sewer pipes, leaky water pipes, and weather events (PA-DEP, 2006).

Pollution found in groundwater can be divided into four different source groupings; municipal, industrial, agricultural, and miscellaneous sources. Human activities that have a major impact on karst aquifers include urbanization, industrialization, agricultural production, and forestry activities. These activities can increase runoff rates and volumes as well as introduce potential contaminants to the system. To protect groundwater against pollution two protective measures must be implemented: preventing pollution from reaching recharge areas and preventing direct discharge of pollutants into the aquifer (Karcaroglu, 1996).

2.2 Recharge Areas

Groundwater recharge can be defined as a flow of surface water that eventually reaches the water table. The water table is generally defined as an area that is saturated with groundwater. In a karst area, an aquifer would be considered as ‘below the water table,’ meaning that the aquifer is filled with water (de Vries and Simmers, 2002). Water exists in two major zones beneath the land surface; the unsaturated vadose zone and the saturated groundwater zone. The water table can also be viewed as the line between the vadose and saturated zones. Voids exist in the soil of both the unsaturated and saturated zones; in the saturated zone these voids are filled exclusively with water. In the zone beneath the water table, the water pressure is great enough to fill wells, allowing for extraction and use as a water supply (USGS, 2008).

Groundwater and surface water react differently with each other based on the terrain in which the interaction occurs. The United States Geological Survey (USGS) groups these areas into five different terrain types: mountainous, riverine, coastal, glacial and dune, and karst. Karst
terrain is widely characterized by areas formed by the dissolution of carbonate rocks. Karst areas may contain sinkholes, underground drainage networks consisting of large rocks and caves, and drainage systems that are often disrupted. Karst areas exhibit very efficient groundwater recharge as water moves slowly through small pore spaces and quickly through enlarged pore spaces. The water movement in karst terrain is highly unpredictable due to the large and variable numbers of fractures in the underlying geology. Seepage and springs are commonplace in karst terrain and exist in a wide range of sizes. It is also common for medium-sized streams to drain entirely into rock openings, while showing up again elsewhere down gradient (USGS, 2008).

There are three principal types of recharge that are typically considered in any terrain: direct recharge, indirect recharge, and localized recharge. Direct recharge refers to water that enters the groundwater from saturated or wet soils and occurs vertically through the soil profile. Indirect recharge is the process whereby water enters the water table through overland flow and infiltration to the water table at a location different from where rainfall landed. Localized recharge occurs where water reaches the water table through horizontal flow (de Vries and Simmers, 2002).

Recharge in karst terrain is categorized into four different types: allogenic recharge, diffuse infiltration, internal runoff, and overflow from caprock or perched aquifers. Allogenic recharge occurs where streams drain from non-carbonate areas and enter a karst aquifer through a swallet, an opening where a stream goes underground. Diffuse infiltration occurs when rainfall moves through the soil and underlying karst geologic formations and enters the aquifer through either fracture permeability or by matrix flow. Internal runoff occurs when storm flow enters depressions that are quickly drained into the aquifer through sinkholes. Sinkholes often have an
open drainage channel to the land surface that can directly charge an aquifer in karst terrains (White, 2002).

In his article on developments and open questions in karst hydrology, White (2002) writes “The characterizing features of karst aquifers are open conduits which provide low resistance pathways for ground water flow and which often short circuit the granular or fracture permeability of the aquifer.” An analysis of karst hydrology requires a consideration of both surface and ground water concepts. In karst areas, the surface water will become groundwater when it passes through stream beds, sink holes, or otherwise reaches the groundwater. Likewise, groundwater turns into surface water when it comes to the surface at springs or seeps.

The rate of recharge is inherently dependent upon the surface topography, soil properties, underlying geologic conditions through which water flows, as well as weather conditions in the region. The rate of recharge can be highly variable depending on these factors. Karst areas are known for their enhancement of recharge. It has been documented by de Vries and Simmers (2002) that an exposed karst area in Saudi Arabia sees 47% of the annual rainfall flowing into sinkholes and rock fractures. In another karst area, the Portuguese Algarve, an average rainfall of nearly 550 mm (21.7 inches) results in an annual recharge estimated at 150-300 mm (5.9-11.8 inches) (de Vries and Simmers, 2002).

Streams also interact with groundwater. Groundwater can charge the stream through the streambed, known as ‘gaining streams’; however, streams can also recharge groundwater through the streambed, known as ‘losing streams.’ These interactions are caused by the elevation of the water table in relation to the stream channel elevation. In a ‘disconnected stream,’ the
water table elevation is lower than the stream elevation and the stream will ‘charge’ or lose water to the groundwater (USGS, 2008).

Lakes and wetlands tend to act similar to streams in their interactions with groundwater. Lakes either charge or receive water from the groundwater aquifer, depending again on the elevation of the water table relative to the elevation of the lake or wetland. Most lakes, however, tend to have a mixture of charging the groundwater in certain areas, and being charged by groundwater in other areas within the lake’s profile (USGS, 2008).

When considering a precipitation event in the Spring Creek basin, one is also able to consider the surface runoff related to the event. Overland runoff directly relates to subsurface stormflow during a rainfall event in the two following manners. Overland runoff occurs when the infiltration capacity of the soil is exceeded by the rainfall intensity, known as a partial source area contribution (PSAc), or when complete saturation of the soil profile above the water table causes overland runoff, known as a variable source area contribution (VSAc). A PSAc occurs in areas of the basin that are highly developed with impervious surfaces, or in areas where a thin soil profile that has a low infiltration capacity exists, while VSAc occurs in varying degrees depending upon the duration and intensity of a storm. Runoff from VSAc occurs in areas of the basin that are vegetated with thinner soils with a higher infiltration capacity because of the thinner soil profile. Runoff in VSAc areas most commonly occurs at the bottom of hill slopes, stream banks, in shallow water tables, and adjacent to drainage ways (Fulton et al., 2005).

Streamflow within the Spring Creek basin is also greatly impacted by the exchange of water between the stream and the underlying aquifers. This is most applicable in areas that have permanent streams within gaps in ridges that also receive runoff from the mountains. These
conditions are true for Buffalo Run, Roaring Run, and Galbraith Gap Run within the Spring Creek basin. Water from streams can be lost by infiltration within the stream or by flowing directly into sinkholes (Fulton et al., 2005).

2.3 Problems Facing Karst Areas

Kacaroglu (1996) suggests that to protect karst areas against pollution, regulators must first understand how recharge to the aquifer is occurring. The areas of concern can be primarily identified through consideration of the recharge type, ranging from diffuse to concentrated systems; the flow, diffuse to conduit systems; and the storage system size. After identifying the area(s) of concern, regulators should reference data and information relative to eleven different categories, described by Kacaroglu (1996) as: “(1) sources of pollution (municipal, industrial, agricultural, mining, etc.), (2) properties of the pollutants (solid, liquid; inorganic, organic, bacteriological, radioactive; toxicity, mobility, persistence, etc.); (3) attenuation mechanisms of the pollutants; (4) water sources (wells, springs, surface waters) and their locations; (5) waste disposal sites and disposal methods (landfilling, land application, subsurface discharge); (6) geology and karst geomorphology of the area; (7) groundwater recharge areas and watershed boundaries; (8) groundwater circulation in a karst aquifer (groundwater flow routes, velocity and discharge); (9) rainfall, stream, and spring discharges, and their fluctuations; (10) groundwater level fluctuations; and (11) relations between surface water and groundwater.” Kacaroglu suggested information in these categories be used to describe the degree of pollution in karst areas.

Kacaroglu (1996) goes on to outline nine measures that can be taken by governmental units to protect aquifers; “(1) regulation of planning, location, and construction of settlements, houses, buildings, roads, industrial plants, etc., (2) treatment of waste waters and liquid wastes,
prohibition of disposal of liquid wastes, waste waters, and solid wastes into underground, (4) construction of proper sewage and waste water collection systems, (5) prohibition or restriction of use of hazardous and toxic materials, (6) proper location, construction and operation of fertilizer and pesticide facilities, (7) construction and operation of proper collection systems for manure and animal slurry, and an application of land spreading policy, (8) correct application of fertilizers and pesticides, (9) application of proper collection, storage, and treatment methods for solid wastes.”

Permeability of karst is typically defined by the hydraulic conductivity of an area through analysis of rock cores, through laboratory testing, or through drilling into the aquifers. Conduits have a large impact on the permeability and flow behavior with the karst terrain. However, it is difficult to isolate and identify individual conduits, which allow permeability rates to change considerably between regional, local, and sublocal regions of karst (White, 2002).

In karst aquifers, conduit or underground flow is extremely important. The average groundwater velocity occurring within karst zones varies between 0.002 to 55 cm/sec (0.00007 to 1.8 ft/sec), but most often has a value near 5 cm/sec (0.164 ft/sec). This rapid movement of water within the flow conduits means any contamination of the karst aquifer can be moved quickly through the aquifer in a short amount of time (Kacaroglu, 1996).

Preventing pollution is much more effective and cost efficient than remediation after an area has been contaminated. The two main focuses of any pollution prevention program are: preventing pollution from reaching recharge areas and preventing direct disposal of pollutants into the aquifer. For areas already experiencing groundwater pollution, the further spread of
pollution should be minimized, the pollution sources eliminated, and protection zones for the groundwater should be formed based upon their contribution to groundwater (Kacaroglu, 1996).

Heinz et al. (2008) showed micro-pollutant and bacterial contamination in karst aquifers and springs due to combined sewer overflow without proper pretreatment. In this study, a stormwater tank located 9 km from a spring proved to be a contamination source. Stormwater tank overflow was found to be responsible for the presence of *E. coli*, which reached 10,000 CFU per 100 mL in a sample in a karst spring in Gallusquelle, Germany. The drinking water standards in Germany specify 0 CFU of *E. coli* per 100 mL sample.

The presence of a highly-traveled road or highway contributes to pollution of groundwater. Twenty to 80% of the water that falls on a road runs off, depending upon evaporation, spray and pool formation, grade of the road, and, most importantly, the road surface used. The composition of the runoff through a storm event is not consistent; the ‘first flush,’ the initial runoff from the road surface, carries a more highly concentrated pollutant load than the rest of the storm. Highly trafficked roads are a cause for concern in karst areas. If the road is close to a sinkhole or recharge area, pollution to an aquifer could occur rapidly due to the increased possibility of contaminant release (Van Bohemen and Janssen Van de Laak, 2003).

Stormwater runoff from highways and other impervious surfaces can flow directly from the surface into aquifers through sinkholes. Stephenson et al. (1999) performed a study on highway runoff into a sinkhole near the I-40/I-640 interchange in Knoxville, TN. The interchange carried an average of 76,000 vehicles on a daily basis, and the sinkhole discharged to a spring that was 128 meters from the sinkhole. The investigators found increases of zinc and lead in the spring water as a result to the runoff entering the sinkhole from the highway. Total
zinc levels peaked at 0.208 mg/L in the spring water after a storm event and lead peaked at 0.031 mg/L (Stephenson et al., 1999).

After the analysis of the spring near the highway interchange, Stephenson et al. (1999) concluded that “contaminant load is more closely related to the volume of runoff than contaminant concentration.” And “urban development of the karst terrain in eastern Knoxville may be responsible for this observed phenomenon.” This indicates the holding capacity and actual runoff had a large impact on the concentrations of a contaminant downstream, but also a high concentration load at the inlet to the aquifer can result in a diluted concentration at the spring outlet. The contaminated runoff will become diluted and impact larger volumes of water as it moves downstream in the system (Stephenson et al., 1999).

Impervious surfaces developed in karst areas can reduce the recharge in karst areas and has two major effects. The aquifer has less incoming water and the water that does enter does so more rapidly due to faster travel times on the surface. The ‘paving over’ of recharge areas can diminish the recharge to the aquifer and restrict the ability of infiltration processes to clean and filter the water. Additionally, pushing larger volumes of water away from their natural recharge areas can contribute to problems such as sinkhole formation. The impacts of land development and reliance upon groundwater as resource contribute to the need for watershed wide stormwater management (Toran et al., 2009).

The BMP Manual (PA-DEP, 2006) further elaborates on the potential for contamination in karst aquifers. Specifically, the manual warns about aquifers being susceptible to contamination due to thin soils, fractures, voids, and sinkholes allowing for the bypass of natural filtration processes. The short travel times in a karst system also allow for contamination to
spread quickly. Land development in karst areas can cause additional sinkholes, contamination, and deterioration of the aquifer system (PA-DEP, 2006).

The BMP Manual goes on to outline design techniques for planning in karst topology. The BMP Manual recommends infiltration be promoted at karst sites where infiltration is feasible, or, as an alternative, to stop infiltration altogether to avoid formation of sinkholes and avoid liability from groundwater contamination. The two options outlined are polar opposites in the way they handle stormwater in a karst environment. The BMP Manual goes on, “The worst scenario is to ignore karst features entirely and thus significantly increase the potential for costly delays, repairs, catastrophes and legal proceedings” (PA-DEP, 2006). The Manual also addresses the two opposite approaches to handling stormwater in karst through the following remark, “Non-infiltration plans may seem safer and more economical even with the increased cost, but, an additional, long-term “cost” is incurred—lowering of the groundwater table, reducing the potential groundwater resources of an area, and increasing the risk of a sudden, catastrophic ground collapse (via a failed impoundment, swale, retention structure, etc.)” (PA-DEP, 2006).

The BMP Manual suggests municipalities within karst areas implement watershed-wide stormwater planning. It advocates the existing karst drainage be incorporated into the plan in order to achieve the best results, but it also recognizes stormwater control plans in Pennsylvania have typically avoided these techniques due to inexperience in working with karst. This is in contrast to areas such as Kentucky and Tennessee where the design professionals are more apt to utilize karst features in their plans. A list of guidelines developed for design professionals suggest designers maintain the natural water balance, avoid building next to or on top of natural drainage features, avoid eliminating recharge areas, avoid concentrated injections, avoid groundwater withdrawals, create a buffer around karst features not used for infiltrating, designate
recharge areas, use only improved sinkholes as injection wells, avoid concentrating water, and reduce runoff velocity and volume. It is important to note this is not the complete list of guidelines presented in the BMP Manual, but are the ones dealing most directly with the concept of recharge in karst areas. In order to better manage karst areas, one needs to understand how and where recharge is occurring (PA-DEP, 2006).

2.4 Recharge Analysis Techniques

Scanlon et al. (2002) wrote a summary article describing different techniques for quantifying groundwater recharge. For discussion purposes, the group first categorized the techniques based upon which zone data were obtained from (surface water, unsaturated zone, or saturated zone). Within each of the zones, the group further categorized the techniques into physical, tracer, or numerical modeling.

Physical techniques based upon surface water studies include channel-water budgets that calculate groundwater recharge based upon stream gauging data. Seepage meters use a reservoir of water attached to a cylinder, pushed into the bottom of a body of water. Seepage meters base groundwater recharge on the flux within the cylinder, giving point data. Many seepage meters must be used in order to attain a recharge estimate over a large area. Baseflow discharge is based upon stream hydrograph separation and used in watersheds with gaining streams (Scanlon et al., 2002).

Another version of a physical technique is the creation of a water table map. The water table depth is not constant and can range from zero to thousands of meters below the earth’s surface; however, the depth of the water table can provide information on where recharge is occurring. For areas in close proximity to natural bodies of water, the depth to the water table
tends to be shallow. The water table depth can easily be found by determining the depth from land surface to water surface in a well. Water table depths vary at individual locations as a function of seasons, changing recharge and discharge patterns, and recent precipitation. Because of these varying factors, a water table map can be constructed if measurements are taken at multiple locations at the same time, with the map being representative of the water table at that point in time (USGS, 2008).

Tracer techniques based upon surface water studies include heat tracers that estimate recharge from surface bodies by monitoring temperature fluctuations in surface water bodies. Isotopic tracer techniques use the presence of stable isotopes in headwater streams, compared to the presence of isotopes in the local precipitation. The isotopic signature from the two sources is then compared to the isotopic presence in the groundwater in order to determine its source (Scanlon et al., 2002).

Tracer techniques based upon unsaturated zone studies include applied tracers, where a pulse of tracer is injected in the soil profile. The time taken and depth traveled allow researchers to estimate a recharge rate at that point on the landscape. Historical tracers are also used to estimate recharge but are based upon previous human activities (e.g. contaminant spills, agricultural activities) rather than an intentional pulse of tracer being released. Environmental tracers (e.g. chloride) use atmospherically deposited tracers. With the rate of atmospheric deposition, and the concentration in drainage water, environmental tracers can be used to estimate recharge (Scanlon et al., 2002).

Physical techniques based upon unsaturated zone studies include the use of lysimeters. Lysimeters can be made of containers of soil isolated hydrologically from surrounding soils, and
should be placed below the root zone to correctly estimate recharge. Lysimeters are expensive, difficult to construct, and involve high maintenance. The zero-flux plane is a relatively expensive technique used to determine where the difference between evapotranspiration and drainage occurs in the soil profile and quantifies those two values. The Darcy’s law technique gives a point value for recharge estimate and many points are necessary for recharge mapping (Scanlon et al., 2002).

The numerical modeling techniques based upon surface water studies generally use a residual term in the water budget equation to find recharge rate. Typically, numerical modeling techniques provide either a ‘lumped’ estimate, when a single recharge estimate is provided for an entire catchment, or provide estimates for smaller units. The spatial resolution of a numerical modeling technique is highly variable from researcher to researcher. Recharge was estimated on areas as small as 0.4 square kilometers to average areas of 3,750 square kilometers based upon the data used and the techniques of estimation (Scanlon et al., 2002).

Numerical modeling techniques are the least expensive of the groundwater recharge techniques and rely upon previously collected data sets. In an area with readily available spatial data, a researcher can incorporate their data into their numerical model quickly and efficiently. Numerical modeling techniques can also be compared to previously conducted recharge testing in order to validate the model in areas where such testing has occurred.

2.5 GIS as a Tool for Recharge Mapping

Geographic information systems (GIS) are database/mapping systems primarily used for data analysis and mapping purposes. A GIS offers advantages in the handling of spatial data. GIS can be used to map and analyze information about areas difficult to access. Analyses of large
areas can be performed quickly. When combined with the use of remote sensing (e.g. satellite photography), GIS can be used to identify and analyze surface features, which can impact fate of water resources of the region analyzed (Sener et al., 2005).

GIS also allows for the integration of different data corresponding to the spatially mapped layers (Tweed et al., 2007). Many data layers are available for public access online and include information such as soils, topographic information, geologic information, and land use data in addition to many other layers of information. Readily available data layers allow the user to perform analyses based on the information stored within.

In a 2009 paper by Yeh et al., a technique was developed to use GIS to analyze the potential for groundwater recharge. In their approach, the research team analyzed aerial photography to determine the different land uses. They combined this information with geological information and lineament (the shape of the ground) information. They considered five different major characteristics of the land to develop a potential groundwater recharge map. These five characteristics were: lithology, land use and cover, lineaments, drainage, and land topographic slope. The group separated information about these factors into two different groups: major and minor factors. Numerical values were assigned to represent the infiltration potential for each factor. The land area was then analyzed using these factors on a weighted scale.

The type of rock at the land surface (lithology) was considered a major factor affecting groundwater recharge. As the team determined weighted values for each of their factors, they assigned a 29% weight to the consideration of lithology making it the factor with the greatest influence on recharge potential. Lithology was then broken down into four different subsets: a
value of 7 was assigned to black schist, shale, phyllite, and slate, a value of 15 was assigned to quartz sandstone mixed with phyllite, 22 assigned to marble, and 29 to gravelly sand (Yeh et al., 2009).

The land use and cover factor used by the research team considered vegetation, concentration of residential areas, and soil deposits. The team assigned a weight of 24% to the land use and cover factor. The land cover/land use factor was broken down into four categories: the presence of a building was assigned a value of 6, forested land was assigned a value of 12, agricultural land was assigned a value of 18, and surface water was assigned a value of 24 (Yeh et al., 2009).

The lineament density factor included consideration of groundwater movement and storage. The team assigned a 19% weight value for the lineament factor. The lineament factor was broken down into three subsets: 0.0-0.4 km lineament/km\(^2\) land was assigned a value of 6, 0.4-0.8 km lineament/km\(^2\) land was assigned a value of 13, and 0.8-1.2 km lineament/km\(^2\) land was assigned a value of 19 (Yeh et al., 2009).

The drainage factor primarily considered the length of surface streams per unit area. A weighting factor for average length of runoff in a square kilometer was determined, and the team assigned a 14% weight value to the drainage factor. The group split the drainage factor into four subsets: a value of 4 was assigned to 0.0-1.5 km/km\(^2\), 7 was assigned to 1.5-3.0 km/km\(^2\), 11 was assigned to 3.0-4.5 km/km\(^2\), and 14 was assigned to >4.5 km/km\(^2\) (Yeh et al., 2009).

The final factor considered was land slope. The average slope of a land area was assigned a 14% weight value and this group factor was split into four minor factors. A value of 4 was
assigned to areas with 55-90° slope, 7 to areas with a 35-55° slope, 11 to areas with a 15-35° slope, and 14 to areas with a 0-15° slope (Yeh et al., 2009).

Shaban et al. (2006) performed a study very similar to Yeh et al. (2009) to also identify recharge areas. Shaban and his research team performed a study in Occidental Lebanon specifically focused on determining recharge potential zones. They considered the factors important to influencing recharge potential as “lineaments, drainage, lithology, karstification, and land cover/land use” (Shaban et al., 2006).

These factors were weighted according to their influence on recharge. Weight values were assigned as 26% value to lineaments, 16% value to drainage, 26% value to lithology, 21% value to extent of karstification, and an 11% value to land cover/land use (Shaban et al., 2006).

Using the weighted scale, Shaban’s group used ERSI’s ArcView program, a GIS software package, to analyze the different factors and create a recharge prediction data layer. The data layer portrayed recharge as a function of percentage of precipitated water to be recharged to subsurface strata. This data layer was divided into five major groups: very high (45-50%), high (30-35%), moderate (10-20%), low (5-10%), and very low (<5%) recharge potential (Shaban et al., 2006).

Singh et al. (2013) identified areas of interest for artificial groundwater recharge zones in the Bist Doab basin of Indian Pujab. The region has experienced water scarcity caused by intense agricultural operations and the Singh et al. (2013) study was focused on identification of areas that could be utilized as artificial groundwater recharge zones. The study was based on eight different thematic layers: geomorphology, geology, land use/land cover, drainage density, slope, soil texture, aquifer transmissivity, and specific yield. These different layers were given an
assigned weight based on their perceived importance to recharge in the region. Further, the thematic layers were subdivided to assign weights based upon their individual properties. The end product of the work was a map grouping recharge prospects into four different categories: Very good, good, moderate, and poor.

Chenini and Mammou (2010), like Singh et al. (2013), conducted a study to identify potential artificial groundwater recharge zones in Tunisia due to increased water demand from agricultural and industrial activities in the country. The study was based on topographic data, geologic data, as well as hydrogeological and groundwater data. The results of the study utilized piezometric maps in order to estimate recharge as a function of depth to aquifers/groundwater. This particular study did not use a consistent resolution across the study area, but broke down the study into averages for entire sub-basins.

Studies aimed at identifying groundwater recharge zones have utilized a variety of selection criteria. The difference in selection of the major components of the studies have depended upon different regions, the personal opinions of the researchers themselves, different conditions with which the researchers had to deal, the available data, and the state of the available software packages at the time of the research. See Table 1 for a summary of these criteria in current recharge models.
Table 1: Summary of criteria used in previous studies (adapted from Huang et al. (2013))

<table>
<thead>
<tr>
<th>Reference</th>
<th>Lithology</th>
<th>Slope</th>
<th>Drainage</th>
<th>Land use</th>
<th>Karst</th>
<th>Lineaments</th>
<th>Soil</th>
<th>Geomorphology</th>
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<tbody>
<tr>
<td>Salama et al. (1994)</td>
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<td>Singh and Prakash (2002)</td>
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<td>Jaiswal et al. (2003)</td>
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<td>Shaban et al. (2006)</td>
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<td>Adham et al. (2010)</td>
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<td>Chenini et al. (2010)</td>
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<td>Rahman et al. (2012)</td>
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<td>Deepika et al. (2013)</td>
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<td>Nag and Ghosh (2013)</td>
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<td>Singh et al. (2013)</td>
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Chenini et al. (2010) study also included consideration of fractured outcrops and piezometry. The Rahman et al. (2012) study, which was focused on site selection for managed aquifer recharge, with known sources of pollutants, also included sub-surface impermeable layer thickness, groundwater depth, distance to groundwater pollution source, aquifer thickness, groundwater quality, and residence time. The Deepika et al. (2013) study also included the consideration of geology. The Singh et al. (2013) study also included geology, aquifer transmissivity, and specific yield.
The use of GIS techniques for delineation of recharge areas have been used by a number of researchers. Shaban et al. (2006) points to studies by “Bradbury and Muldoom (1994), Gustafsson (1994), Teeuw (1994), Per Saner et al. (1996), Edet et al. (1998) and Travaglia and Ammar (1998),” and makes the observation that the recharge potential can be determined by different interactive factors, and the factors considered vary in each one of the listed studies. More recently, works have been published by Jiménez-Madrid et al. (2013), Singh et al. (2013), Chenini and Mammou (2010), and Rahman et al. (2012) related to mapping groundwater recharge areas using GIS.

Karst factors have a large effect on a ‘recharge potential factor,’ yet such karst conditions have been considered by relatively few studies of recharge area identification using GIS. Karstification has been determined through remote sensing for the purposes of previous studies, by identifying a ‘pitted surface’ on the ground surface. The limitation of this method is that it is not effective when considering land areas with heavy cover (Shaban et al., 2006).

The USGS released a Water Budget and Recharge-Area Simulations for the Spring Creek, Nittany Creek, and portions of the Spruce Creek Basins in 2015. This Scientific Investigations Report includes estimates of recharge in the Spring Creek Basin based upon the GSFLOW Model, a tool that estimates recharge by simulating the hydrologic cycle. This simulation will be further discussed in the ‘Discussion’ section of this paper (Fulton et al., 2015).

2.6 TR-55 Method

Technical Release 55 (TR-55) is a document that presents a modeling technique used to estimate stormwater runoff and peak flow rates in small watersheds. In Pennsylvania, TR-55 is
commonly used in engineering projects to perform pre- and post-development analyses for post-construction stormwater evaluations (USDA, 1986).

To establish a runoff estimate, TR-55 begins with a rainfall depth uniformly distributed over a landscape. This depth of rainfall is distributed over a time period of interest, most commonly a 24-hour period. The rainfall is then converted to a runoff estimate through the use of a runoff curve number (CN). The CN for a particular land use and hydrologic soil group (HSG) is chosen from tables available in TR-55. CNs were assigned to these land uses and HSGs based upon studies in agricultural watersheds. This estimation of runoff is called the SCS (since renamed NRCS) runoff curve number method (USDA, 1986).

The SCS runoff curve number method breaks down the depth of rainfall into two main components known as the initial abstraction and the potential maximum retention after runoff begins in order to estimate a runoff depth. Each of these components is derived from the CN.

TR-55 gives the SCS runoff equation as:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

where

- $Q =$ runoff (in)
- $P =$ rainfall (in)
- $S =$ potential maximum retention after runoff begins (in) and
- $I_a =$ initial abstraction (in)

TR-55 gives the definition of initial abstraction as:

$$I_a = 0.2S$$
TR-55 gives the definition of potential maximum retention after runoff begins as:

\[ S = \frac{1000}{CN} - 10 \]

The initial abstraction component of the equation is comprised of “interception, initial infiltration, surface depression storage, evapotranspiration, and other factors” (USDA, 1986). It is important to note the assumptions that went into developing the initial abstraction component. The component was originally developed on agricultural watersheds and may imply a larger initial abstraction than is true in urban settings where stormwater flows directly into a stormwater system. However, the opposite can also be true, and the initial abstraction may not be large enough in areas where depressions such as infiltration basins have been built to retain runoff. Initial abstraction can be arranged for values other than 0.2S depending upon known watershed conditions (USGS, 1986).

Additional limitations of the SCS method include that the equations do not account for snowmelt or rain when the ground is frozen. Using the CN becomes less accurate in events where the runoff is less than 0.5 inches. The SCS method only considers surface runoff and does not take large subsurface flows into account (USGS, 1986).

Diamond and Melesse (2016) incorporated TR-55 in their study to create an artificial recharge area mapping in the Bahamas. In the study, volumes of runoff were calculated using the SCS CN model and then coupled with aquifer location, elevation, and slope data. Through this study, locations were evaluated that could be utilized as injection well sites and be suitable for artificial recharge (Diamond and Melesse, 2016).
Worksheet 4 of the Pennsylvania BMP Manual provides a methodology where runoff from a 2-year return period storm is determined for each land use and HSG in the watershed area of interest. These individual runoff values for each of these areas is then totaled and compared in pre- and post-development conditions. The two-year volume increase caused by development of land is taken as the required control volume in Pennsylvania (PA-DEP, 2006).

The SCS equations rely on two coverage inputs in order to assign a CN to a land area. The CN is assigned based on land use and the hydrologic soil group. Once the CN is determined, a 24-hour rainfall depth allows for the estimation of runoff. By subtracting the determined depth of runoff from the 24-hour rainfall depth, the depth of water remaining water will be considered surface recharge.
Chapter 3. GOALS AND OBJECTIVES

The goal of this research is to use GIS technology to predict the surface location of critical recharge areas in karst topography, defined as the surface areas that contribute the most to recharge. This research will be conducted in the Spring Creek watershed, Centre County, near State College, PA. The research will investigate the feasibility of a GIS-based mapping approach using available spatial data coverages indicative of recharge potential mapping for a local watershed. This is important, as recharge areas are vital to maintaining and protecting the volume and quality of water supply in communities. Further, the information gathered from such a study can contribute to decisions made in local development plans to minimize risk of groundwater contamination.

In seeking to complete this goal, the following objectives will be pursued:

• Identify criteria and processes important in identifying and delineating critical recharge areas in a central Pennsylvania karstic watershed.

• Develop GIS methodology and acquire necessary datasets to identify and map these critical recharge areas.

• Provide general data layers for future works, similar to those used in other models, regardless of their applicability to the present modeling efforts.

• Develop a GIS-based recharge model using the approach of the Yeh et al. (2009) study.

• Develop a GIS-based infiltration potential model based on the NRCS procedure (TR-55) for quantifying watershed response to rainfall events that incorporates areas tributary to sinks and sinkholes as well as impervious surfaces.
• Evaluate these two models and make suggestions for future recharge modeling studies.

Overall, the research question to be explored is whether it is reasonable to use GIS to effectively identify and map critical recharge areas in a small karst watershed using local, countywide, and statewide datasets.
To develop a groundwater recharge model in ArcGIS, information was collected on previous groundwater recharge models available in published literature (see Chapter 2. Literature Review). The bulk of the previous models used a weighted linear combination method to develop their model. A typical weighted linear combination equation would look like this:

$$Recharge \ Value = x_1y_1 + x_2y_2 + \cdots x_ny_n$$

Where $y_n$ are the input variables, $x_n$ are the weighting coefficients, and Recharge Value is the response variable. A model based on this type of equation is simplistic and allows for additional inclusion of variables and weighting factors. Shortcomings of a model created by this method include the inability to address interdependent model data layers and the inability to handle overriding input variables. For example, if the presence of a land use completely inhibits infiltration, then that land use should give the model output a zero infiltration value.

In the models studied, a major trend was that a typical model equation result was limited by the resolution of data the researchers were using, a typical resolution in studied works was 1000 meters by 1000 meters. The resultant model values are dependent upon the scoring system employed (e.g., recharge values scaled from 0-1, 0-100, or 0-10). There is no common scoring system used by researchers. Thus, comparison of two or more different models requires some mathematical manipulation.

Previous datasets used in groundwater recharge studies include lithology, slope, drainage, land use, karst, lineaments, soil, geomorphology, fractured outcrops, geology, aquifer transmissivity, and specific yield. In this study, there is a recognition that data layers can be used within the model in many different ways. Several model data layers will be presented, as well as
several approaches to categorizing and processing each of those model data layers. These model data layers were chosen based on their use in previous GIS models in Spring Creek watershed, to utilize widely available information when possible for applicability to different areas, and were also chosen to allow new approaches to handling data that were not used in the reviewed literature.

The categorized/processed model data layers developed by this study were input into two different models across the Spring Creek watershed. First, the model of Yeh et al. (2009) was adapted and applied to the watershed of interest. Second, a new model, based on stormwater runoff calculations, was used to identify infiltration potential areas in the karstic Spring Creek watershed.

4.1 Methodology Overview Statement

After analysis of the available data and consideration of previous studies, the decision was made to utilize five main datasets in this study. Soils data, geology data (which contained sinkhole mapping), elevation data (used to determine sinks and areas tributary to sinkholes), land use data, and building footprint data were used in this work. These data sets were chosen based on previous studies and to take advantage of available land use data for Centre County, Pennsylvania.

4.2 Case Study Location

This research project focused on the Spring Creek watershed, Centre County, PA. In the Spring Creek watershed, groundwater pumpage rates from public supply wells have increased with rapid growth in the area. The average annual pumpage rate from three local public water suppliers; the State College Borough Water Authority, the Penn State University, and College
Township was documented in Fulton et al. (2005) for the years 1980-2002. The annual daily averages for the water suppliers have increased from lows of approximately 9,100 m$^3$/day (2.4 Mgal/day) in 1981 and 1982 to a high of approximately 34,000 m$^3$/day (9.1 Mgal/day) in 2000. Pumpage rates from private wells were not available. As population grows in the Spring Creek watershed, so does demand for groundwater resources (Fulton et al., 2005).

In addition to water used from public supply wells, local water suppliers also withdraw spring water for public use. Water supplied from springs is estimated at approximately 26,000 m$^3$/day (6.9 Mgal/day). Due to the groundwater/surface water interaction within the karstic system, it is important to note that spring water can often be considered as groundwater coming to the surface (Fulton et al., 2005).

GIS analysis was conducted using ESRI’s ArcGIS 10.5. Figures 1 and 2 show the location of the Spring Creek watershed within Pennsylvania.
Figure 1: Location of Centre County in Pennsylvania (PA Department of Transportation, 2011)

Figure 2: Location of the Spring Creek study area in Centre County, PA (from PA Department of Transportation, 2011 and Fulton et al., 2005)
4.3 Data Descriptions

In order to conduct this study, publicly available data sources were compiled and collected to provide information on features related to recharge. Table 2 provides the sources of these compiled data.

Table 2: Data sources

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Source</th>
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<tbody>
<tr>
<td>Soils</td>
<td>USDA: NRCS, Soil Survey Geographic Database</td>
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<tr>
<td>Elevation</td>
<td>Penn State Institutes of Energy and the Environment PAMAP Program</td>
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<tr>
<td>Drainage</td>
<td>Pennsylvania DCNR</td>
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<tr>
<td>Geology</td>
<td>Pennsylvania DCNR</td>
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<tr>
<td>Land Use</td>
<td>Centre County Government</td>
</tr>
<tr>
<td>Building Footprints</td>
<td>Centre County Government</td>
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<tr>
<td>Fracture Trace Intersections</td>
<td>Fulton et al. (2005)</td>
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<tr>
<td>Sinkholes</td>
<td>Pennsylvania DCNR</td>
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<tr>
<td>Study Area</td>
<td>Fulton et al. (2005)</td>
</tr>
</tbody>
</table>

4.3.1 Soils

The Soil Survey Geographic Database (SSURGO) for Centre County, PA was obtained from the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). The data are available from the following URL: https://websoilsurvey.sc.egov.usda.gov/, and carries a publication date of 2008-12-19. The data have the NRCS code for Centre County, PA (pa027). The purpose of the data set is to provide a digital soil survey, which is consistently the most detailed soil geographic data available in the United States. The data is a field verified inventory of soil types and distribution of those soils across the landscape. The data provided was produced by soil scientists as part of the National Cooperative Soil Survey, and major fieldwork was completed between 1965 and 1974. The soils
classification and correlation for Centre County, PA was approved in January 1975 (USDA: NRCS, 2008).

The SSURGO data are presented as individual map units which are linked to attributes defined in the National Soil Information System relational database. The National Soil Information System relational database provides the extent and properties of soils. The data provided are not designed for use in permitting or regulatory applications, but are provided as a need-based reference to the public. The intent of the NRCS is that the data are to be used for planning purposes only (USDA: NRCS, 2008).

4.3.2 Elevation

Elevation data were obtained from the Penn State Institutes of Energy and the Environment’s Centre County 3m County Mosaic Digital Elevation Model, which is a resampled 9.6 foot horizontal data set covering Centre County, PA created from the original PAMAP Program’s 3.2 foot horizontal dataset (PAMAP Program, 2007). This resampling of the 3.2 foot horizontal dataset was performed by Penn State Institutes of Energy and the Environment in 2015 (Penn State Institutes., 2015). The associated metadata indicates these data are useful for many applications including hydrologic modeling.

4.3.3 Drainage

Drainage data were obtained from the PAMAP Program, PA Department of Conservation and Natural Resources and contains stream and river location data that were provided by county governments across the state (PAMAP Program, 2007b).
4.3.4 Geology

The geology data were also obtained from the Pennsylvania DCNR as part of the Pennsylvania Geologic Survey. The geologic data are given as a 1:250,000 scale map of the bedrock geology of Pennsylvania. The data were originally organized by Berg et al. (1980). In 2001, as a response to requests, the Pennsylvania Geologic Survey digitized the bedrock geology based upon the Berg et al. (1980) work. The Pennsylvania Geologic Survey also went beyond the original scope of Berg’s map and incorporated new mapping completed after Berg’s 1980 work in their digitized dataset. The data available from the DCNR consists of geologic units (pagpoly), dikes (padike), and geologic contacts/faults (pagarc). This dataset is seamless across the state and provided in a geographic coordinate system with a NAD 1927 datum (Berg et al., 1980 and Miles and Whitfield, 2001).

The downloaded geology dataset contained polygon shapefiles (named ‘pagpoly’) which defined the lithology of individual mapping rock units, the name of the dataset, age of the unit, and the map symbol for the polygon. Also present in the geology data package was a polyline shapefile (named ‘pagarc’) that provides the user with information on contact lines (where two formations come together) and fault lines. The final shapefile present in the geology data is polyline information on dikes; however, as dikes were only present in the southeastern part of the state (and no dikes were shown as present in Centre County, PA), this information was not utilized in this study.

4.3.5 Land Use

Land use data were obtained from the Centre County Government. This information is used by the local government to track land uses in the county. The data are stored in a projected coordinate system using the Pennsylvania State Plane North, and the NAD 1983 datum. The data
stored as a polygon shapefile feature class classified into categories and subcategories. The categories used to define land uses are agriculture, commercial, communications, forests, industrial, mined land, mixed use, public or semi-public, reclaimed land, recreation, residential, transportation, utility, vacant and unused land, vacant structure, and water. The subcategories include: a no data field, airport, cell tower, churches and cemeteries, commercial, drainage basin, education, gas wells, government, heavy commercial, heavy industry, industrial, light industry, median, miscellaneous service, mobile home, multi-family residence, parking, pipe line, power generating station, power line, public or semi-public, quarry, radio tower, railways, residential, retail, roads, ROW (Right-of-Way), service institutions, services, single family conventional, solid waste processing and disposal, strip mine, telephone communications, telephone and radio stations, terminal, two to four family residences, urban forest, and water utility. The land use data were obtained on 13 March 2013 and were last updated in 2010 (Centre County Government, 2010).

4.3.6 Building Footprints

Building footprint data were also obtained from the Centre County Government (CCG). The building footprint data are tracked by the local government and can be used in land use calculations. The data are stored in a polygon shapefile feature class format, use a projected coordinate of PA State Plane North and use NAD 1983 as a datum. Embedded in the attributes of the data (among other codes used for local planning) are the municipality, street address, and Tax ID of the parcel on which the building is located. The building footprint data were obtained from the CCG on 15 March 2013 (Centre County Government, 2013).
4.3.7 Fracture Trace Intersections

Fracture trace intersections in the Spring Creek Basin were used from the appendix of the Fulton et al. (2005) study. These data were presented on a point file that showed where multiple fractures intersect in ten high density fracture trace areas across the Spring Creek Basin. This information was adapted from a 1989 study by Nittany Geosciences. These data are not a complete coverage of the Spring Creek watershed, this intersection mapping was only conducted in the area that was being considered for well locations.

4.3.8 Sinkholes

Karst features were obtained from the Pennsylvania Department of Conservation and Natural Resources (DCNR)’s ‘Digital data set of mapped karst features in south-central and southeastern Pennsylvania’ point data set. The dataset is an incomplete inventory that has been collected by the Pennsylvania Geological Survey since 1985. In Centre County, the inventory was conducted countywide. Most features identified in this dataset were identified using aerial photography and is not inclusive of all sinkholes in the watershed. There were limitations of identifying karst features through use of aerial photography, notably that features hidden by vegetative cover were potentially missed. The dataset categorizes karst features as ‘sinkholes, surface depressions, surface mines, or cave entrances’ (DCNR, 2007).

4.4 Study Area

The study area for this project was taken from the Fulton et al. (2005) study. The Spring Creek Basin has different extents in the surface water and groundwater. The groundwater basin encompasses 453 km² (175 mi²), while the surface water basin covers 378 km² (146 mi²). The Fulton et al. (2005) study provided a basin boundary that encompasses both regions and was used as the boundary for this study.
4.5 Data Processing Overview

To incorporate data into different models, each dataset was categorized and processed in several ways. Each categorized dataset was converted to a raster format, and those raster formats were snapped to the elevation raster county mosaic within the ‘Environments’ portion of ArcMap® tools. Snapping the datasets ensured that a common raster grid was used across the Spring Creek Basin. Any raster that surpassed the limits of the study area was trimmed to the boundary using the Extract by Mask tool.

For this study, Pennsylvania State Plane North, North American Datum 1983 was used as the XY Coordinate system. The linear unit used was US Survey feet. Any dataset that was not in this coordinate system already was projected into the coordinate system using the ArcMap® Project tool. This coordinate system and linear unit was used because professionals who survey in Centre County, PA would need to use PA State Plane North.

4.6 Yeh Model Data Layers

4.6.1 Land Use

The Yeh land use model data layer was created from the Centre County land use data in a manner similar to that used by Yeh et al. (2009). The Yeh study used a total of four classifications to describe land cover/land use; the Centre County land use data has multiple categories that were placed into these four classifications shown in Table 3.
Table 3: Yeh land use model data layer

<table>
<thead>
<tr>
<th>Yeh Land Use</th>
<th>Centre County Land Use</th>
<th>Yeh Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>Commercial</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Industrial</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residential</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vacant Structure</td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>Forests</td>
<td>12</td>
</tr>
<tr>
<td>Agricultural Land</td>
<td>Agriculture</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Communication</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mined Land</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mixed Use</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Public/Semi Public</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recreation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Utility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vacant/Unused Land</td>
<td></td>
</tr>
<tr>
<td>Surface water body or river channel</td>
<td>Water</td>
<td>24</td>
</tr>
</tbody>
</table>

To complete this classification, the polygon to raster tool was used in ArcMap®, and the maximum combined area was assigned to each raster cell.

4.6.2 Lineaments

The Yeh lineament density model data layer was created using the point density tool in ArcMap® with a 1 km neighborhood using a circular radius around the points. This model data layer was used as a proxy for the lineament density model data layer in the Yeh et al. (2009) study. The values shown in Table 4 were assigned to reflect that study.

Table 4: Yeh lineament density model data layer

<table>
<thead>
<tr>
<th>Lineament Density (km/km²)</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.4</td>
<td>6</td>
</tr>
<tr>
<td>0.4-0.8</td>
<td>13</td>
</tr>
<tr>
<td>0.8-1.2</td>
<td>19</td>
</tr>
</tbody>
</table>

The Yeh lineament density model data layer was created using the fracture trace intersection data from the Fulton et al. (2005) study whereas the original Yeh lineament density
model data layer was created using linear lineament data. Due to this distinction, the decision was made to use the equal interval classification within ArcMap® to divide the Yeh lineament density model data layer into the same three values shown in Table 4. The reclassify tool in ArcMap® was used to assign the values.

### 4.6.3 Geology

The Yeh geology (lithology) model data layer was created by using the Pennsylvania geology data set in a manner similar to the Yeh et al. (2009) study. Table 5 shows the values used for each geology type.

<table>
<thead>
<tr>
<th>Yeh Geology Type</th>
<th>PA Geology Type</th>
<th>Yeh Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale, slate phyllite black schist</td>
<td>Calcareous shale</td>
<td>7</td>
</tr>
<tr>
<td>Phyllite intermixed quartz sandstone</td>
<td>Shale</td>
<td></td>
</tr>
<tr>
<td>Marble</td>
<td>Quartzite</td>
<td>15</td>
</tr>
<tr>
<td>Gravelly sand</td>
<td>Sandstone</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Dolomite</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>High calcium limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
<td></td>
</tr>
</tbody>
</table>

To complete this classification, the polygon to raster tool was used in ArcMap®, and the maximum combined area was assigned to each raster cell.

### 4.6.4 Slope

The Yeh slope model data layer was based on Yeh et al. (2009). The slope values were assigned as shown in Table 6.
Table 6: Yeh slope model data layer

<table>
<thead>
<tr>
<th>Slope Value</th>
<th>Yeh Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>55-90°</td>
<td>4</td>
</tr>
<tr>
<td>35-55°</td>
<td>7</td>
</tr>
<tr>
<td>15-35°</td>
<td>11</td>
</tr>
<tr>
<td>0-15°</td>
<td>14</td>
</tr>
</tbody>
</table>

The Reclassify tool in ArcMap® was used to assign the model values to the raster.

4.6.5 Drainage

The Yeh drainage model data layer was based on Yeh et al. (2009). The drainage model data layer was determined by using the Line Density function in ArcMap®. The function works by counting a line length within the radius of a cell. The tool gave an output in km/km² for consistency with the output of the Yeh study (Table 7).

Table 7: Yeh drainage density model data layer

<table>
<thead>
<tr>
<th>Drainage Density Value (km*km²)</th>
<th>Yeh Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-1.5</td>
<td>4</td>
</tr>
<tr>
<td>1.5-3.0</td>
<td>7</td>
</tr>
<tr>
<td>3.0-4.5</td>
<td>11</td>
</tr>
<tr>
<td>&gt;4.5</td>
<td>14</td>
</tr>
</tbody>
</table>

The reclassify tool in ArcMap® was used to assign the model values to the output raster.

4.7 Infiltration Potential Model Layers

4.7.1 Infiltration Potential Model Data Layers (1 year, 2 year, 10 year, 25 year, and 100 year)

The infiltration potential model data layer utilized data from both the land use data layer and the soils data layer. For this model data layer, the soils data layer and the land use data layer were combined by using the intersect tool in ArcMap®. The dominant hydrologic soil group for each map unit was used to determine the HSG for land areas (Table 8). The land use was
assigned based upon the land use data and the classifications in Table 3 were chosen for each category (USDA: NRCS, 1986).
Table 8: Centre County land use designations with assumed NRCS curve number classifications used for land use model data layer

<table>
<thead>
<tr>
<th>Land Use Category</th>
<th>NRCS Designation Assigned</th>
<th>CN HSG A</th>
<th>CN HSG B</th>
<th>CN HSG C</th>
<th>CN HSG D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Pasture, grassland...: Good</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Commercial</td>
<td>Commercial and Business</td>
<td>89</td>
<td>92</td>
<td>94</td>
<td>95</td>
</tr>
<tr>
<td>Communications</td>
<td>Industrial</td>
<td>81</td>
<td>88</td>
<td>91</td>
<td>93</td>
</tr>
<tr>
<td>Forests</td>
<td>Woods: Good</td>
<td>30</td>
<td>55</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>Industrial</td>
<td>Industrial</td>
<td>81</td>
<td>88</td>
<td>91</td>
<td>93</td>
</tr>
<tr>
<td>Mined Land</td>
<td>Impervious Dirt</td>
<td>72</td>
<td>82</td>
<td>87</td>
<td>89</td>
</tr>
<tr>
<td>Mixed Use</td>
<td>Open Space: Fair</td>
<td>49</td>
<td>69</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>Public or Semi-Public</td>
<td>Open Space: Fair</td>
<td>49</td>
<td>69</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>Recreation</td>
<td>Open Space: Good</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Residential</td>
<td>1/3 Acre Recreational Lots</td>
<td>57</td>
<td>72</td>
<td>81</td>
<td>86</td>
</tr>
<tr>
<td>Transporation</td>
<td>Paved Streets</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Utility</td>
<td>Open Space: Fair</td>
<td>49</td>
<td>69</td>
<td>79</td>
<td>84</td>
</tr>
<tr>
<td>Vacant and Unused Land</td>
<td>Open Space: Good</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Vacant Structure</td>
<td>1/3 Acre Recreational Lots</td>
<td>57</td>
<td>72</td>
<td>81</td>
<td>86</td>
</tr>
<tr>
<td>Water</td>
<td>Paved Streets</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

Curve Numbers were assigned based upon Table 8. Using the methodology outlined in Pennsylvania DEP’s Best Management Practices Stormwater Manual Worksheet 4, a quantity of runoff was determined for the 1-, 2-, 10-, 25-, and 100-year 24 hour storms (PA-DEP, 2006).

Rainfall depths (see Table 9) for these return year storms were taken from NOAA Atlas 14, Volume 2, Version 3 Bellefonte 4 S, Station ID: 36-0530 (NOAA, 2018). This storm data location was chosen because of its proximity to the geographic center of the Spring Creek watershed.

Table 9: NOAA rainfall depths

<table>
<thead>
<tr>
<th>Return Year Interval</th>
<th>24 Hour Rainfall Depth (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.20</td>
</tr>
<tr>
<td>2</td>
<td>2.65</td>
</tr>
<tr>
<td>10</td>
<td>3.82</td>
</tr>
<tr>
<td>25</td>
<td>4.58</td>
</tr>
<tr>
<td>100</td>
<td>5.91</td>
</tr>
</tbody>
</table>
The Worksheet 4 Methodology was applied in the intersected Land Use and Curve Number data in the following manner. The Curve Number for each land use and HSG was used to determine a depth of runoff. Depths of runoff were calculated for the 1-, 2-, 10-, 25-, and 100-year storms using the equations outlined in the TR-55 Method section of the Literature Review. The TR-55 model data layer was determined for more return year periods than those outlined in Worksheet 4. These return year periods were chosen because they are commonly used in stormwater management design. Once a depth of runoff was determined, that depth was used to calculate a ‘percentage runoff’, which was determined by dividing the depth of runoff by the depth of rainfall. The percentage runoff was then subtracted from 100% to determine a ‘percentage remaining.’ The results of this calculation are presented in Table 10.
Table 10: Percent infiltration based on Hydrologic Soil Group (HSG) and return period (or recurrence interval)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>HSG</th>
<th>Return Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>One Year</td>
</tr>
<tr>
<td>Agriculture</td>
<td>A</td>
<td>100.00%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>94.73%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>79.66%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>68.72%</td>
</tr>
<tr>
<td>Commercial</td>
<td>A</td>
<td>45.64%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>35.56%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>27.98%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>23.90%</td>
</tr>
<tr>
<td>Communications/</td>
<td>A</td>
<td>66.60%</td>
</tr>
<tr>
<td>Industrial</td>
<td>B</td>
<td>48.70%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>39.08%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>31.87%</td>
</tr>
<tr>
<td>Forests</td>
<td>A</td>
<td>100.00%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>98.35%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>85.44%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>74.56%</td>
</tr>
<tr>
<td>Mined Land</td>
<td>A</td>
<td>82.69%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>64.37%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>51.61%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>45.64%</td>
</tr>
<tr>
<td>Mixed Use/</td>
<td>A</td>
<td>99.94%</td>
</tr>
<tr>
<td>Public or Semi Public/ Utility</td>
<td>B</td>
<td>86.71%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>70.76%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>59.61%</td>
</tr>
<tr>
<td>Recreation/</td>
<td>A</td>
<td>100.00%</td>
</tr>
<tr>
<td>Vacant/</td>
<td>B</td>
<td>94.73%</td>
</tr>
<tr>
<td>Unused Land</td>
<td>C</td>
<td>79.66%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>68.72%</td>
</tr>
<tr>
<td>Residential/</td>
<td>A</td>
<td>97.36%</td>
</tr>
<tr>
<td>Vacant Structure</td>
<td>B</td>
<td>82.69%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>66.60%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>54.40%</td>
</tr>
<tr>
<td>Transportation/</td>
<td>A</td>
<td>10.33%</td>
</tr>
<tr>
<td>Water</td>
<td>B</td>
<td>10.33%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>10.33%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>10.33%</td>
</tr>
</tbody>
</table>
4.7.2 Sink/Sinkhole Model Data Layers (proximity and tributary)

For the sinkhole model data layers, the DCNR’s karst features dataset was used. A point dataset was created by selecting all the features with the karst type listed as ‘sinkhole’ within the Spring Creek watershed. Sinks were created using the ‘Sink’ tool and the flow direction raster within ArcMap®.

The proximity approach was to consider the closeness to the sinks/sinkholes. To combine the sink and sinkhole data, the raster to polygon tool was used on the sink data. The feature to point tool was then used to create points at the centroid of the sinks. The centroid data was merged with the sinkhole data to create a points of interest dataset. Then, the point density tool was used, and a 50 cell neighborhood using a circular radius around the points and sinks was used. Cells are 9.6’x 9.6’, therefore the search radius was taken as 480’. The output was given as points per square mile. The search radius should be adjusted based on the researcher’s opinion. The 50 cell neighborhood was chosen to demonstrate the proximity layer for this paper. This radius was chosen to demonstrate the tool and, given the cell size, this corresponded to a 480’ radius.

The tributary approach combined the elevation information and the sinks/sinkholes. A flow direction raster was created using the elevation data. The Watershed tool was used to determine the contributing area to the sinkholes and sinks. This information was merged together and assigned a value equal to the lowest infiltration potential (0).

4.7.3 Impervious Model Data Layers

The impervious model data layer was created by combining the Building Footprint Data with the Airport, Median, Parking, Roads, and Terminal subcategories from the Land Use Data
using the Merge tool in ArcMap®. The polygon to raster tool in ArcMap® was used to convert the impervious areas to a raster format.

4.8 General Data Layers

The following section contains general data layers that are similar in nature to those that have been used with other GIS surface and deep recharge models. The geology and fracture trace data layers were excluded from the infiltration potential model because these data should be more related to deep recharge models. The slope model data layer was excluded from the infiltration potential model because of slope being one of the factors considered when assigning a HSG to a soil and those data were already included in the infiltration potential model.

4.8.1 Fracture Trace Model Data Layers (proximity, tributary)

The fracture trace intersection data were obtained from USGS Scientific Investigations Report 2005-5091 (Fulton et al., 2005). Two approaches to processing the fracture trace intersection data are reflected in the presented model data layers.

The proximity approach was to consider the closeness to the fracture trace intersections. For this model data layer, the point density tool in ArcMap® was used, and a 50 cell neighborhood using a circular radius around the points was used. The output was given as a density per square mile.

The tributary approach combined the elevation information and the fracture trace intersection data. A flow direction raster was created using the elevation data. The Watershed tool was used to determine the contributing area to the fracture trace intersection data.
4.8.2 Slope Model Data Layers (Continuous, Categorical)

Elevation data were processed using the slope tool within ArcMap®. The slope tool determines the maximum rate of change between one raster cell and the neighboring raster cells. The tool outputs the maximum change. For this model data layer, the output units were chosen as degrees.

The continuous slope model data layer contains the slope for each raster cell and is the output of the slope tool in ArcMap®. The categorical slope model data layer was made by using the Natural Breaks (Jenks) classification of the slope model data layer in ArcMap® to create four categories. This categorization type is done by determining category splits where there are large differences in the groupings of data, and is based on the Jenks Natural Breaks algorithm in ArcMap® (ESRI, Data).

4.8.3 Geology Model Data Layer

The attributes available in the geology data include map symbol, name (e.g. Tuscarora Formation, Juniata Formation), age, dominant lithology type, second most dominant lithology, and other major lithologies in the rock unit. For the purposes of this study, it was decided that the dominant lithology would be used to define the bedrock. The dominant geology was determined by taking the most prevalent lithology by volume within the individual rock units.

The major lithologies present in the Spring Creek watershed are: calcareous shale, dolomite, high-calcium limestone, limestone, quartzite, sandstone, and shale. A British Geological Survey (BGS) (2006) study on permeability indexing with respect to bedrock was used to assign values to the Geology model data layer. The BGS (2006) study defines the permeability of lithologies into five different categories: very high, high, moderate, low, and
very low. The BGS (2006) study calls out the following values for the dominant lithology types present in the Spring Creek watershed.

Table 11: Lithology types in Spring Creek watershed with BGS (2006) study classifications

<table>
<thead>
<tr>
<th>Lithology Type</th>
<th>BGS Maximum Permeability</th>
<th>BGS Minimum Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcareous Shale</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Very High</td>
<td>High</td>
</tr>
<tr>
<td>High Calcium Limestone</td>
<td>Very High</td>
<td>High</td>
</tr>
<tr>
<td>Limestone</td>
<td>Very High</td>
<td>High</td>
</tr>
<tr>
<td>Quartzite</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Sandstone</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Shale</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The BGS study does not explicitly assign a maximum and minimum permeability value to calcareous shale, shale, and quartzite found in this study area; however, it does give a typical hydraulic conductivity for shale and dense crystalline rock, which is similar to quartzite. The hydraulic conductivity value for karstic limestone was given as $10^{-1}$ to $10^{3}$ m/day, and the value for sandstone was given as $5\times10^{-5}$ to $2\times10^{-1}$ m/day. The hydraulic conductivity value for shale was given as $5\times10^{-8}$ to $10^{-4}$ m/day and the hydraulic conductivity value for dense crystalline rock is given as $5\times10^{-8}$ to $10^{-4}$ m/day. The lowest hydraulic conductivity for sandstone ($5\times10^{-5}$ m/day) was close to the highest hydraulic conductivity for both shale and dense crystalline rock ($10^{-4}$ m/day), so the BGS maximum permeability for calcareous shale, shale, and sandstone was assumed as the ‘low’ categorization while the BGS minimum permeability was assumed as the ‘very low’ categorization (British Geological Survey, 2006).

To derive the model data layer from the base geology data, a categorization was done using the given and assumed BGS maximum and minimum permeabilities. To do this, a value of 5 was assigned to the category ‘very high’, a value of 4 to the category ‘high’, a value of 3 to the category ‘moderate’, a value of 2 to the category ‘low’, and a value of 1 to the category of ‘very
low.’ These values were averaged together in order to obtain an ‘assigned value’ for each lithology type. The results of this exercise are shown in Table 12.

Table 12: Assigned values for formulation of geology model data layer

<table>
<thead>
<tr>
<th>Lithology Type</th>
<th>Assigned Value (Max)</th>
<th>Assigned Value (Min)</th>
<th>Average Assigned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcareous Shale</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Dolomite</td>
<td>5</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>High Calcium Limestone</td>
<td>5</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>Limestone</td>
<td>5</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>Quartzite</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Sandstone</td>
<td>4</td>
<td>2</td>
<td>3.0</td>
</tr>
<tr>
<td>Shale</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

These values were entered into the following formula to determine a Geology Factor:

$$\frac{\text{Average Assigned Value} - 1.5}{4.5 - 1.5} = \text{Geology Factor}$$

This equation resulted in dolomite, high calcium limestone, and limestone being assigned a geology factor of 1, sandstone was assigned a geology factor of 0.5, and calcareous shale, quartzite, and shale were assigned a geology factor of 0.

4.9 Model Processing

Two modeling approaches were used in this research. One approach followed the Yeh et al. (2009) GIS recharge assessment method, and the second was conducted using a TR-55 based approach (infiltration potential model). All model runs were performed using the raster calculator tool within ArcMap®.

4.9.1 Yeh Model

The Yeh model was adapted on the Yeh et al. (2009) study and contained five model data layers; slope gradient, drainage density, lineament density, land cover/land use, and lithology. The
model composite map was developed by combining these model data layers together with raster calculator.

4.9.2 Infiltration Potential Model

The infiltration potential model was created with a decision making matrix and, ultimately, the infiltration potential model data layers. The Impervious data layer was used to assign areas of zero (0.0 model value) infiltration. The Sink/Sinkhole Tributary model data layer was used to assign areas of maximum (1.0 model value) infiltration, and in the case where an impervious surface was tributary to a sink/sinkhole, maximum infiltration was assigned. In the areas of the watershed where neither of these overriding conditions applied, the infiltration potential model data layer was used. In Figures 16-20, the minimum and maximum infiltration values are shown as distinct values to show the areas of maximum and minimum infiltration according to the model.

The infiltration potential model was created by using the merge rasters tool in ArcMap®. The infiltration potential model data layers were used for each return year period, the impervious model data layer was then merged with the infiltration potential model data layer (with the impervious model data layers taking priority). The sink/sinkhole tributary model data layer was then merged with the resultant raster from the previous merge, with the sink/sinkhole tributary model data layer taking priority over the impervious model data layer. This priority ordering means that when impervious areas are tributary to a sink/sinkhole, they would be given a value of maximum infiltration instead of zero infiltration. In cases where the area was not covered with an impervious surface or tributary to a sinkhole, the infiltration potential model data layer value was used.
Chapter 5. RESULTS AND DISCUSSION

The following narrative presents and discusses both the contributing data layers and the resultant composite maps from integrating the data layers. The results of this study can be viewed in two major categories: the proposed model data layers and the model composite maps. (It was the intent of the author to provide model data layers that may play an important role in recharge area identification regardless of whether those model data layers were used in either model.) This Results and Discussion section outlines both the model data layers and the model composite maps.

5.1 Yeh Model Data Layers

Figure 3 shows the drainage density model data layer from Yeh (2009) as mapped in the Spring Creek watershed. The drainage model values shown in Figure 3 correspond to those shown in Table 7. This figure shows that only two low drainage density categories are present in the Spring Creek study area for the Yeh model. The orange areas show higher drainage density and reflect the intersections of the major flowing streams in the Spring Creek watershed. This illustrates why direct application of a recharge model developed in another part of the world with different topographic features can be problematic. This model data layer gives little differentiation across the Spring Creek study area as 98.1% of the area falls in the lowest category of 4 and the other 1.9% of the area falls in the category of 7. No areas within the Spring Creek watershed fell in the two higher categories of 11 or 14 for this model data layer.
Figure 3: Yeh drainage density model data layer

Figure 4 shows the geology model data layer from Yeh (2009) as mapped in the Spring Creek watershed. The geology model values shown in Figure 4 correspond to those shown in Table 5. Four different recharge values based on dominant geologic formations were assigned
across the study area. 63.7% of the watershed (shown in green) is underlain by dolomite, high
calcium limestone, and limestone (highest recharge contributing value according to Yeh’s
model). 28.4% of the watershed (shown in yellow) is underlain by sandstone. 1.2% of the
watershed (shown in orange) is underlain by quartzite. 6.7% of the watershed (shown in red) is
underlain by calcareous shale and shale (lowest recharge contributing). The development of this
model data layer required assignment of Pennsylvania geology types to the categories that were
used in the Yeh study.
Figure 4: Yeh geology model data layer

Figure 5 shows the land use model data layer based on the Yeh (2009) approach for the Spring Creek watershed. The land use model values shown correspond to those given in Table 3.
As shown, much of the area classified as red represents the highly developed urban areas, whereas the yellow represents agricultural areas, and orange represents forested areas. According to the Yeh model, the land use most conducive to recharge are waterbodies or river channels. This resulted in only 0.3% of the Spring Creek watershed being classified as the highest recharge value.

Waterbodies and streams are an interesting land use classification when it comes to recharge; an argument can be made, as Yeh et al. (2009) did, that these areas result in high recharge because of the constant presence of water on the surface. However, a counter-argument can be made that these areas are the opposite, that they are restrictive because water remains on the surface. These features can be fed by groundwater returning to the surface, or the opposite of recharge.

A better analysis of water features in the Spring Creek watershed would include consideration of whether a stream is ‘gaining’ or ‘losing.’ Considering that only 0.3% of the study area is overlain by surface water features, and that surface water features are already protected areas in Pennsylvania, a detailed analysis of gaining and losing streams was not performed for this study.
Figure 5: Yeh land use model data layer

Figure 6 shows the lineament density model data layer from Yeh (2009) for the Spring Creek watershed. The lineament density model values shown correspond to those provided in
Table 4. The model data layer was created from a limited coverage dataset adapted from the Fulton et al. (2005) study. These data were focused on ten known high fracture intersection areas in the Spring Creek watershed and do not provide a coverage of the entire watershed’s fracture trace intersections. These data are not consistent with data used in the original Yeh (2009) study which included linear features and was a coverage of the entire watershed of interest.

Fulton et al. (2005) dataset was selected for use because it was the most expansive and detailed digitized mapping information related to lineaments/fracture traces commonly available at the time of this work. The input data for this model data layer could be improved through the digitizing and use of a more detailed lineament study; however, this task was not completed as part of this research as this went beyond the scope of the current study.

The use of point data rather than linear data also significantly impacts the spatial presentation of the data. Point data results in circular features around the points of interest while linear data results in elongated offsets around linear data.
Figure 6: Yeh lineament density model data layer

Figure 7 shows the slope model data layer from Yeh (2009) for the Spring Creek watershed. The slope model values correspond to those shown in Table 6. Using the categories
laid out in the Yeh study, 87.9% of the area (in green) of the watershed received the highest recharge value for slope (0°-15°). This is a result of the Yeh model being developed and intended for use in an area with much steeper terrain than exists in the Spring Creek watershed. This model data layer shows that only 12.1% of the Spring Creek watershed has a slope that exceeds 15°. Because of the slope values not varying widely across these categories, the slope model data layer does little to differentiate the contribution to recharge of land areas across the watershed.
Table 13 shows coverage statistics of the Yeh model data layers across the Spring Creek watershed. Of the five model data layers, Land Use is the only model data layer that does not
have a single category with a coverage of 63.7% or greater. Three of the five model data layers have a single category with a coverage of 87.9% or greater. This low variation across the watershed results in the final Yeh model being disproportionately influenced by the geology and land use data layers.

Table 13: Yeh model data layer statistics

<table>
<thead>
<tr>
<th>Model Data Layer</th>
<th>Yeh Values</th>
<th>Cell Count</th>
<th>Percentage of Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage Density</td>
<td>4</td>
<td>53,653,201</td>
<td>98.1%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1,014,375</td>
<td>1.9%</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Geology</td>
<td>7</td>
<td>3,608,947</td>
<td>6.7%</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>642,203</td>
<td>1.2%</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>15,264,314</td>
<td>28.4%</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>34,229,944</td>
<td>63.7%</td>
</tr>
<tr>
<td>Land Use</td>
<td>6</td>
<td>10,016,513</td>
<td>18.6%</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>22,533,570</td>
<td>41.9%</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>21,007,083</td>
<td>39.1%</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>169,473</td>
<td>0.3%</td>
</tr>
<tr>
<td>Lineament Density</td>
<td>6</td>
<td>51,559,424</td>
<td>94.3%</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>2,664,896</td>
<td>4.9%</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>443,256</td>
<td>0.8%</td>
</tr>
<tr>
<td>Slope</td>
<td>4</td>
<td>11,530</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>202,831</td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>6,382,956</td>
<td>11.7%</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>48,070,259</td>
<td>87.9%</td>
</tr>
</tbody>
</table>

5.1.1 Yeh Model Recharge Potential Composite Map

Figure 8 provides the composited results of the Yeh Model. The dark green areas are the areas with the highest predicted recharge according to the Yeh Model in the Spring Creek watershed. The Yeh model was intended to measure deep recharge and is useful for
identification of groundwater exploitation areas. The Yeh model combined surface data layers and deep data layers to arrive at this outcome.

The highest recharge areas shown in Figure 8 are also the areas where mapping data showed fracture trace intersections located in the Spring Creek watershed. The areas for fracture trace intersection mapping were selected based on their perceived suitability for groundwater exploitation by professional hydrogeologists (Fulton et al., 2005), and a complete mapping was not available for all of the Spring Creek watershed. It reasons that these areas would show up as high recharge areas in the Yeh model because data were not provided for the other areas in the watershed, and these were the areas that professionals had slated for well exploration. The limitation of the data availability for the watershed led to the Yeh model showing high recharge to these limited locations.

The Yeh model also shows lowest recharge at the base of the ridges in the area. This was driven by the geology data and the presence of shale and calcareous shale at the base of the ridges. These data are important to the results of the Yeh model, but were excluded from the infiltration potential model as the goal of the infiltration potential model was to consider infiltration alone.
5.2 Infiltration Potential Model Data Layers

Figure 9 shows the 1-year infiltration potential model data layer. The infiltration potential 1-year fractional model values shown in Figure 8 correspond to the percentages shown in Table
10. Using the SCS Method, the lowest infiltration value in the watershed is 10.33% of rainfall during a 1-year storm, the maximum infiltration value is 100%.

Figure 9: 1-year infiltration potential model data layer
Figure 10 shows the 2-year infiltration potential model data layer. The infiltration potential 2-year model fractional values shown in Figure 9 correspond to the percentages shown in Table 10. Using the SCS Method, the lowest infiltration value in the watershed is 8.68% of rainfall during a 2-year storm, the maximum infiltration value is 100%.
Figure 10: 2-year infiltration potential model data layer

Figure 11 shows the 10-year infiltration potential model data layer. The infiltration potential 10-year model fractional values shown in Figure 10 correspond to the percentages
shown in Table 10. Using the SCS Method, the lowest infiltration value in the watershed is 6.14% of rainfall during a 10-year storm, the maximum infiltration value is 100%.

Figure 11: 10-year infiltration potential model data layer
Figure 12 shows the 25-year infiltration potential model data layer. The infiltration potential 25-year fractional model values shown in Figure 11 correspond to the percentages shown in Table 10. Using the SCS Method, the lowest infiltration value in the watershed is 5.16% of rainfall during a 25-year storm, the maximum infiltration value is 100%.
Figure 12: 25-year infiltration potential model data layer

Figure 13 shows the 100-year infiltration potential model data layer. The infiltration potential 100-year model fractional values shown in Figure 12 correspond to the percentages
shown in Table 10. Using the SCS Method, the lowest infiltration value in the watershed is 4.03% of rainfall during a 100-year storm, the maximum infiltration value is 98.94%.

Figure 13: 100-year infiltration potential model data layer
Figures 9 through 13 show the infiltration during the return period storm according to the infiltration potential model. This model data layer considers the HSG of the soils in the watershed as well as the land use. The intent of this model data layer is to provide a means of estimating infiltration in areas where land use and soils data are available. As shown and discussed later, Figures 16 through 20 show these model data layers combined with limiting data layers (impervious and sink/sinkhole tributary) to create the infiltration potential model composite maps.

The infiltration potential model data layers are driven by the CN of the land. This means that areas with HSG A soils are shown with higher recharge potential than areas with identical land use but a more recharge restrictive HSG. Land uses such as forest and agriculture are more conducive to infiltration than developed land. In this manner land use and HSG directly impact the infiltration percentages and creates the output shown in Figures 8 through 12.

Table 14 provides a summary of the results of the infiltration potential model data layer by presenting the number of raster cells in five equal interval categories across the Spring Creek watershed. This summary shows the differences in expected water available for recharge on a percentage basis for the five different return year storms studied. There is a higher percentage of water as infiltration in more frequent return year storms because the SCS equations were developed to take initial abstraction into account and show more runoff after soil saturation occurs.
Table 14: Infiltration potential model data layer summary

<table>
<thead>
<tr>
<th>%Infiltration</th>
<th>1 Yr</th>
<th>2 Yr</th>
<th>10 Yr</th>
<th>25 Yr</th>
<th>100 Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Cells</td>
<td># Cells</td>
<td># Cells</td>
<td># Cells</td>
<td># Cells</td>
</tr>
<tr>
<td></td>
<td>% Area</td>
<td>% Area</td>
<td>% Area</td>
<td>% Area</td>
<td>% Area</td>
</tr>
<tr>
<td>0-20%</td>
<td>2,973,224</td>
<td>2,973,224</td>
<td>3,191,374</td>
<td>3,679,408</td>
<td>3,723,916</td>
</tr>
<tr>
<td></td>
<td>5.5%</td>
<td>5.5%</td>
<td>5.9%</td>
<td>6.8%</td>
<td>6.9%</td>
</tr>
<tr>
<td>20-40%</td>
<td>750,691</td>
<td>750,691</td>
<td>1,354,028</td>
<td>1,040,215</td>
<td>4,170,323</td>
</tr>
<tr>
<td></td>
<td>1.4%</td>
<td>1.4%</td>
<td>2.5%</td>
<td>1.9%</td>
<td>7.8%</td>
</tr>
<tr>
<td>40-60%</td>
<td>995,707</td>
<td>1,148,691</td>
<td>5,411,265</td>
<td>14,306,444</td>
<td>17,794,490</td>
</tr>
<tr>
<td></td>
<td>1.9%</td>
<td>2.1%</td>
<td>10.1%</td>
<td>26.6%</td>
<td>33.1%</td>
</tr>
<tr>
<td>60-80%</td>
<td>10,365,663</td>
<td>14,153,458</td>
<td>15,732,062</td>
<td>20,043,014</td>
<td>27,016,273</td>
</tr>
<tr>
<td></td>
<td>19.3%</td>
<td>26.3%</td>
<td>29.3%</td>
<td>37.3%</td>
<td>50.3%</td>
</tr>
<tr>
<td>80-100%</td>
<td>38,640,991</td>
<td>34,700,212</td>
<td>28,037,547</td>
<td>14,657,195</td>
<td>1,021,274</td>
</tr>
<tr>
<td></td>
<td>71.9%</td>
<td>64.6%</td>
<td>52.2%</td>
<td>27.3%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

Figure 14 shows the sink/sinkhole tributary model data layer. This model data layer was created by using the flow direction raster with point information on sinks and sinkholes, and creating a tributary area for each of the identified points. This model data layer was included in the infiltration potential model composite maps and was given a recharge value of ‘1’ in that model for each of the infiltration potential model composite maps. The reason behind this decision was that if stormwater flows into a sinkhole or a sink, it will quickly penetrate the ground surface and become recharge.

The sink/sinkhole tributary model data layer was used instead of the sink/sinkhole proximity model data layer because there is not a certainty that flow will make it to a sink/sinkhole solely due to proximity. If a land area is tributary to a sink/sinkhole, the stormwater flow must either infiltrate through the soil or flow into the sink/sinkhole. The sink/sinkhole tributary model shows the sink/sinkhole drainage area. Although Figure 14 appears to show a very small area as being tributary to sinks/sinkholes, over 2.4 square miles is included in these areas.
Figure 14: Sink/sinkhole tributary model data layer

Figure 15 shows the impervious areas across the Spring Creek watershed. This model data layer is intended to provide a limiting value for recharge models. Of the entire watershed
area, 6.4% is overlain by either transportation land use features, airport land use features, or building footprints. This model data layer shows these areas with a recharge value of zero because impervious surfaces, by definition, do not allow infiltration. The impervious area data layer was included in the infiltration potential model and values of zero recharge were assigned for all impervious areas in all return year model runs.
Table 15 provides summary statistics of the model data layers that supplement the infiltration potential model. 6.4% of the watershed is overlain by impervious surfaces while 1.4% of the watershed is tributary to a sink/sinkhole. These maps are used as overriding factors in the
infiltration potential model to assign limiting conditions. The areas tributary to sinkholes are given the maximum surface recharge value while the areas overlain by impervious surfaces are given the minimum surface recharge value.

<table>
<thead>
<tr>
<th>Model Data Layers</th>
<th>Jenks Ranges Or Values</th>
<th>Cell Count</th>
<th>Percentage of Area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sink/Sinkhole</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tributary</td>
<td>1 (True)</td>
<td>739,566</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>0 (False)</td>
<td>53,930,190</td>
<td>98.6%</td>
</tr>
<tr>
<td><strong>Impervious</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 (False)</td>
<td>51,174,557</td>
<td>93.6%</td>
</tr>
<tr>
<td></td>
<td>0 (True)</td>
<td>3,495,199</td>
<td>6.4%</td>
</tr>
</tbody>
</table>

5.2.1 Infiltration Potential Model Composite Maps

Figure 16 shows the 1-year return period storm infiltration potential model composite map. The model is the combination of the sinkhole tributary model data layer, the impervious model data layer, and the 1-year infiltration potential model data layer. The dark green areas are those with the highest predicted infiltration. The infiltration potential models are intended to predict infiltration potential at the surface and serve as part of a more complex recharge model.

A comparison of Figure 16 with the Yeh model composite map (Fig. 8) suggests the two approaches produced very different results. However, for Fig. 16, as well as Figs. 17-20, what has been mapped is really infiltration potential, or the initial entry of precipitation into the ground surface. The rate and extent to which this infiltrated water will replenish or recharge a groundwater aquifer suitable for exploitation as a water resource is complicated and depends on many factors. Analyses of such conditions is not the subject of this research.
Figure 16: Infiltration potential model composite map, 1-Year

Figure 17 shows the 2-year return period storm infiltration potential model composite map. The model is the combination of the sinkhole tributary model data layer, the impervious
model data layer, and the 2-year infiltration potential model data layer. The dark green areas are those with the highest predicted infiltration potential.

Figure 17: Infiltration potential model composite map, 2-Year
Figure 18 shows the 10-year return period storm infiltration potential model composite map. The model is the combination of the sinkhole tributary model data layer, the impervious model data layer, and the 10-year infiltration potential model data layer. The dark green areas are those with the highest predicted infiltration potential.
Figure 18: Infiltration potential model composite map, 10-Year

Figure 19 shows the 25-year return period storm infiltration potential model composite map. The model is the combination of the sinkhole tributary model data layer, the impervious
model data layer, and the 25-year infiltration potential model data layer. The dark green areas are those with the highest predicted infiltration potential.

Figure 19: Infiltration potential model composite map, 25-Year
Figure 20 shows the 100-year return period storm infiltration potential model composite map. The model is the combination of the sinkhole tributary model data layer, the impervious model data layer, and the 100-year infiltration potential model data layer. The dark green areas are those with the highest predicted infiltration potential.
Table 16 gives statistics on the coverage of the Yeh model results. 91.7% of the Yeh model results are in the second and third columns with 2.5% of the watershed in the highest value category.
recharge value. The highest recharge values were driven by their proximity to the fracture trace intersections, which resulted in a high Yeh recharge value. It is important to note that the fracture trace intersection data were not available in a watershed-wide dataset and thus these areas were thus skewed as higher recharge areas than their surroundings.

The Yeh model also considered agricultural land as more suitable for recharge than forested land, a distinction that runs contrary to the CN values for land cover. It is possible that these choices were made due to irrigation of agricultural fields or forested areas being located on steep slopes. In any regard, distinctions such as the value of the land use in the Yeh model contribute to a case against the reasonableness of the direct application of recharge models in watersheds in a different part of the world.

Table 16: Yeh model results

<table>
<thead>
<tr>
<th>Yeh Model Score</th>
<th># Cells</th>
<th>% Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-45</td>
<td>3,143,544</td>
<td>5.9%</td>
</tr>
<tr>
<td>45-60</td>
<td>21,688,614</td>
<td>40.4%</td>
</tr>
<tr>
<td>60-75</td>
<td>27,540,403</td>
<td>51.3%</td>
</tr>
<tr>
<td>75+</td>
<td>1,352,992</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Table 17 gives statistics on the coverage of the infiltration potential model results. More intense and less frequent return year storms have a higher proportion of occurrences in the lower recharge categories. This is a product of the SCS equations being designed to account for initial abstraction and the effects of saturation. Identical Curve Numbers were used for land areas in each run. This method shows the difference return year storms have on the proportion of
runoff/infiltration. More frequent return-year storms have a higher proportion of rainfall contributing to infiltration, and in the case of a 1 Year storm, 71.6% of the Spring Creek watershed has 80-100% of rainfall available for infiltration.

Table 17: Infiltration potential model results

<table>
<thead>
<tr>
<th>% Available For Recharge</th>
<th>1 Yr</th>
<th>2 Yr</th>
<th>10 Yr</th>
<th>25 Yr</th>
<th>100 Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Rainfall-Runoff)</td>
<td># Cells</td>
<td>% Area</td>
<td># Cells</td>
<td>% Area</td>
<td># Cells</td>
</tr>
<tr>
<td>0-20%</td>
<td>3,850,849</td>
<td>7.2%</td>
<td>4,077,365</td>
<td>7.6%</td>
<td>4,417,127</td>
</tr>
<tr>
<td>20-40%</td>
<td>603,402</td>
<td>1.1%</td>
<td>1,081,695</td>
<td>2.0%</td>
<td>880,693</td>
</tr>
<tr>
<td>40-60%</td>
<td>843,569</td>
<td>1.6%</td>
<td>5,058,519</td>
<td>9.4%</td>
<td>13,482,315</td>
</tr>
<tr>
<td>60-80%</td>
<td>9,962,183</td>
<td>18.5%</td>
<td>17,488,307</td>
<td>28.1%</td>
<td>19,681,176</td>
</tr>
<tr>
<td>80-100%</td>
<td>38,466,539</td>
<td>71.6%</td>
<td>28,425,689</td>
<td>52.9%</td>
<td>15,265,231</td>
</tr>
</tbody>
</table>

5.3 General Data Layers for Use in Refining Recharge Models

This section provides general data layers for use in refining recharge models. These layers are shown as possible interpretations of data as they have been included in previously studied recharge models. These data layers are included as an example, there are many possible ways to interpret a dataset; how data are categorized, assigned values, and weighted all have a direct impact on the ultimate results of a model. Careful consideration should be given to how data are included in a model.

Figure 21 shows the fracture trace proximity model data layer. This data layer provides higher values for regions that are close to multiple fracture trace intersections through using a point density tool. The model data layer results as presented could be changed by increasing or
decreasing the search radius, and the values of the data layer can also be normalized by dividing the values by the maximum model value.

This data layer was not used in either model presented in this study. It is presented because data layers such as this one have been used in previously studied works. The fracture trace data is helpful for finding deep recharge locations.
Figure 21: Fracture trace proximity data layer

Figure 22 shows the fracture trace tributary data layer. This data layer was created by taking the fracture trace intersections and combining that with the flow direction raster to create
areas tributary to fracture trace intersections. The fracture trace tributary data layer was created by pairing surface topographic features with features that exist below the surface. This data layer could be improved upon if detailed groundwater elevation contour maps were used rather than surface elevation data.

This data layer was not used in either model presented in this study. It is presented because data layers such as this one have been used in previously studied works. The fracture trace data is helpful for finding deep recharge locations.
Figure 22: Fracture trace tributary data layer

Figure 23 shows the sink/sinkhole proximity data layer. This data layer provides higher values to areas that are close to multiple sink or sinkhole features using a point density tool. The
data layer as presented could be refined by increasing or decreasing the search radius, and the values of the data layer could be normalized by dividing the values by the maximum value.

This data layer was not used in either model presented in this study. It is presented because data layers such as this one have been used in previously studied works. The sink/sinkhole proximity may be helpful for finding surface recharge locations, however the sink/sinkhole tributary data layer was chosen over the proximity data layer.
Figure 23: Sink/sinkhole proximity data layer

Figure 24 shows the continuous slope data layer across the Spring Creek watershed. This data layer provides a slope value for each raster cell in the watershed based upon the maximum elevation change between the cell of interest and the surrounding cells. The continuous slope
data layer could be normalized by dividing by the steepest slope. Higher slopes are less conducive to recharge than lower slopes because water moves more quickly on the surface and has less time to infiltrate on higher slopes.

The continuous slope data layer was not used in either model presented in this study. It is presented because data layers such as this one have been used in previously studied works. The continuous slope data layer is helpful for finding surface recharge locations, however the determination of HSGs for soils uses slope to help decide which HSG will be assigned. Due to the slope of the land being represented in the infiltration potential model through the soil, the continuous slope data layer was excluded from the infiltration potential model.
Figure 24: Continuous slope data layer

Figure 25 shows a categorical slope data layer across the Spring Creek watershed. This data layer is provided to show an example of another method that slope could be used in creating
a model data layer. The four categories shown above were determined by using the Natural Breaks (Jenks) classification system in ArcMap®.

The categorical slope data layer was not used in any of the models shown in this research. The Yeh model did use slope data, but not in the form in Figure 25. To include a data layer such as this, additional consideration should be given to the limits of the categories as well as the number of categories in the data layer.
Figure 25: Categorical slope data layer

Figure 26 shows the geology data layer across the Spring Creek watershed. The geology values shown in Figure 26 correspond to those shown in Table 12. This data layer is provided to
show an example of how a geology data layer would look in the Spring Creek watershed. The three categories shown here were assigned in the manner outlined in the methodology section. The geology data layer was not used in any of the models presented in this research. Geology (lithology) data was used in the Yeh model, but not in the manner presented in Figure 26. The underlying geology data is a helpful model data layer in identification of deep recharge locations.
Figure 26: Geology data layer

Table 18 provides a summary of the values of model data layers. Not all of the model data layers that were developed were used in the infiltration potential or Yeh models. The model data layers that were not used are provided as an acknowledgement that there are many possible
ways to approach a recharge model. The intent of the infiltration potential model was to only include data layers that had influence on surface recharge, therefore layers dealing with deep recharge such as geology and fracture traces were excluded.

Table 18: Summary of data layers not used in the recharge or infiltration models in this study

<table>
<thead>
<tr>
<th>Model Data Layers</th>
<th>Jenks Ranges Or Values</th>
<th>Cell Count</th>
<th>Percentage of Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture Trace</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity</td>
<td>0</td>
<td>52,246,223</td>
<td>95.6%</td>
</tr>
<tr>
<td></td>
<td>&gt;0-37.8</td>
<td>1,460,257</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>37.8-114.8</td>
<td>830,440</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>114.8-191.8</td>
<td>123,349</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td></td>
<td>&gt;191.8</td>
<td>9,487</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Fracture Trace</td>
<td>1 (True)</td>
<td>19,504</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Tributary</td>
<td>0 (False)</td>
<td>54,650,252</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td>Sink/Sinkhole</td>
<td>0</td>
<td>45,774,574</td>
<td>83.7%</td>
</tr>
<tr>
<td>Proximity</td>
<td>&gt;0-76.1</td>
<td>6,8484,535</td>
<td>12.5%</td>
</tr>
<tr>
<td></td>
<td>76.1-192.4</td>
<td>1,734,937</td>
<td>3.2%</td>
</tr>
<tr>
<td></td>
<td>192.4-306.6</td>
<td>257,754</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>&gt;306.6</td>
<td>53,956</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Slope</td>
<td>0-5.2</td>
<td>30,628,619</td>
<td>56.0%</td>
</tr>
<tr>
<td></td>
<td>5.2-12.1</td>
<td>15,295,514</td>
<td>28.0%</td>
</tr>
<tr>
<td></td>
<td>12.1-21.9</td>
<td>5,757,553</td>
<td>10.5%</td>
</tr>
<tr>
<td></td>
<td>&gt;21.9</td>
<td>2,985,890</td>
<td>5.5%</td>
</tr>
<tr>
<td>Geology</td>
<td>1</td>
<td>34,229,951</td>
<td>63.7%</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>15,264,323</td>
<td>28.4%</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>4,251,160</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

5.4 Recharge Model Discussion

In comparing and contrasting recharge models that were created using GIS, it is vital to understand the intent of the original researchers. If these models were created with the intent of exploitation of groundwater recharge, that needs to be understood and considered when
evaluating the data input and the model data layers used. Models that are focused on identification of these ‘deep recharge’ areas give a high weight to locations of fractured bedrock and subsurface features.

Combining data input layers that include surface features and subsurface features inherently makes the assumption of a ‘top-down’ recharge, where the subsurface features are inextricably linked to the directly-overlying surface features. In a karst environment where sinkholes and springs carry water across the landscape, and the boundary of the surface watershed does not coincide with that of the subsurface watershed, this assumption is not reasonable and three-dimensional movement of water must be considered.

An acknowledgement of the complexities of groundwater recharge is present in the Pennsylvania Wellhead Protection Program and the Pennsylvania Safe Drinking Water Regulations. The Wellhead Protection Program contains a three zone buffer area in which wellhead protection is established. Zone I is the innermost zone which consists of a 100 to 400 foot radius. For new wells, Zone I must be under the control of the owner of the water supply, through ownership or agreements. Zone II is the capture zone for the source, this zone is usually taken as a half-mile radius about the source, but can also be defined with a detailed hydrogeologic study. Zone III is defined as area that contributes recharge to the aquifer beyond the capture zone (PA-DEP, Wellhead Protection Program).

Through detailed hydrogeologic studies, different high fracture areas can be used to identify areas of ‘deep recharge’ and tributary areas to these areas of deep recharge can be found through detailed hydrogeologic studies as outlined in the Wellhead Protection Program. When considering a wellhead tributary area, these delineated areas can prove more helpful in karst
environments than the traditionally-used wellhead protection offsets. Using the half-mile radius for Zone II would give the well owner an over 500 acre area to manage. Mostly likely, a portion of this area will not actually be tributary to the well of interest. By delineation of these areas to the surface, one could establish a better understanding of how to effectively manage the tributary areas. This, then, is a critical next stage in developing a more realistic and useful mapping product for Spring Creek.

5.5 Yeh Model Discussion

The Yeh Model was based on a study conducted in Taiwan. The study area in the initial Yeh study contained much steeper terrain, it also had a much more dense drainage network, and streams were more frequent across the terrain and closer together. The original Yeh study also contained more complete data on lineaments than was available for the Spring Creek Basin.

The Yeh Model was selected for use in this work because it provided a detailed description of how the model was developed and seemed initially to be pertinent. It is important to recognize that this study was conducted in a different terrain than that which is present in the Spring Creek watershed, and that Yeh et al. made different decisions based upon that knowledge. Yeh et al. (2009) state that “the weights of different factors for groundwater recharge potential and the score under various characteristics were assessed based on the characteristics of the Chih-Pen basin.” Thus, it is apparent that they felt basin characteristics were important considerations.

The Yeh model in the Spring Creek watershed (with values and weightings from Taiwan) revealed issues with a recharge model developed for one area being used elsewhere with different basin characteristics. The ranges of the model data layer weightings may have made
sense in Taiwan, but in Centre County, the model data layers like Slope and Drainage did not give much differentiation in values across the watershed. This does not preclude use of such a model; however, it would require modification of the factor domain categories and associated weightings. This would require more expertise and guidance from the original model developers (as how such weightings and factor categories should be adjusted).

5.6 Infiltration Potential Model Discussion

The model developed in this research was completed with the intent of incorporating conventional stormwater engineering methods into a recharge model. Many of the previous works involving GIS and groundwater recharge were focused on groundwater exploitation, i.e. identifying areas that would be suitable for wells or used as a water supply. The intent of this study was to show the potential sources of groundwater recharge at the land surface.

TR-55 is first and foremost a runoff model. This study used a TR-55 style calculation to calculate a quantity of runoff, and that runoff was subtracted from the 24-hour rainfall event that was being studied. In conducting the calculations in this manner, consideration was not given to other fates of rainfall such as evaporation or transpiration. The infiltration potential model provides a percent of rainfall that is available for infiltration after runoff has occurred. The depth of rainfall that is used could be multiplied by the percentages in order to determine the quantity of infiltration.

If the surface source of potential groundwater recharge can be successfully shown, the use of that information has the potential to be valuable to a community or an entire region. Ideally, areas of interest with high recharge would be identified by a municipality, work would be conducted by someone with a background in hydrogeology, tributary areas to those areas of
interest could be determined, and that information could be coupled with a surface groundwater recharge study to allow the municipality to make informed zoning decisions. Land uses could be restricted or promoted in the tributary recharge areas.

The infiltration potential model is intended to be used as a coarse guide and a first step towards identifying groundwater recharge sources at the surface. If an interest arises in any specific area of the watershed, a more detailed approach should be applied to that area. Elements such as storm drainage systems, infiltration/detention basins and their discharge, stormwater BMPs, and evapotranspiration rates should be considered in a more detailed work. Some of the challenges presented by this approach include the handling of high infiltration areas on ridges. While the infiltration potential model gives the appearance of similar amounts of infiltration, it is known that these areas are unlikely to directly contribute to recharge unless through sinks or sinkholes. In a complete recharge model, they should be screened as recharge areas by limiting factors.

5.7 Limitations

The infiltration potential model composite maps could be improved upon through consideration of the type of vegetative cover throughout the watershed. The modeling approach that was presented in this paper did not consider the effects of evapotranspiration on infiltration. Due to this assumption, areas such as ridgetops showed high infiltration rates, although it is known that these areas do not generally exhibit high recharge rates, since infiltrated water enters the soil root zone and is quickly transpired via canopy. In forested areas such as the ridgetops of Centre County, much of the rainfall is put back into the air through the process of evapotranspiration and does not contribute to deep percolation. Likewise, fields in the valleys
also are filled with plants that exhibit evapotranspiration but only during the times in which fields are vegetated and at a much lower rate than that in the forested areas.

5.8 Ideas for Future Works

In addition to the works outlined above, it should be noted that in order to compare recharge models, a common system should be established. The Yeh model has a minimum overall value of 27 and a maximum overall value of 100. In order for models to compare directly to each other, they would need to be rescaled to a common numerical basis for comparison.

In regards to the infiltration potential model, commonly used recurrence interval storms were chosen for the study. However, it should be acknowledged that the more frequent (and smaller) rain events are the major sources of infiltration due to the frequency of the storms. This model may be more useful if smaller, frequent storm depths are used. Further, knowing that precipitation is variable throughout the calendar year, modeling could be conducted on a monthly, weekly, or daily basis to provide greater information on predicted infiltration.

The results of the infiltration potential model are to be understood as infiltration potential mapping. To create an effective groundwater recharge model, these results should be coupled with a deep recharge model through the use of groundwater contours. The general data layers presented in Section 5.3 are an example of the types of information that could be used to create a deep recharge model. When combined, a three-dimensional mapping could be created that relates the surface features to subsurface features in a useful manner. For instance, a question could be posed asking whether infiltrated water ultimately reaches a fracture trace or an aquifer, and a prediction could be made by combining the infiltration potential mapping with these general data layers. A more complete model would allow for determination of source water protection areas
as well as determination of the fate of contaminants. These data can be combined in many different ways to provide insight into the modeled watershed.

Evapotranspiration is a factor that could be used in a more detailed infiltration potential mapping. However, it must be noted that evapotranspiration rates are variable throughout the year. In order to adequately address this factor, the modeling approach would need to be conducted on a calendar basis, and recognition would need to be given to the change in infiltration potential throughout the year based on variable precipitation, temperature, and evapotranspiration.

5.9 Final Conclusions

The GIS-based recharge models reviewed for this study were predominantly based upon weighted linear equations. In a karst area such as the Spring Creek watershed, these models do not capture the breadth of overriding circumstances that can occur. Further, model data layers are often not independent of one another. For instance, slope can impact land use or the HSG assigned to the soil of the study area. The largest takeaway from this study is that relevant, available data should be incorporated in a recharge model, and that extraneous data layers be excluded from the model. A strictly ‘top-down’ approach to recharge modeling is not valid if subsurface elements are directing groundwater flow away from surface water flow.

Models that were created for particular regions of the world may not be directly valid for other regions. This was evident in the processing of the Yeh model. This does not mean that these models cannot be applied to different areas, however, thoughtful modification of the factor domain categories and associated weightings should be completed by the researcher adapting the model.
This study used data that were available on a statewide (e.g. geology, sinkholes), countywide (e.g. land use), and local (e.g. fracture trace intersection) basis. Modeling approaches such as the one outlined in this paper can be conducted in other areas, however, they may require modification, or exclusion, of variables based upon available data in each locale.

The effectiveness of a recharge model is difficult to quantify and expensive to ground truth. There are assumptions inherently built into each modeling approach. Limitations of a model should be recognized and acknowledged by researchers and those making decisions based on a model’s results. When possible, several approaches using differing methodologies should be considered.

Recharge models are more useful if the intent of the model is clearly outlined, especially in karst areas. The Spring Creek watershed’s geologic conditions greatly impact what happens to water after infiltration. The presence of sinkholes and springs further complicates the task of identifying the destination of infiltrated water. By pairing surface recharge modeling with an understanding of groundwater hydrology, useful information can be disseminated and inform decision-making within the watershed.
References


combined sewer overflow: Evidence of bacterial and micro-pollutant contamination.  

_Environ. Geol._ 57: 797-808. doi: 10.1007/s00254-008-1359-0.


Tweed, S. O., M. Leblanc, J. A. Webb, and M. W. Lubczynski. 2007. Remote sensing and GIS for mapping groundwater recharge and discharge areas in salinity prone catchments,


