Identifying Optimal Groundwater Recharge Locations and Critical Aquifer Recharge Areas Within the Susquehanna River Basin

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EXECUTIVE SUMMARY

Maintaining or preserving groundwater recharge is the primary means of ensuring water is available in aquifers for water supply and as baseflow to streams. Different geologic materials, structures, and land uses all influence the rate in which water can recharge underlying aquifers. This study incorporated factors influencing recharge through standardization and weighting assignments using the GIS-MCDA framework to identify land-surface areas with the best/highest capacity for sustained or enhanced recharge. We used percent impervious cover, land surface slope, percent sand and clay, depth to bedrock, drainage density, karst density, and fault density to describe recharge potential within the Susquehanna River Basin (basin).

The GIS tool developed for this study can be applied at a basinwide scale, and local scale for sub-watershed, county, or regional assessments, based on the needs of the user. The local application enables the user to identify areas of higher recharge potential in locations that may otherwise have limited recharge potential, such as indicated by results of the basinwide assessment. Additionally, the framework can be applied to define Critical Aquifer Recharge Areas (CARAs) where water supply has become more limited amid development and increasing impervious cover. Results from the tool will aid in developing and/or prioritizing preservation, restoration, or enhancement projects in the basin. Protecting and enhancing CARAs will assist with drought resiliency, improving or maintaining water quality, and preserving water supply for future use.

INTRODUCTION AND PURPOSE

Groundwater recharge is the processes involved in the addition of water to the zone of saturation (Bates and Jackson, 1984), e.g., the mechanism that transports surface water to underlying aquifers. The Susquehanna River Basin Commission (SRBC or Commission) defines groundwater as "*water beneath the surface of the ground within a zone of saturation, whether or not flowing through known and definite channels or percolating through underground geologic formations, and regardless of whether the result of natural or artificial recharge*" (SRBC §806.3). Excluding precipitation and evapotranspiration, groundwater recharge is governed primarily by land cover, soil characteristics, and subsurface geologic features. The Susquehanna River Basin's (basin's) (27,500 mi^2) diverse geology, topography, and land uses leads to complex interactions and considerable variations in local recharge rates. As such, some portions of the landscape are more conducive to recharging aquifers than others; these areas may be responsible for contributing the majority of baseflow to streams during low flows. The natural capacity of a landscape to infiltrate water and recharge aquifers may be disrupted by the removal of forest cover and increased impervious cover from land development; such transformations can exacerbate drought conditions.

An objective in the Commission's Comprehensive Plan is to identify and promote open space and other land uses that provide for increased groundwater recharge to enhance the resiliency of water supply, stream baseflow, and water temperatures. The Commission's Groundwater Management Plan (SRBC, 2005) and Northern Lancaster Groundwater Study (Edwards and Pody, 2005) emphasize the importance of identifying and protecting Critical Aquifer Recharge Areas (CARAs), particularly as water supply becomes more limited amid development and increasing impervious cover. The Commission's Groundwater Management Plan (2005) defines CARAs as land surface areas that are responsible for a large fraction of the recharge. An area may be classified as a CARA by virtue of its high aquifer permeability, soil characteristics, vegetative cover, and location with respect to discharge areas and/or withdrawals, topographic setting, or a combination of these (SRBC, 2005). With the identification of CARAs, Commission staff and stakeholders can identify actions to ensure the sustainability of groundwater resources, preservation of baseflow and water temperature in streams, and overall resiliency of the basin during periods of drought in areas that could have the most potential for impact.

The intent of this study is to develop a Geographic Information Systems (GIS) framework to identify areas of greater and lesser recharge potential, and CARAs throughout the basin. Recharge potential is assessed relative to surrounding areas, which may include the Susquehanna Basin as a whole, sub-watersheds, counties, or other user-defined areas, depending on the need of the user. Outputs from the GIS tool can be used by Commission staff and stakeholders in support of improved groundwater resources management and identification of restoration and protection priorities on the landscape.

REVIEW OF EXISTING METHODS

Groundwater recharge suitability mapping is generally associated with site selection for artificial recharge or Managed Aquifer Recharge (MAR). MAR is most prevalent in the western United States, primarily in arid regions with expansive, confined, valley fill aquifers, and increased demand for water resources. A database of MAR case studies show few MAR projects in the eastern U.S. (International Groundwater Resources Assessment Centre, 2022). Those that have been constructed in the eastern U.S. have been designed to preserve freshwater supply in brackish coastal plain aquifers and offset salt water intrusion. Expansive recharge suitability mapping efforts have yet to be conducted in the eastern U.S.

Sallwey et al. (2019b) indicates there is no consistent approach to generating recharge suitability maps. One commonality in contemporary efforts is the use of GIS, and more specifically, the use of GIS-Multi-Criteria Decision Analysis (MCDA). With MCDA, many different and potentially conflicting data sources can be combined through standardization and weighting-assignments to produce a meaningful output and/or index (Figure 1). MCDA can be applied over a geographic area using a raster matrix to classify and compare target values represented by each pixel cell. Each input raster is weighted according to its importance or percent influence. The weight is a relative percentage, and the sum of the percent influence weights must equal 100 (ESRI, 2023). To have a meaningful output, and enable each of the criteria to be compared, the values of the individual rasters must be normalized or re-classified into a consistent scale. The scale can be alphanumeric and does not need to represent a unit-value. Once input datasets are reclassified, a composite, output raster can be generated by multiplying each raster's weight by the cell value, and summing the resulting values for each overlapping cell of the rasters.

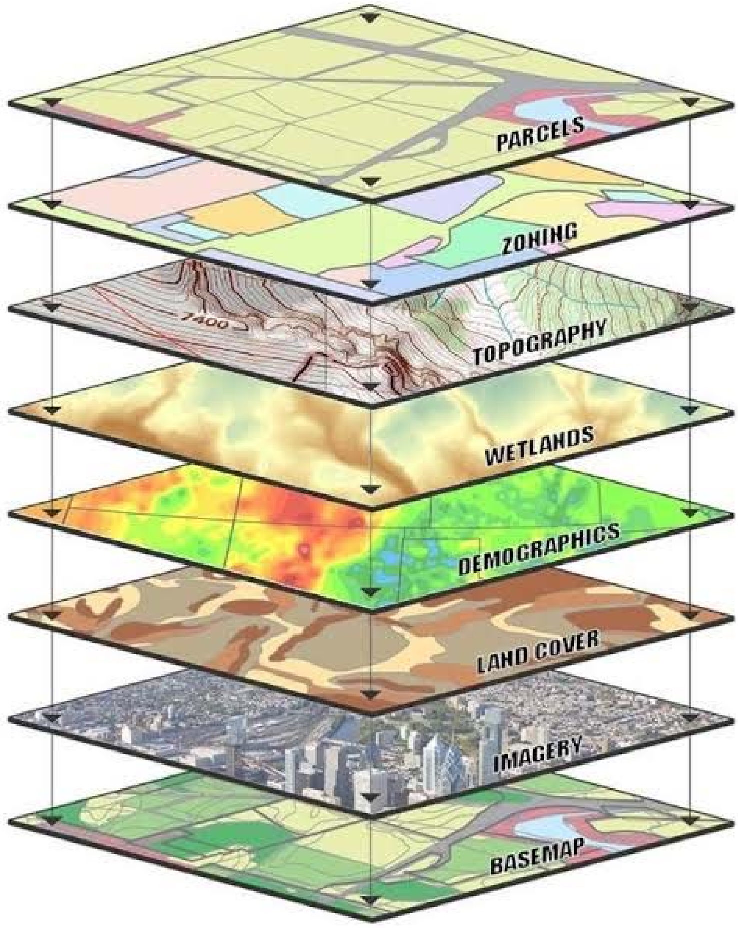

Figure 1. Multi-Criteria Decision Analysis Representation (Ryan and Nimick, 2019)

While various thematic layers have been considered in MAR suitability mapping, there is no single guideline or consistent approach applicable for all conditions (Fathi et al., 2020; Goode, 2021). In an inventory of 63 aquifer recharge projects around the world, as many as 21 different parameters were used to identify areas with high recharge potential (Sallwey et al., 2019a). These often included parameters such as slope, land use, geology, aquifer thickness, soil type, geomorphology, drainage density, flow capacity, storage capacity, precipitation, runoff, economy, impact assessment, hydrography, and the quality of groundwater and surface water. Goode (2021) indicates there is a tendency to use as many parameters as available, rather than using what is essential and expedient; in several cases, more parameters were used than would have been necessary to produce a similar outcome.

The most directly applicable data layers, given the study area, are physical basin characteristics used in regional regression equations to predict baseflow in locations where U.S. Geological Survey (USGS) streamflow-gaging stations are not available. Baseflow is often used as an approximation of recharge when losses of groundwater from the watershed are thought to be minimal. As such, baseflow has been referred to as "effective recharge" (Daniel, 1996), "base recharge" (Szilagyi et al., 2003), or "observable recharge" (Holtschlag, 1997). Basin characteristics found to be significant explanatory variables in regional baseflow regression equations are presented in Table 1. For this study, groundwater recharge potential is assessed relative to surrounding areas, and is assumed to be governed by surface and subsurface characteristics, rather than precipitation, temperature, evapotranspiration, climate variability, and/or water use. Therefore, this MCDA does not consider precipitation or temperature criteria.

Table 1. Basin Characteristics Considered in Regional Baseflow Regression Equations

PREDICTOR VARIABLES	CITATION
Mean annual precipitation (inches)	Stuckey, 2006; Risser et al., 2008; Balay et al., 2016; Carpenter and Hayes, 1996
Percent underlain by carbonate bedrock	Stuckey, 2006; Risser et al., 2008
Percent forested area	Stuckey, 2006
Percent urban area	Stuckey, 2006
Average daily maximum temperature (degrees Fahrenheit)	Risser et al., 2008
Percent sand in the soil	Risser et al., 2008
Channel slope (foot per mile)	Risser et al., 2008
Mean elevation	Balay et al., 2016
Baseflow Index	Balay et al., 2016
Stream density	Balay et al., 2016
Hydrostratigraphic folded shale rock type	Balay et al., 2016
Topographic position index valley area	Balay et al., 2016
Percent type A soils (Sa), classified as having "low runoff potential")	Carpenter and Hayes, 1996
Percent type D soils (Sd), classified as having "high runoff potential")	Carpenter and Hayes, 1996

METHODS

Input Criteria

The Susquehanna River Basin is geologically and topographically diverse, and recharge can vary spatially from kilometers to meters based on soil, bedrock, faults, fractures, land-surface slope, land use, and other discrete variables. The intent was to select representative criteria, so the tool performs well in all parts of the basin without over-representing or underrepresenting any particular area or specific variable. Many relevant GIS datasets were available for our study area; however, there are inevitably trade-offs with the accuracy, resolution, and spatial coverages of individual datasets. For our study, the following standards were considered for input-criteria datasets: 1) minimum of 30 by 30 meter raster cell resolution; 2) complete coverage of the basin; and, 3) open source data that are available to the public. For this reason, we relied heavily on nationwide coverages, such as land cover, hydrography, and soil datasets from federal agencies. Some state-specific datasets, including those associated with higher-resolution, structural geologic mapping efforts, were aggregated for a contiguous dataset.

After reviewing a comprehensive list of potential data layers (Appendix A), we determined many criteria had overlapping characteristics, or were analogous to others. Criteria were prioritized using the Analytic Hierarchy Process (AHP) (Saaty, 1980), which is an additive weighting model that can be combined with MCDA. Three general “first-level factors” were initially identified based on three primary zones of infiltration or recharge; those include land surface, shallow-subsurface (soil) geology, and structural/bedrock geology. Within those classes, we limited our selection to two to three “second-level factors,” to arrive at a final selection of eight unique criteria (Table 2). Six of eight criteria correspond to basin characteristics used in regional baseflow regression equations. Depth to bedrock (or soil thickness) was not used in baseflow regression though it was used to estimate the 7-day, 10-year low flow statistic

(Stuckey, 2006), which is assumed to be comprised entirely of baseflow. Fault density was incorporated into the MCDA, as it is important in describing local, preferential recharge pathways at higher spatial scales, which is typically not required for regional streamflow predictions.

Table 2. Multi-Criteria Decision Analysis Input Criteria

FIRST-LEVEL FACTORS	SECOND-LEVEL FACTORS
Surface Features	Impervious Area
	Land Surface Slope
Shallow-Subsurface Geology	Percent Sand
	Percent Clay
	Depth to Bedrock
Structural / Bedrock Geology	Drainage Density
	Karst Density
	Fault Density

MCDA requires input raster datasets to be reclassified into a consistent scale, such that each dataset can be compared. Raster values representing percentages, depths, and/or densities were reclassified into five unique classes. For each class, an index value from 1-5 (with 5 indicating the greatest recharge potential) was applied to each pixel value within the class. Values in the first class represent land surface areas with low recharge potential and values in the 5th class indicate highest recharge potential. Input criteria selected for the MCDA are described in detail below.

Impervious Cover

Impervious surfaces inhibit precipitation from entering the soil and recharging underlying aquifers. As impervious cover is increased, runoff increases in volume and rate. Surface runoff can double when impervious surfaces reach as low as 10%; at 100% impervious surface coverage, runoff can be five times that of a forested watershed (Arnold and Gibbons, 1996; Paul and Meyer, 2001). Areas of zero impervious cover, such as those with forest and/or agricultural land cover, are assumed to be more conducive to recharge. Impervious cover was incorporated into the MCDA by using the National Land Cover Database (NLCD) 2019 Impervious dataset, which represents urban impervious surfaces as a percentage of developed surface over every 30-meter pixel in the United States (Dewitz, 2021). The dataset was reclassified for MCDA based on the five classes representing recharge potential in Table 3.

Table 3. Impervious-Recharge Classification Schema

IMPERVIOUS PERCENTAGE	ASSIGNED RECHARGE VALUE
50-100	1
15-50	2
10-15	3
5-10	4
0-5	5

Surface Slope

As slope increases, stormwater runoff increases in velocity, not allowing as much time for infiltration. If the soil infiltration rate is slower than the runoff velocity, more water will be lost and unavailable for recharge. Areas with low slopes are better suited for recharging aquifers than areas with moderate to steep slopes. The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) classifies soils based on percent slope-gradient ranges. Slope information was extracted from the Soil Survey Geographic Database (SSURGO) (NRCS, 2022). Associated polygon coverages were clipped to the basin and processed as a raster. Percent slope values were reclassified for MCDA based on slope recommendations from the Pennsylvania Stormwater Best Management Practices Manual, Section 6 Structural BMPs (PADEP, 2006). Infiltration is not recommended for any slope greater than 15%, and slopes within 0-4% have the highest recharge potential (Table 4).

Table 4. Slope-Recharge Classification Schema

SLOPE PERCENTAGE	ASSIGNED RECHARGE VALUE
>15	1
12-15	2
8-12	3
4-8	4
0-4	5

Percent Clay and Sand

The time it takes for water to reach the aquifer is dependent on soil texture (percentage of sand, silt, and clay). Coarser soil textures (high percent sand) allow for water to move rapidly through the soil profile and into the aquifer, while fine grained soil textures infiltrate more slowly. Soils with small pore spaces, such as those with high percent clay, absorb less water and drain slowly, which results in more runoff and less recharge. There is potential for soils to have high sand content, but also contain clay. In such instances, clay can fill available pore space and limit infiltration. For this reason, percent clay and sand were both incorporated as criteria in the MCDA analysis. Percent clay and sand information was extracted from the NRCS (2022) SSURGO database and was reclassified based on septic system suitability ratings provided within the database (Table 5).

Table 5. Sand/Clay-Recharge Classification Schema

SAND/CLAY PERCENTAGE	ASSIGNED RECHARGE VALUE FOR SAND	ASSIGNED RECHARGE VALUE FOR CLAY
>25	5	1
20-25	4	2
15-20	3	3
10-15	2	4
0-10	1	5

Depth to Bedrock

The depth of soil and/or depth to bedrock has been found to be a primary control on the timing and magnitude of baseflow (Asano and Uchida, 2012; Buttle et al., 2004). In shallow bedrock settings, lateral groundwater flow can be susceptible to atmospheric influences, which may result in increased evapotranspiration and streamflow losses. As the soil column is increased, there is greater potential for water storage. Briggs et al. (2022) found streams in Virginia with greater soil thicknesses to have higher summer baseflow and cooler water temperatures. Depth to bedrock information is available as an attribute in the SSURGO database (NRCS, 2022). The dataset was reclassified for MCDA using an equal-interval classification for 5 classes representing recharge potential (Table 6).

Table 6. Depth to Bedrock-Recharge Classification Schema

DEPTH TO BEDROCK (INCHES)	ASSIGNED RECHARGE VALUE
>40	5
30-40	4
20-30	3
10-20	2
0-10	1

Drainage Density

Stream networks generally evolve as a function of surface runoff and erosion. Stream channels that convey more water, relative to watershed size, typically incise faster. Such is the case for streams that overlay geology types in which water quickly runs off (i.e., shale, quartzite), rather than infiltrating. Conversely, in areas with more transmissive geology types (i.e., carbonate, sandstone), precipitation will infiltrate at a greater rate, and runoff is limited, leading to sparse drainage networks. Drainage density is therefore a surrogate for generalized rock types. Drainage density refers to the total length of natural, mapped stream channels found in a watershed. This metric is commonly used for regional streamflow regression equations. For our purposes, we used the Density toolset in ArcGIS with a search radius of 1 kilometer to produce a raster "heat-map" of stream features in the National Hydrography Dataset (NHD) (USGS, 1999) to illustrate the density of stream features. Density is calculated in units of length per unit of area. The dataset was reclassified for MCDA using an equal-interval classification for 5 classes representing recharge potential (Table 7).

Table 7. Drainage Density Classification Schema

DRAINAGE DENSITY (STREAM LENGTH/KILOMETER X 100)	ASSIGNED RECHARGE VALUE
0-100	5
100-200	4
200-300	3
300-400	2
>400	1

Fault Density

Faults provide preferential pathways for surface water to recharge aquifers. They can also act as hydraulic conduits connecting shallow and deep geologic units. A contiguous fault dataset did not exist for the basin, so we aggregated mapped faults from state-specific digital geologic maps. The New York fault dataset was extracted from the New York State Museum's "Preliminary Brittle Structure Map of New York" shapefile, which is based on the work of Isachsen and McKendree (1977). The Pennsylvania fault dataset was extracted from the Pennsylvania Bureau of Topographic and Geologic Survey, Department of Conservation and Natural Resources (PADCNR) "Geologic Map of Pennsylvania" shapefile, which is based on the work from Berg and others (1980). Both map products were published at a 1:250,000 scale; faults depicted as polylines are therefore not intended to be used at finer scales. The aggregated fault dataset of polyline features was also processed into a raster "heat-map" using the Density toolset in ArcGIS and a search radius of 1 kilometer. This approach spreads the area of influence (potential recharge) into surrounding areas of concentrate fault features with potentially fractured rock, which may have higher transmissivities. The dataset was reclassified for MCDA using an equal-interval classification for 5 classes representing recharge potential (Table 8).

Table 8. Fault Density-Recharge Classification Schema

FAULT DENSITY (FAULT LENGTH/KILOMETER X 100)	ASSIGNED RECHARGE VALUE
0-100	1
100-200	2
200-300	3
300-400	4
>400	5

Karst Density

Mildly acidic rainwater can infiltrate into the subsurface and dissolve soluble limestone and dolomite rock types, enlarging cracks, fractures, and holes. The resulting landscape, referred to as karst, has features such as sinkholes, closed topographic depressions, sinking streams, caves, and springs. In karst systems, recharge and aquifer flow can be quick and direct through conduits, or slow and diffuse through fine fractures. Diffuse flow occurs in less soluble rocks such as shaley limestones or crystalline dolomites (White, 1969). Well-developed karst aquifers have low storativity and high hydraulic conductivities, allowing for rapid infiltration. However, not all carbonate regions in the basin have karst features, or high infiltration capacities. For this reason, we used the digital compilation of mapped karst features in Pennsylvania (Reese and Kochanov, 2003) to produce a "heat-map," similar to the faults dataset, using a radial search radius of 250 meters. Density is the sum of karst features within the search radius divided by the area of the search radius. The dataset was resampled to create a 30 x 30 meter raster cell compared to 25 x 25 meter resolution of the original Reese and Kochanov (2003) karst density map. The resulting dataset illustrates areas of dense karstification that are more conducive to recharging aquifers than non-karst, carbonate areas. The dataset was reclassified for MCDA using a modified equal-interval classification for 5 classes, representing recharge potential (Table 9).

Table 9. Karst Density Classification Schema

KARST DENSITY (FEATURES PER/KM^2)	ASSIGNED RECHARGE VALUE
0	1
1-50	2
50-100	3
100-150	4
>150	5

Data Processing and Weighting Assignments

In MCDA, each input can be weighted according to its importance or its percent influence. Weights were initially assigned to "first-level factors," following the Analytic Hierarchy Process (Saaty, 1980). Weighting for "second level factors" were determined through an iterative process of comparing outputs from various MCDA model configurations to: 1) areas underlain by geologic formations with known, high recharge rates (SRBC, 2020); and, 2) CARAs identified in Northern Lancaster Groundwater Study (Table 10) (Appendix B).

Table 10. Weighting Assignments for Multi-Criteria Decision Analysis Input Criteria

WEIGHT	FIRST-LEVEL FACTORS	WEIGHT	SECOND-LEVEL FACTORS
40	Land Cover / Terrain	25	Impervious Area
		15	Land Surface Slope
20	Shallow-Subsurface Geology	15	Percent Sand
		2.5	Percent Clay
		2.5	Depth to Bedrock
40	Structural / Bedrock Geology	25	Drainage Density
		10	Karst Density
		5	Fault Density

Input datasets were combined into a composite MCDA output raster in ArcGIS using the Weighted Overlay tool in the Spatial Analyst toolbox. The MCDA output raster illustrates recharge potential on a scale of 100 to 500. Values of the resulting raster output are dimensionless, as they are a suitability index. The raster output was reclassified into 5 unique classes using a quantile classification scheme. Each class contains an equal number of features, and an index value from 1-5 (indicating recharge potential) was applied to each pixel value within each class. Values in the first class represent land surface areas with low recharge potential and values in the 5th class indicate highest recharge potential. As a nonparametric classification scheme, the quantile classification was most applicable, as output raster values do not fit a normal distribution.

The literature indicates MCDA is a largely subjective and qualitative process that relies heavily on professional judgement. In an attempt to quantitatively validate our criteria and weighting assignments, we compared pixel values from the MCDA output raster within USGS gaged-watersheds to average annual baseflow (or recharge) of those watersheds. With an accurate MCDA model, watersheds yielding higher average annual baseflow, per unit area, would also illustrate higher recharge potential area pixel values.

We found that the sum of all "high recharge potential area" pixels can predict average annual baseflow within 19.7% (standard error) on average (n=40 gaged watersheds), which suggests our criteria selection and weighting assignments are reasonable. This analysis is described in detail in Appendix C.

Areas of high recharge potential depicted in the final raster output may potentially overlie open water in features such as rivers, streams, lakes, or reservoirs. Open water locations may be suitable for recharge; however, some input datasets may not be applicable and/or complete for these areas. For this reason, we recommend excluding or masking areas of high recharge potential that correspond to areas of open water. To comprehensively describe surface waters in the basin, we combined "waterbody" features from the NHD (USGS, 1999) and areas classified as "open water" in the NLCD (Dewitz, 2021) into a single polygon coverage. For display purposes, we masked high recharge potential areas overlying surface water features in figures presented in the Product Availability section below.

All input rasters were projected to an Albers equal area conic projection. When processing input rasters, the Snap Raster function was used to ensure all raster cells were aligned prior to completing the MCDA analysis. By adjusting the extent of output rasters so that all cells are aligned, some rasters contain "NoData" cells. This was evident near the basin boundary, due to clipping and/or masking of rasters to the extent of the polygon; however, we consider the input datasets to satisfy the quality standards relative to the purpose for which they were collected and are utilized for this study.

IMPLEMENTATION

The GIS-based framework was designed to be applied at a basinwide scale and local scale for sub-watershed, county, or regional assessments, based on the needs of the user. A 30 x 30 meter resolution output is intended to provide sufficient resolution and flexibility for the end user in incorporating the dataset in additional geospatial analyses.

Basin Scale

A primary objective of the tool was to provide a meaningful output for agencies, stakeholders, researchers, and others with basinwide interests. Mapped areas with high recharge potential may assist water resource managers with planning and prioritizing activities over potentially large jurisdictions. As such, areas with the highest recharge potential within the basin may be critical in identifying projects that could potentially preserve a large fraction of water as baseflow during periods of drought. Additionally, it may be beneficial to a user group to have awareness that a larger area or particular region, as a whole, has less recharge potential. The basinwide output may also be used to assess the relative impact and cost-benefit of particular projects and/or determine if efforts should be focused in potentially more sensitive locations. Of particular relevance is the solicitation of projects by the Commission to mitigate potential local and basinwide impacts related to consumptive water use (CU); these projects include, but are not limited to, land preservation/acquisition activities and aquifer recharge enhancements.

Local Scale

For local applications, the basinwide raster can be resampled in a user-defined area to illustrate areas of high recharge potential, relative to all other areas within the user-defined area. In ArcGIS, the Extract by Mask tool in the Spatial Analyst toolbox can be used to extract the cells of the basinwide raster that correspond to user-defined areas such as sub-watershed, county, or township boundaries (mask). The output raster values can then be re-classified using the quantile classification to illustrate areas with the highest recharge potential (pixels within the 5th class). This application enables the user to identify such areas in locations that may otherwise have limited recharge potential, increasing development, and/or water supply limitations. At a finer project scale, the tool could have applications for water purveyors or planners in analyzing more productive and sustainable groundwater sources, or avoiding potentially over-utilized areas with limited water availability.

RESULTS

Broad conclusions from the basinwide assessment were noted. In general, areas underlain by carbonates with well-developed karst features coincided with areas of high recharge potential; such areas include the Great Valley limestones, State College carbonates, and the Onondaga and Heidelberg Limestone belt found on the northern edge of the basin. In the West Branch Susquehanna subbasin, large swaths of high recharge potential areas were located on the flat upland portions of the Allegheny plateau. Major contributing factors include the upland's horizontal slope, relatively low population density, and/or lack of development. High recharge potential areas also coincide with the locations of bituminous and anthracite coal fields. It is unknown why this occurs, but large-scale earthworks, excavation, and water-filled mines may provide some clues which impact slopes and soil composition, although further investigation is needed to ascertain the presence of high recharge potential areas in this region. Recharge potential is illustrated for the basin in Figures 2 and 3. A detailed analysis of recharge potential at a consistent, local scale, such as for HUC 10-12 watersheds, was not completed for this study. However, a large focus was given to identifying CARAs, watersheds, and sub-watersheds that contain areas of higher recharge potential, where surface and groundwater resources are relied on heavily to supply substantial potable, industrial, and habitat-supporting water resources. The identification of CARAs is further discussed below.

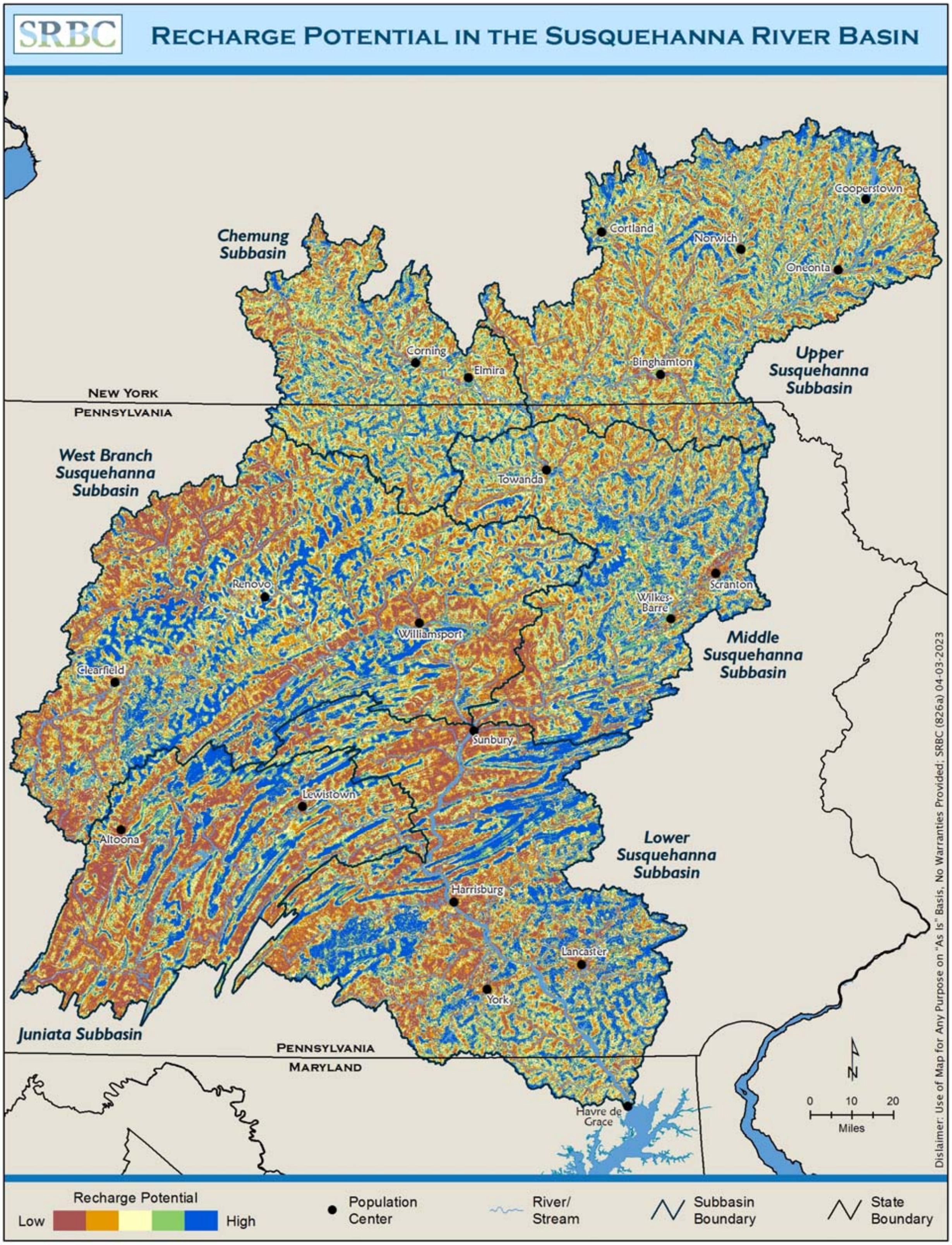

Figure 2. Basinwide Recharge Potential

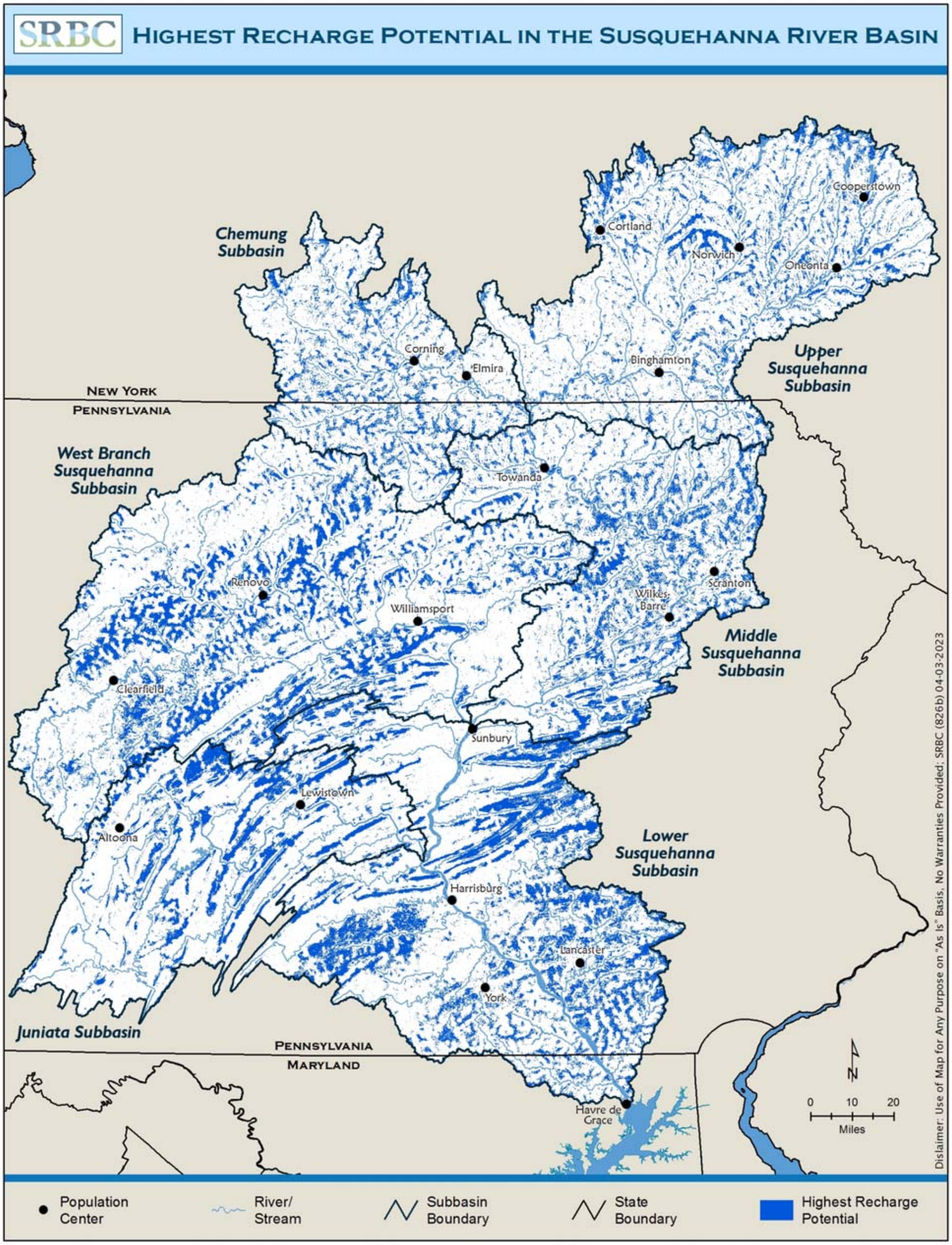

Figure 3. Areas with Highest Recharge Potential within the Basin

CRITICAL AQUIFER RECHARGE AREAS

The Commission's (2021) Comprehensive Plan indicates there is an essential need to delineate and properly manage CARAs in the basin to help ensure water supply sources are sustainable, and to preserve local baseflow in streams, now and into the future. Such efforts should be directed to areas where water supply has become more limited amid development and increasing impervious cover. The Commission's Groundwater Management Plan (SRBC, 2005) identified seven potentially stressed areas (PSAs) where the utilization of groundwater resources has approached or is exceeding the sustainable limit of the resource, defined as the average annual baseflow (recharge) available in the local watershed during a 1-in-10-year drought. Three of the seven PSAs represent the State College area (Spring Creek Watershed), Hanover area (South Branch Conewago Creek Watershed), and Manheim/Lititz Valley (Chiques Creek and Conestoga River Watersheds). The Commission's Cumulative Water Use and Availability Study (CWUAS) indicates water use within these watersheds is expected to increase among some of the highest rates of any watershed given population projection estimates. The Spring Creek, South Branch Conewago Creek, and Conestoga River Watersheds were also recommended for designations of Critical Water Planning Areas (CWPA) by State Water Plan (SWP) regional committees, following a statewide screening.

Using our framework, we delineated CARAs relative to hydrologic unit code (HUC) 10 watershed boundaries for Spring Creek and South Branch Conewago Creek. HUCs are standardized watershed delineations at varying scales; they may overlap with other HUC-10 contributing areas (nested), particularly as drainage area increases. Spring Creek and South Branch Conewago HUC-10 Watersheds are non-nested, headwater HUC-10 watersheds. The Manheim/Lititz Valley PSA is based on a regional groundwater basin and contributing area, which represents portions of multiple HUC-10 watersheds. CARAs in the Manheim/Lititz Valley were mapped relative to the 22 mi^2 PSA boundary identified in the Northern Lancaster Groundwater Study (Edwards and Pody, 2005). The CARA delineations described above represent two separate, local applications of the tool on different spatial scales, including watershed boundaries and a user-defined area.

Spring Creek Watershed (State College Area)

Spring Creek is a 146.0 mi^2 watershed in western Centre County, and represents one of the largest and most productive regional karst carbonate aquifer systems in Pennsylvania. The Commission's (2005) Groundwater Management Plan indicates the State College area has undergone rapid residential, educational, and commercial growth, which has resulted in increased impervious cover, less recharge, and stormwater issues. Municipal water for the State College Borough and Pennsylvania State University is currently drawn from several well fields in the headwaters of Spring Creek. This scenario has the potential to create additional losing stream reaches and sinkholes within the headwaters of Spring Creek. Additionally, high calcium limestone mining at the foot of the mountains has removed portions of the karst aquifer that previously collected runoff from the mountain slopes. Dewatering of quarries has also altered natural recharge pathways and contributed to flow loss in springs and perching of streams (SRBC, 2005).

CARAs in the Spring Creek Watershed are dispersed in forested and agricultural lands underlain by both carbonate and sandstone rock types (Figure 4). One of the most expansive CARAs is located near the Penns-Spring Creek Watershed divide in the carbonate valley southwest of Centre Hall. This area is underlain by the Bellefonte Formation, which is a dolomite with well-developed karst features. CARAs are also concentrated in a south-east to north-west trending pattern on the carbonate uplands between the Buffalo Run and Spring Creek Watersheds. This area is considered the western extent of the Nittany Valley, which is part of an eroded anticline. The southern terminus of the Nittany Valley is Mount Nittany, which is underlain by the Bald Eagle Formation (sandstone). The forested saddles between the Mount Nittany ridges are identified as a CARA.

CARAs were also located in the forested land directly north-west of Park Forest, which is referred to as the Scotia Barrens (including State Game Lands 176). The tract of land is one of few remaining forested areas in the Nittany Valley. The barrens are underlain by the lower members of the Gatesburg Formation which is interbedded with sandstone layers up to 10 feet thick (Butts and Moore, 1936). The soils are sandy and acidic, which may have contributed to the development of karst features in other carbonate members of the Gatesburg Formation. The barrens also host many vernal pools, which fluctuate seasonally with groundwater levels (Hughes, 2010).

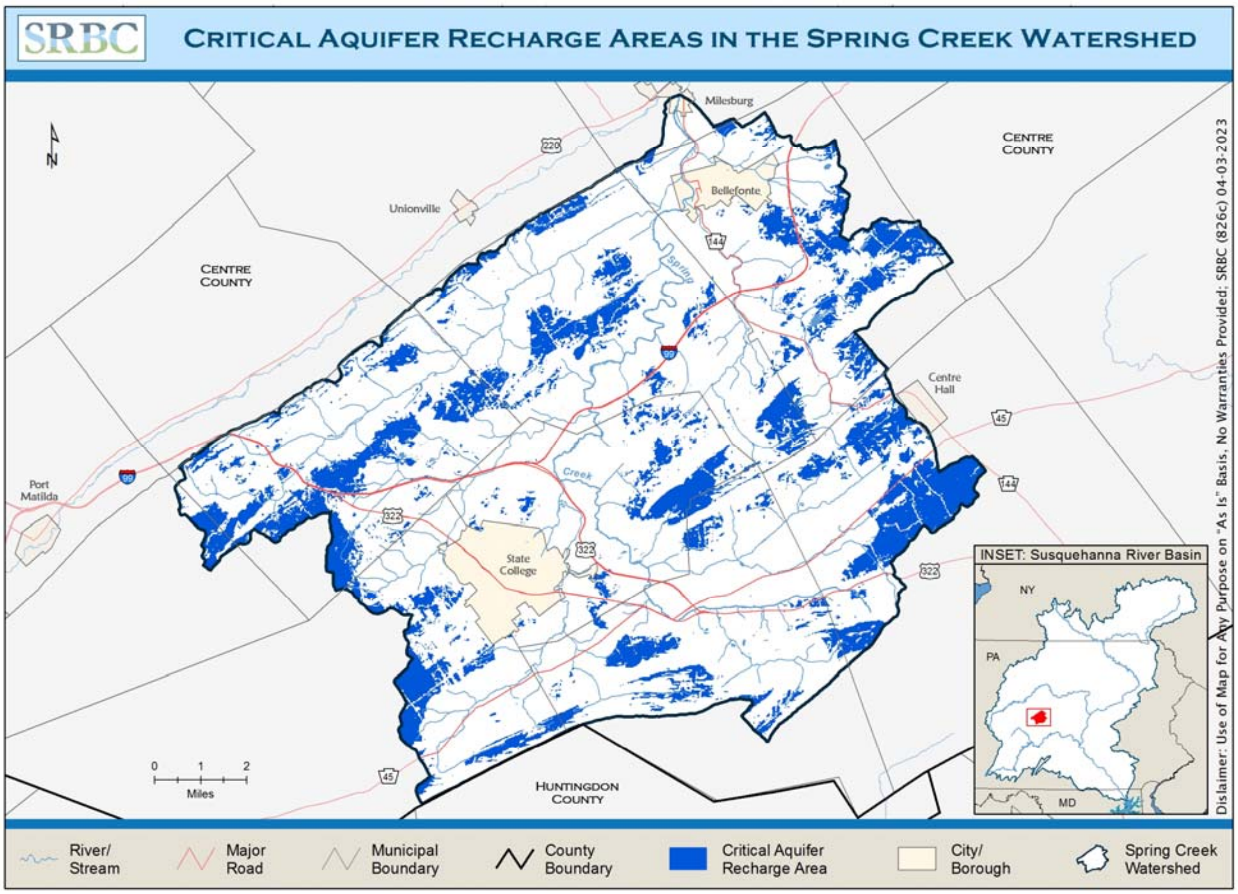

Figure 4. Critical Aquifer Recharge Areas within Spring Creek Watershed

South Branch Conewago Creek Watershed (Hanover Area)

The South Branch Conewago Creek is a 73.5 mi^2 watershed in southern York County. A considerable amount of water use (10.1 mgd) in the watershed is primarily associated with the Borough of Hanover; a portion of this water is diverted out of the local watershed. The Borough of Hanover relies primarily on surface water reservoirs. These reservoirs have relatively small contributing drainage areas, and have slow refill times, which has contributed to water supply shortages during droughts (SRBC, 2005). Groundwater supply is limited, with the exception of a relatively small area (9 mi^2) of carbonate rock aquifer, with well-developed karst permeability. However, the aquifer cannot support high yielding municipal water supply wells as nearby quarry and dewatering operations deplete the aquifer, lowering regional groundwater levels (SRBC, 2005). The surrounding area also includes the Bonneauville Shale Belt, which is low-yielding and produces limited amounts of groundwater to support water resource development; this area has also been designated as a Water Challenged Area (WCA) (SRBC, 2005).

CARAs in the South Branch Conewago Creek Watershed are located primarily in the south-west corner along the Susquehanna-Potomac River Basin divide and in low gradient, carbonate uplands of the Conestoga and Kinzers Formations-some of which have well-developed karst features (Figure 5) (Reese and Kochanov, 2003). Other extensive CARAs were identified in the forested area surrounding Long Arm Reservoir, which is part of the Borough of Hanover's water supply. Sandy soils overlying the Marburg Schist (phylite) are present at this location. Small, isolated CARAs were also located in a highly faulted and fractured area at the base of Pigeon Hill, which is the surface expression of an anticline. The hill is comprised of volcanic rock (metabasalt), which overlies older conglomerates, quartzites, and phyllites of the Chickies Formation (Stose and Stose, 1944).

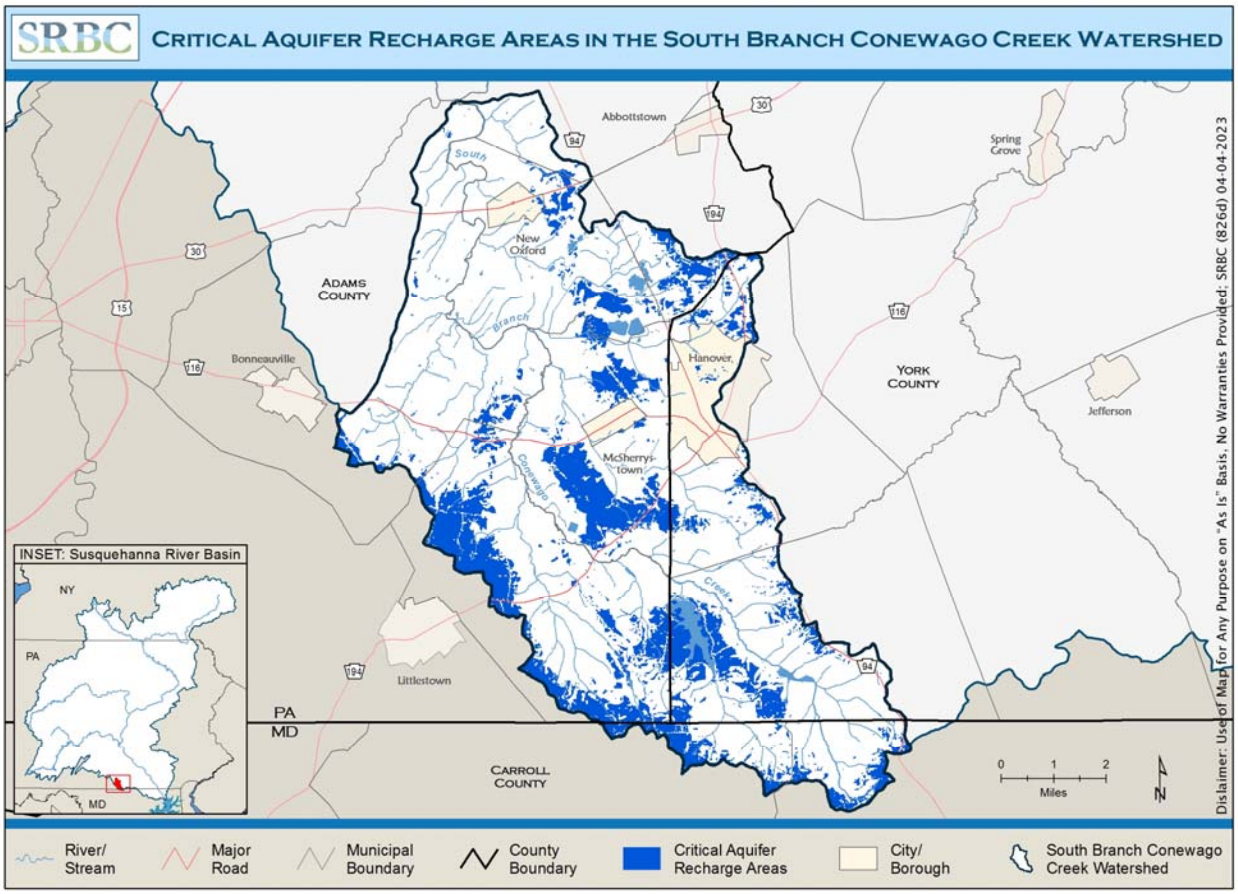

Figure 5. Critical Aquifer Recharge Areas within South Branch Conewago Creek Watershed

Manheim/Lititz Valley Potentially Stressed Areas

The Manheim/Lititz Valley PSA encompasses a 22 mi^2 area in northern Lancaster County. The valley is underlain by a highly productive carbonate aquifer. The PSA includes portions of the Chiques, Conestoga, Cocalico, and Lititz Run Watersheds. The well-developed karst valley is surrounded by upland areas with lower permeability. Water supply for eight townships and five boroughs within the study area is met almost entirely by groundwater. Water use in the Manheim-Lititz area groundwater basin is 70 percent of the sustainable limit. The population in the carbonate valley is rapidly growing, leading to increased urban and suburban cover in an otherwise agricultural area. Impervious cover comprised 9 percent of the study area, which has the potential to reduce average annual recharge by 1,575 million gallons (Edwards and Pody, 2005).

CARAs in the Manheim/Lititz Valley PSA are concentrated in the south-central portion of the PSA, between Manheim and Lititz (Figure 6). This area is a well-developed and highly fractured carbonate upland with agricultural land cover. The underlying geology is a highly deformed and recrystallized limestone with interbedded sandstone. In the Northern Lancaster Groundwater Study (Edwards and Pody, 2005), this area is referred to the Limerock dry valley. The dry valleys are thought to contribute an exceptional amount of recharge because the underlying bedrock has greater karst permeability (more voids and conduits), the water table is below the land surface so that head conditions are favorable to recharge, and the surface runoff covers a large surface of absorption while pooled water is present. Conduits in the "headwaters" of the Limerock dry valley extend westward, capturing the groundwater in the area, and discharge to the Lititz spring (Edwards and Pody, 2005).

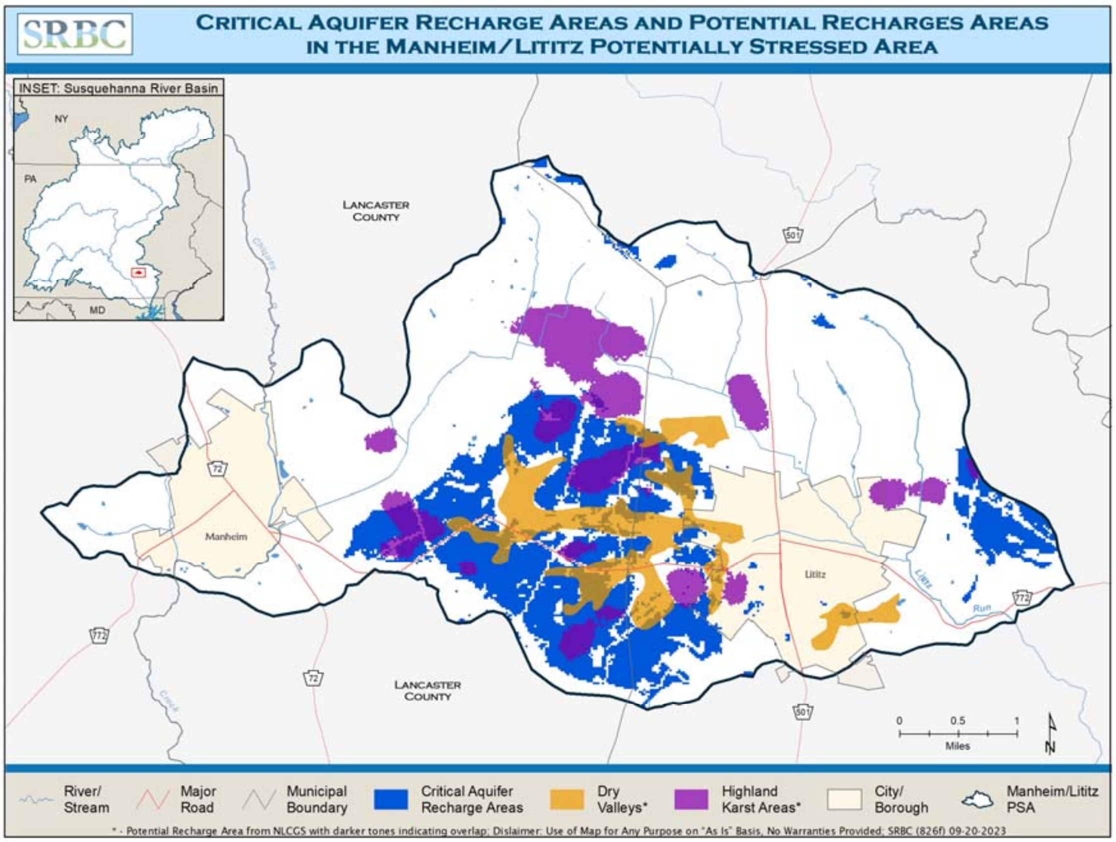

Figure 6. Critical Aquifer Recharge Areas within the Manheim/Lititz Valley Potentially Stressed Area

LIMITATIONS

This tool provides a desktop-based means of identifying areas with increased potential for recharge based on a combination of physical characteristics, excluding precipitation. The study does not provide a quantitative analysis of recharge, but the likelihood of recharge. This preliminary screening tool has a multitude of uses and can be updated over time to understand longitudinal changes in recharge, such as when land uses are converted. As with all recharge studies, the geospatial variability beneath the surface can vary widely over short distances, and may produce results that are inconsistent with mapping products. Site conditions should be verified in the field prior to pursuing projects or activities in such areas. Any errors or omission in the underlying base data cited will impact the results and could change the distribution of recharge potential.

PRODUCT AVAILABILITY

All recharge suitability datasets were compiled and stored in an ArcGIS Geodatabase, and will be made available for download on the Pennsylvania Spatial Data Access (PASDA) geospatial data portal. Although these datasets have been reviewed for accuracy and completeness, no warranty expressed or implied is made regarding the display or use of the data. The Commission also reserves the right to update the framework as needed pursuant to further analysis and review. If a local assessment of potential recharge is desired for any regional, county, watershed, or other user-defined scale, individuals can request the desired output. These requested can be made on an as-needed basis using the Commission's Request for Reported Data page (requires Firefox browser). The Commission is committed to open and transparent operations and accessibility of records to the public, academics, students, and consulting firms, among others.

Feature classes within the geodatabase include the following:

1) Unclassified raster coverage from the MCDA weighted overlay analysis illustrating recharge potential, on a scale from 100-500, for all areas within the basin (Figure 2). This dataset can be extracted and reclassified for local assessments using the quantile classification scheme.
2) Polygon feature class of "high recharge potential areas," which represents all land surface areas that have corresponding pixel values within the 5th (or highest) quantile class (Figure 3).
3) All post-processed input raster datasets used in the MCDA-GIS analysis to describe basinwide recharge potential; these datasets have been reclassified using the quantile classification scheme, and are unitless. These include:
    - Impervious Area
    - Land Surface Slope
    - Percent Sand
    - Percent Clay
    - Depth to Bedrock
    - Drainage Density
    - Karst Density
    - Fault Density
4) Polygon feature class of surface waters described by "waterbody" features in the NHD (USGS, 1999) and areas classified as "open water" in the NLCD (Dewitz, 2021). This dataset may be used to exclude or mask areas of high recharge potential.

RECOMMENDATIONS

- Work with partners/stakeholders to utilize mapped coverages of high recharge potential areas to inform agricultural and forested land preservation activities, aquifer/stormwater recharge enhancement projects, and abandoned mine land/drainage reclamation efforts.
- Apply MCDA framework in a standardized fashion for each HUC-10 watershed in the basin to supplement the basinwide assessment of high recharge potential areas.
- Identify project opportunities to optimize, preserve, or enhance recharge in delineated CARAs that have elevated recharge potential.
- Improve estimations of baseflow and/or recharge rates by incorporating gridded (30-year average) precipitation information (PRISM Climate Group, 2023) as MCDA input criteria in the basinwide assessment.

- Document existing protected lands accessible to the public, such as State Forests and Game Lands, that have high recharge potential and conduct outreach to responsible agencies to raise awareness of the added value of their assets.
- In select CARAs, evaluate field conditions following precipitation events to verify increased infiltration and/or recharge relative to surrounding lands with lower recharge potential.

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APPENDIX A

Potential Criteria Considered for Recharge Suitability Mapping

CRITICAL AQUIFER RECHARGE / MANAGED AQUIFER RECHARGE VARIABLES		DESKTOP OR SITE-SPECIFIC EVALUATION	DATA AVAILABILITY	SPATIAL SCALE	DATA SOURCE
Aquifer Properties	Transmissivity	Desktop / Site Evaluation	Unknown	Basinwide by Formation / Aquifer	Unknown
	Hydraulic Conductivity	Desktop / Site Evaluation	Unknown	Basinwide by Formation / Aquifer	Unknown
	Static Water Level	Desktop	Available	Basinwide by Formation / Aquifer	PaGWIS, NY DEC, MDE
	Depth to Water	Desktop	Available	Basinwide / Polygons	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO)
	Hydraulic Gradient	Desktop / Site Evaluation	Available (limited accuracy)	Variable	PaGWIS, NY DEC, MDE
	Estimated Recharge	Desktop	Available	Basinwide by Formation / Aquifer / Gaged Drainages	SRBC / Various USGS Reports
	Aquifer Thickness	Desktop / Site Evaluation	Unknown	Basinwide by Formation / Aquifer	Unknown
	Storage Capacity	Desktop / Site Evaluation	Unknown	Basinwide by Formation / Aquifer	Unknown
	Confining Layers	Desktop / Site Evaluation	Not Available	Variable	Unknown
	Unsaturated / Vadose Zone Thickness	Desktop / Site Evaluation	Not Available	Variable	Unknown
	Coarse-Grained Sedimentary Units (Presence/Absence)	Desktop	Available	Basinwide by Formation / Aquifer	USGS (2017) State Geologic Map Compilation (SGMC) geodatabase
	Well Yield	Desktop	Available	Basinwide by Formation / Aquifer	PaGWIS, NY DEC, MDE Well Databases
	Infiltration Rate	Site Evaluation	Not Available	Variable	Unknown
Climate	Mean Annual Precipitation	Desktop	Available	Basinwide 4km	PRISM
	Minimum and Maximum Air Temperature	Desktop	Available	Basinwide / TBD	NOAA
	Evapotranspiration	Desktop	Available	Basinwide / TBD	Internal Database (Calculated)

CRITICAL AQUIFER RECHARGE / MANAGED AQUIFER RECHARGE VARIABLES		DESKTOP OR SITE-SPECIFIC EVALUATION	DATA AVAILABILITY	SPATIAL SCALE	DATA SOURCE
Soils	Hydrologic Soil Class	Desktop	Available	Basinwide / Polygons	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO)
	Saturated Hydraulic Conductivity (KSAT)	Desktop	Available	Basinwide / Polygons	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO)
	Percent Sand	Desktop	Available	Basinwide / Polygons	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO)
	Percent Clay	Desktop	Available	Basinwide / Polygons	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO)
	Soil Drainage / Infiltration Capacity	Desktop	Available	Basinwide / Polygons	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO)
Hydrology	Baseflow Index	Desktop	Available	Basinwide	USGS (2003) Base-flow index grid for the conterminous United States
	Average Annual Runoff	Desktop	Not Available	TBD	Unknown / Modeled
	Flow Direction	Desktop	Available	Basinwide - 30 Meter or 1ft	LiDAR or USGS DEM
Geology	Bedrock Geology	Desktop	Available	Basinwide	USGS (2017) State Geologic Map Compilation (SGMC) geodatabase
	Faults/Folds	Desktop	Available	Basinwide	USGS (2017) State Geologic Map Compilation (SGMC) geodatabase
	Karst Density	Desktop	Available	Basinwide / Pennsylvania	PTGS digital dike mapping
	Epikarst Type	Site Evaluation	Not Available	TBD	USGS (2017) State Geologic Map Compilation (SGMC) geodatabase
	Diabase Dikes	Desktop	Available	Basinwide / Pennsylvania	PTGS digital dike mapping
	Alluvium / Colluvium	Desktop	Available	Basinwide	USGS (2009) Map Database for Surficial Materials in the Conterminous United States
	Depth to Bedrock	Desktop	Available	Basinwide	USDA NRCS (2022) Soil Survey Geographic Database (SSURGO) or PaGWIS, NY DEC, MDE Well Databases
Land Use / Land Cover	Urban/Agricultural/Forested	Desktop	Available	Basinwide - 30 Meter	USGS (2019) NLCD 2016 Land Cover Conterminous United States
	Impervious Area	Desktop	Available	Basinwide - 30 Meter	USGS (2019) NLCD 2016 Land Cover Conterminous United States
	Normalized Difference Water Index (NDWI)	Desktop	Not Available	Basinwide - 30 Meter	USGS (2019) NLCD 2016 Land Cover Conterminous United States
Topography	Land Surface Slope	Desktop	Available	Basinwide / TBD	LiDAR, USGS DEM, or NRCS SSURGO Database
Geophysical	Electrical Resistivity	Site Evaluation	Not Available	Site Specific	Unknown

CRITICAL AQUIFER RECHARGE / MANAGED AQUIFER RECHARGE VARIABLES		DESKTOP OR SITE-SPECIFIC EVALUATION	DATA AVAILABILITY	SPATIAL SCALE	DATA SOURCE
	Penetrometer Testing	Site Evaluation	Not Available	Site Specific	Unknown
Geographic / Proximity	Road Density	Desktop	Unknown	Basinwide	Unknown
	Proximity to Power Lines	Desktop	Unknown	Basinwide	Unknown
	Proximity to Water	Desktop	Unknown	Basinwide	Unknown
	Stream / Drainage Density	Desktop	Available	Basinwide	National Hydrography Dataset (NHD)
	Proximity to Landfills / Contaminated Sites	Desktop	Unknown	Basinwide	Unknown
	Well Density	Desktop	Available	Basinwide	PaGWIS, NY DEC, MDE Well Databases
Economic	Aquifer Stress / Limited Availability	Desktop	Available	HUC 10/12	SRBC
	Water-use Trends	Desktop	Available	HUC 10/12	SRBC
	Demographic Trends	Desktop	Available	County Scale	US Census Bureau
	Pollution Concerns	Desktop	Unknown	Site Specific	Unknown
	Regional Water Demand	Desktop	Available	HUC 10/12	SRBC
Ecologic	Threatened / Endangered Species	Desktop	Unknown	Basinwide	PADCNR, NYDEC, MDE
Water Quality	Source Water Quality	Desktop / Site Evaluation	Unknown	Site Specific	PADEP, SRBC, NYDEC, MDE
	Groundwater Quality	Desktop / Site Evaluation	Unknown	Site Specific	Unknown

APPENDIX B

Comparison of High Recharge Potential Areas and Critical Aquifer Recharge Areas Identified in Northern Lancaster Groundwater Study

A comparison of the Northern Lancaster County Groundwater Study with potential recharge areas indicate a substantial overlap (Figure B1). A spot check of areas identified in the NLCGS being outside mapped recharge areas were noted as having changed land use characteristics or were slightly below the threshold for highest recharge potential.

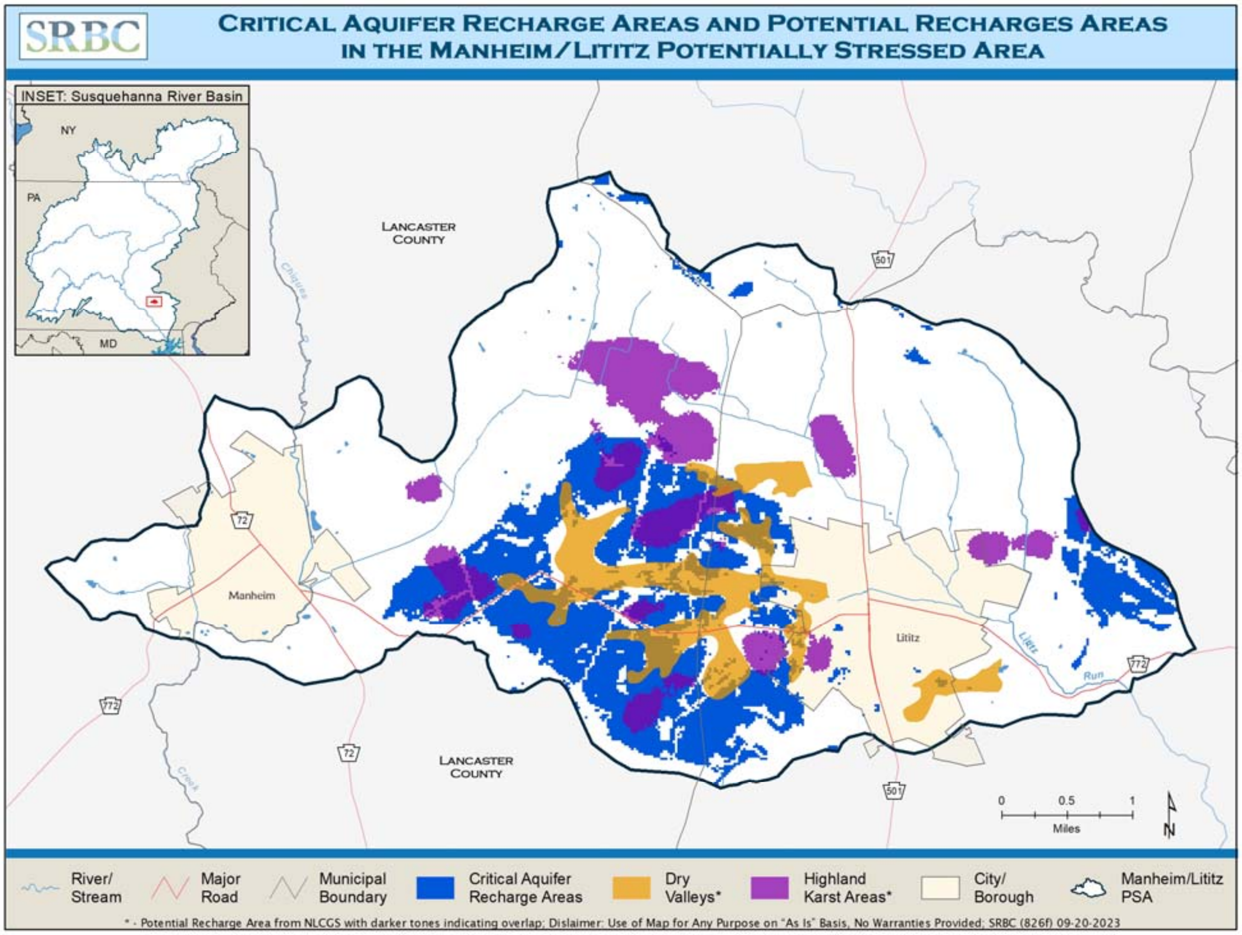

Figure B1. Critical Aquifer Recharge Areas in the Manheim/Lititz Potentially Stressed Area

APPENDIX C

Average Annual Baseflow Prediction Using Basinwide Recharge Potential Raster Output

Since baseflow is an approximation of recharge, we assessed the appropriateness of MCDA input criteria and weighting assignments by comparing average annual baseflow of USGS gaged watersheds to pixel values from the basinwide recharge potential raster for those watersheds. In theory, watersheds yielding higher average annual baseflow would also illustrate higher recharge potential, as indicated by the output of our basinwide MCDA composite raster. For this assessment, 40 USGS gages were selected based on the following criteria:

- Minimally impacted by upstream reservoir regulation, mining, diversions, or quarry operations
- Consistent period of record from 1991-2020
- Less than 1,000 mi^2 drainage area

Annual baseflow estimates for each stream gage were determined using an automated hydrograph separation program—PART. PART is a streamflow partitioning program developed by the USGS to estimate a daily record of baseflow (Rutledge, 1998). This method uses linear interpolation to estimate groundwater discharge during periods of surface runoff. Average annual baseflow for each USGS gage was calculated by averaging annual estimates from 1991-2020.

USGS gaged-watershed coverages were accessed from the USGS (2012) Streamgage NHDPlus Version 1 dataset. For each gaged-watershed, all pixel values from the basinwide MCDA output were extracted and summarized with the "R" programming environment. The amount of pixels (count) contained in each watershed is analogous to drainage area, as each pixel represents a 30 by 30 meter cell. The sum of all pixel values within a watershed provides an overall estimate of recharge potential, as it represents drainage area (count) and recharge potential information (index values) for all cells in a watershed.

The amount of baseflow within a stream is primarily covered by the contributing area of the watershed or drainage area size. For our dataset, the coefficient of determination (R^2) between average annual baseflow and drainage area is 0.91 (Figure C1). This relationship is used as a baseline to assess the relative impact or influence of recharge information provided by the basinwide MCDA composite raster.

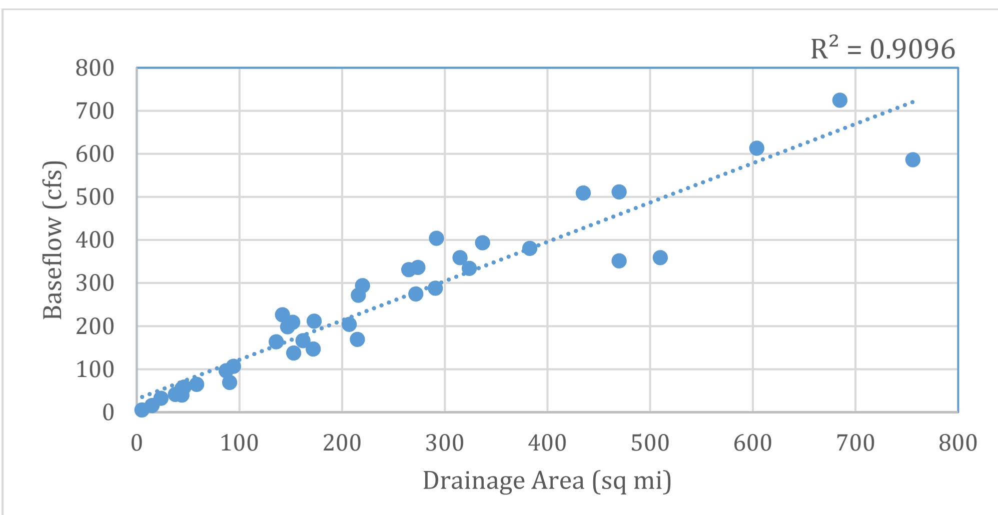

Figure C1. Average Annual Baseflow Versus Drainage Area for USGS Gages

It is assumed that the sum of all pixel values within each USGS gaged watershed should predict average annual baseflow better than drainage area alone, as the sum represents drainage area (count) and recharge potential information (index value of each cell). The coefficient of determination (R^2) between average annual baseflow and the sum of all recharge potential index pixels is 0.93 compared to 0.91, which suggests our MCDA input criteria (recharge variables) and weighting assignments are reasonable. The standard error of prediction is 48.1 cfs (19.7%), compared to 54.6 cfs (22.4%) when using drainage area alone (Figure C2).

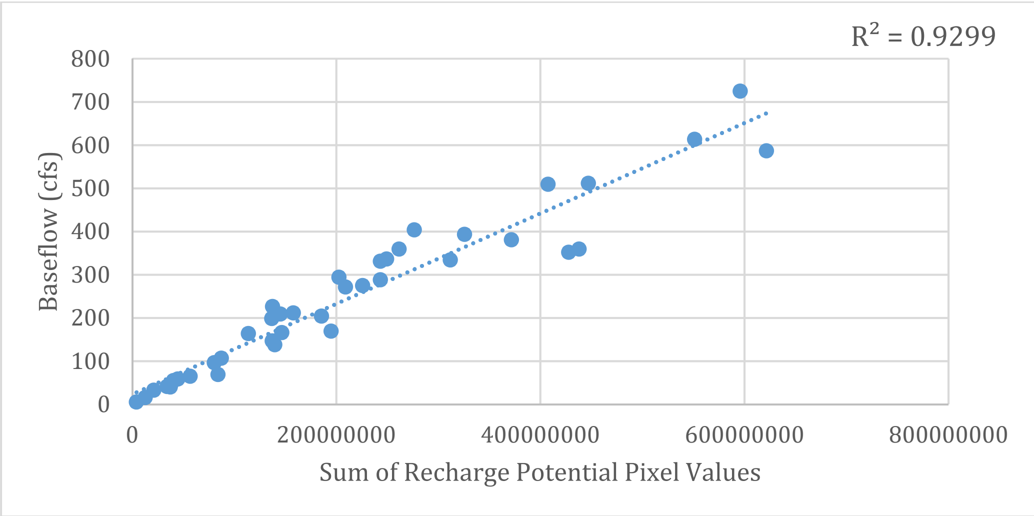

Figure C2. Average Annual Baseflow of USGS Gages Versus the Sum of Recharge Potential Pixel Values

In addition to drainage area, baseflow is also dependent upon precipitation. Average annual precipitation from 1991-2020 ranges from 32" in the northwest part of the basin to 60" in the central east. The relationship between average annual baseflow and the sum of recharge potential pixel values (described above) can be improved if precipitation is accounted for. By normalizing average annual baseflow by average annual precipitation, the sum of recharge potential pixel values within a watershed can predict average annual baseflow within 17.1% on average (R^2 of 0.95) (Figure C3).

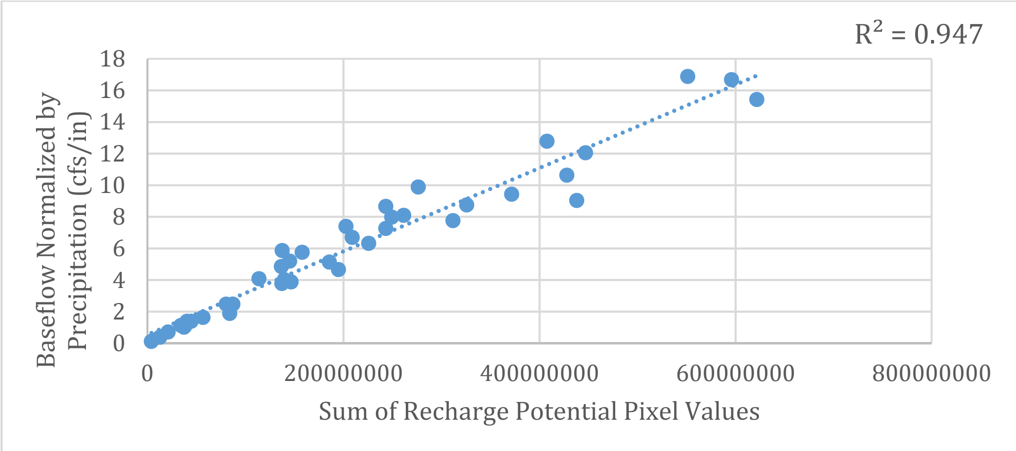

Figure C3. Average Annual Baseflow Normalized by Precipitation Versus the Sum of Recharge Potential Pixel Values

We also attempted to validate the quantile classification scheme used to describe areas of greater/lesser recharge potential by comparing average annual baseflow and the sum of recharge potential pixel values within each of the 5 classes (Figure C4). The slope and significance of the relationship is expected to increase as areas of greater recharge potential are considered. For this assessment, we normalized (divided) average annual baseflow by drainage area and average annual precipitation to demonstrate the influence of the recharge potential index on average annual baseflow without the influence of drainage area and precipitation. The significance of the relationship increases from 0.13 for the first class of recharge potential cells (lowest recharge potential) to 0.002 for the 5th class (highest recharge potential). The relationship is increasingly co-related and the slope is increasingly steeper for class-values of greater recharge potential, which provides evidence that the top 20% recharge pixels (5th class) provide the greatest amount of baseflow in a watershed. The relationship demonstrates the utility and appropriateness of the quantile classification scheme used to illustrate areas of greater/lesser recharge.

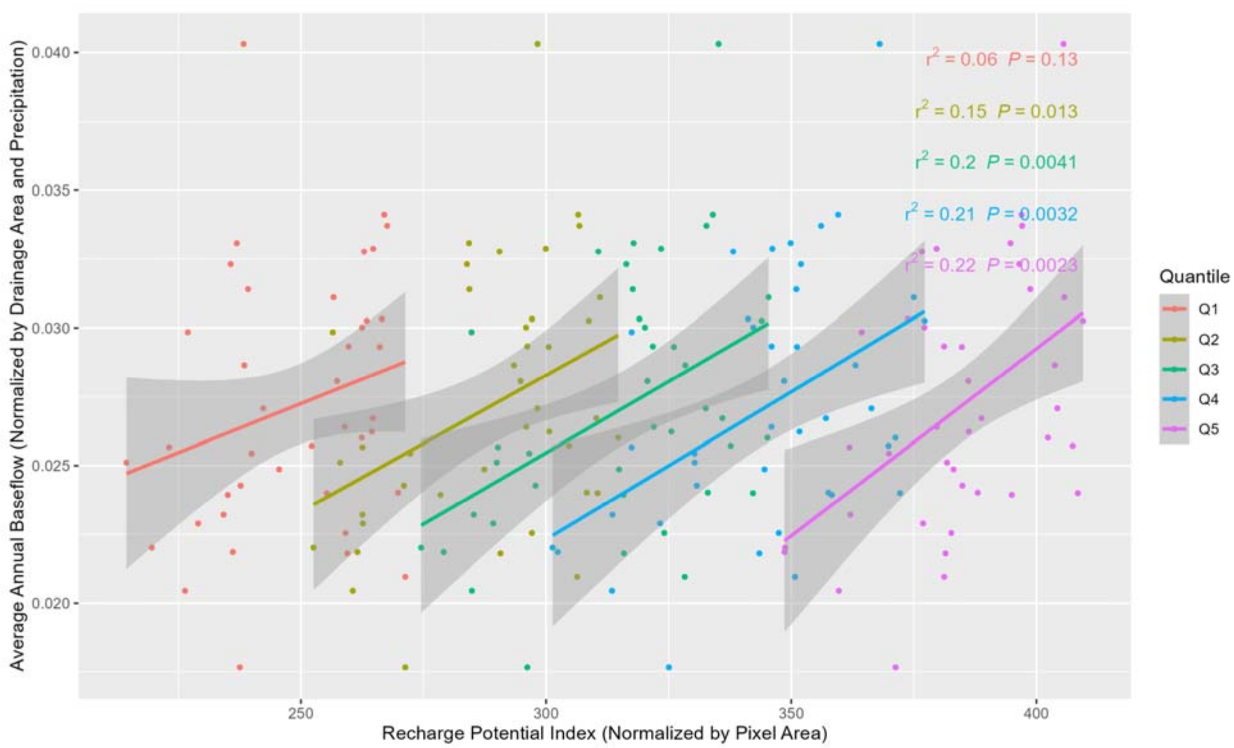

Figure C4. Average Annual Baseflow Versus the Sum of Recharge Potential Pixel Values within Each of the 5 Classes

APPENDIX D

Plates

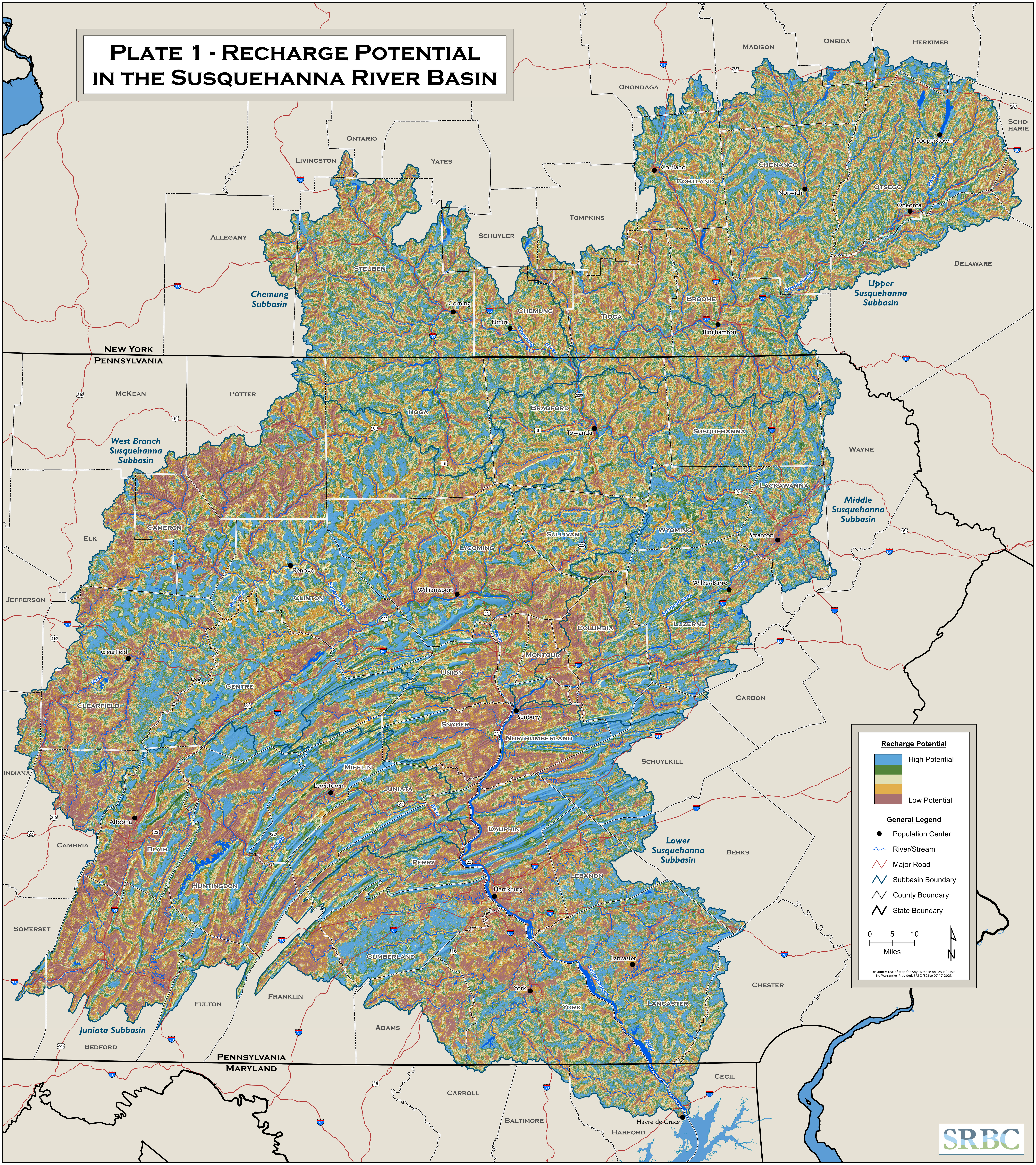

Plate 1 - Recharge Potential in the Susquehanna River Basin
Chemung Subbasin
Upper Susquehanna Subbasin
West Branch Susquehanna Subbasin
Middle Susquehanna Subbasin
Lower Susquehanna Subbasin
Juniata Subbasin
New York
Pennsylvania
Maryland
Madison
Oneida
Herkimer
Onondaga
Schoharie
Ontario
Livingston
Yates
Cortland
Chenango
Otsego
Tompkins
Allegany
Schuyler
Steuben
Chemung
Tioga
Broome
Delaware
McKean
Potter
Bradford
Susquehanna
Wayne
Lackawanna
Cameron
Elk
Sullivan
Wyoming
Lycoming
Clinton
Jefferson
Columbia
Luzerne
Montour
Union
Centre
Clearfield
Carbon
Snyder
Northumberland
Schuylkill
Indiana
Mifflin
Juniata
Cambria
Blair
Dauphin
Perry
Lebanon
Berks
Huntingdon
Somerset
Cumberland
Lancaster
Chester
York
Fulton
Franklin
Adams
Bedford
Carroll
Baltimore
Harford
Cecil
Cortland
Norwich
Cooperstown
Oneonta
Corning
Elmira
Binghamton
Towanda
Scranton
Wilkes-Barre
Renovo
Williamsport
Clearfield
Sunbury
Lewistown
Altoona
Harrisburg
Lancaster
York
Havre de Grace
Recharge Potential
High Potential
Low Potential
General Legend
Population Center
River/Stream
Major Road
Subbasin Boundary
County Boundary
State Boundary
0
5
10
Miles
N
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