GIS Analysis of Potential Storm Water Infiltration and Runoff Modeling for BMP Construction in Hadley Valley Watershed, Rochester, Minnesota

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Abstract

This research examines potential storm water recharge, infiltration, and runoff throughout Hadley Valley Watershed in Rochester, Minnesota. The three most influential properties of infiltration include: *Land Use* – based on percent impervious surface, *Hydrologic Soils* – based on permeability and porosity, and *Percent Slope* – derived from elevation points. These primary factors are selected, classified, and ranked according to their influence on infiltration and runoff. A geographic information system organizes these data layers and clips features to the watershed boundary using ArcGIS 9.1. The vector features are converted to grid and develop a Potential Infiltration Model through a weighted overlay process. This infiltration model identifies and maps current locations and levels of storm water recharge in the watershed. A second model is developed to locate possible storm water best management practices. Locations in proximity to wetlands, sinkholes, other BMP structures, and environmentally sensitive areas are restricted; areas within drinking management supply areas (DWSMA), and some clay soils require testing prior to construction. The BMP Model reveals optimal locations where infiltration ponds and trenches, dry wells, rain gardens, and vegetated swales may be implemented to increase infiltration. A Runoff Model intersects land use and soils and a comparative analysis of the Potential Infiltration Model is completed. Further analysis including: peak runoff rate, time to concentration, and average runoff coefficient are calculated using the intersection of the primary layers. This type of water resource management provides a base hydrological system with benefits for all people, businesses, and ecosystems.

Introduction

Historically, societies arose along waterways where transportation routes were accessible and drinking water resources were abundant. Concern for community growth, long-term resource availability, and groundwater contamination were not taken into consideration. Storm water and drinking water management has become a prevalent concern and increases the need for quality infiltration practices.

As the City of Rochester grows, so must its commitment to protecting and improving the quality of water

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resources. Assets such as Silver Lake and the Zumbro River help make the area one of the nation's most habitable communities. Keeping water resources clean and useable is in everyone's interest.

Many local and regional institutions have successfully used GIS based infiltration and runoff models to plan and manage groundwater recharge events and practices. The data, information, models, and analysis established by this research demonstrates potential infiltration, runoff coefficients, and provides best management practices suited to the City of Rochester, Minnesota.

Efficient management of surface groundwater resources relies on a comprehensive database, representation of the hydrologic processes and characteristics, and modeling tools to describe the impacts of decision alternatives. A groundwater system is defined by hydrogeological data (aquifer parameters, geological layers, boundaries) and observations of the historical behavior of the groundwater (groundwater levels, concentrations of solutes, etc.). For regional groundwater management problems, the information on the groundwater system has to be related with land use, surface water, soil characteristics, topography, and environmental issues (Furst, 1997).

Infiltration Modeling

Planning and assessment in land and water resource management are evolving from simple, local-scale problems toward complex, spatially explicit regional issues. Such problems have to be addressed with distributed models that can compute runoff and erosion at different spatial and temporal scales. The extensive data requirements and the difficult task of building input parameter files, however, have long represented an obstacle to the timely and cost-effective use of such complex models by resource managers (Semmens, et al., 2004).

Ultimately, management of surface water that integrates groundwater recharge must focus on the primary source of water, precipitation. Recharge through infiltration is a very complex process to model. It involves processing rainfall, topography, soils, vegetation, climate, and land use. As development and urbanization grow, storm water management should provide a mechanism and a location to infiltrate water in order to control runoff volume increases. Urbanization typically increases the percent of impervious area. This development increases storm water runoff rates and volumes while decreasing infiltration. Management approaches, such as storm water infiltration basins, are opportunities to maintain and sometimes increase infiltration in developed areas (Donavon et al., 2000).

Best Management Practices (BMP's)

There are numerous reasons and strategies in integrating groundwater and surface water management practices. Infiltration BMP's are developed for the management of increased storm water volume. The reduction in volume of storm water runoff to mimic pre-development hydrology provides benefits other than simply decreasing erosion and sedimentation. Worthy infiltration policies sustain groundwater recharge and improves both surface and groundwater quality. This in turn preserves base-water flow and maintains thermal integrity in streams. A healthy balance of land use planning in coordination with proper surface water management provides protection of groundwater resources.

An infiltration basin is a natural or manmade impoundment that captures, temporarily stores, and allows a designated volume of surface water to infiltrate over several days, thus recharging the groundwater. In the case of a constructed basin, the impoundment is created by excavation or embankment. Constructed infiltration basins are typically sized to serve drainage areas of five to fifty acres, with land slopes that are less than twenty percent. Typical water depths range from two to twelve feet.

An infiltration trench is a shallow excavated trench, generally three to twelve feet deep. It is backfilled with a coarse stone aggregate allowing for temporary storage of runoff in the void space of the material. Discharge of this stored runoff infiltrates into the surrounding, naturally permeable soil. Trenches are commonly sized to serve drainage areas less than five acres. Small-scale infiltration BMP's also include rain gardens, vegetated swales, and dry wells. These typically serve areas less than one acre.

There are also several alternatives for areas needing infiltration with space restrictions. Underground infiltration systems, including premanufactured pipes, vaults, and modular structures, have been developed as alternatives to infiltration basins and trenches. These areas with constraints typically serve less than ten acres.

Constraints

Infiltration BMP's should be well thought-out and consider all public and private land uses, aesthetic factors, hydrological processes, economic costs, and effects on flora and fauna.

Locations well suited to storm water infiltration must not compromise groundwater quality (Minnesota Stormwater Steering Committee, 2006). The Minnesota Stormwater Manual states that infiltration BMP's should be located:

- outside the 100 year floodplain
- outside utility easements or public rightaways
- 100 feet from sinkholes
- 100 feet from bodies of water and other wetlands
- 50 feet from drain fields
- 35 feet from septic tanks and leach fields
- 25 feet from restoration or protected sites
- 10 feet from property lines
- 100 feet from other storm water infiltration basins
- 50 feet from small-scale BMP's
- geotechnical testing required within karst areas to determine site suitability
- soil testing required in sites with mixed clay textures
- testing required in drinking water supply management areas (DWSMA)
- BMP's may not be hydraulically connected to structure foundations or pavement to avoid seepage and frost heave concerns

"An infiltration BMP is a high maintenance facility. A storm water management plan must include maintenance, inspection, access, and enforcement of the basin's operating requirements or the system will fail" (Furst, 1997).

Runoff Modeling

Rochester, Minnesota receives an average annual rainfall of 31.4 inches. Rainfall is the primary source of water involved in runoff. The main factors affecting the volume of rainfall that runs off are the hydrologic properties of the soil and cover of the land use. Factors that affect the rate at which water runs off are the watershed's shape, topography, along with conservation practices.

Hydrologic soils have been classified into four hydrologic groups defined by the Natural Resources Conservation Service (NRCS). Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of sands and gravels that are deep, well drained to excessively drained, and have a high rate of water transmission, greater than 0.30 inches per hour. Group B soils have moderate infiltration rates when thoroughly wetted and consist chiefly of soils that are moderately deep to deep, moderately well drained to well drained, and have moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission, 0.15 to 0.30 inches per hour. Group C soils have low infiltration rates when thoroughly wetted and consist chiefly of soils having a layer that impedes downward movement of water and soils of moderately fine to fine texture. These soils have a slow rate of water transmission, 0.05 to 0.15 inches per hour. Group D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission, 0 to 0.05 inches per hour

Cover type affects runoff in several ways. The foliage and its litter maintain the soil's infiltration potential by preventing the impact of the raindrops from sealing the soil surface. Some of the raindrops are retained on the surface of the foliage, increasing their chance of being evaporated back into the atmosphere. Some of the intercepted moisture takes so long to drain from the plant down to the soil that it is withheld from the initial period of runoff. Ground cover also allows soil moisture from previous rains to transpire, leaving a greater void in the soil to be filled. Vegetation, including its ground litter, forms numerous barriers along the path of the water flowing over the surface of the land. This increased surface roughness causes water to flow more slowly, lengthening the time of concentration and reducing the peak discharge.

BMP's reduce erosion and runoff and thereby provide greater infiltration at the soil surface. Detention basins, diversions, and vegetation increase time of concentration by slowing runoff. These effects diminish rapidly with increases in storm magnitude.

The slopes in a watershed have a major effect on the peak discharge at downstream points. As watershed slope increases, velocity increases, time of concentration decreases, and peak discharge increases. An average small watershed is fan shaped. As the watershed becomes elongated or more rectangular, the flow length increases and the peak discharge decreases. Depressions may trap a small amount of rain, thus reducing the amount of expected runoff. If depressions and marshland areas make up one-third or less of the total watershed and do not intercept the drainage from the remaining two-thirds, they will not significantly change the peak discharge. These areas may be excluded from the drainage area for estimating peak discharge.

The potential maximum retention can range from zero on a smooth, impervious surface to infinity in deep gravel. These S-values are then converted to runoff curve numbers (CN's). The CN is 100 when S is zero and approaches zero as S approaches infinity. Runoff curve numbers can range from zero to 100, but for practical purposes usually fall between 40 and 98.

Runoff modeling of this nature is performed on open channel watersheds. These networks are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geological Survey (USGS) quadrangle sheets. Manning's equation or water surface profile is usually determined for bank-full elevation (Donavon et al., 2000).

Methods

All data is acquired or converted to Rochester Defined geographic coordinate system (GCS). The projection is set to Rochester Defined Lambert Conformal Conic and a spatial extent of Olmsted County.

Data Collection

The data used for this project is acquired from the City of Rochester, Public Works Department. Original shapefile datasets include: city limits, land use and zoning boundaries, geomorphology, hydrology, utilities, and drinking water management areas (DWSMA). A topography contour map, elevation points, and transportation layer come in AutoCAD drawing (.dwg) format. The city also provides a 2005, aerial photograph of Rochester in Mr.SID image format. SSURGO soil profiles are obtained from the Natural Resources Conservation Service (NRCS).

A land use layer based on percent impervious surface is digitized on-screen using the Rochester imagery, current land use, zoning, and survey descriptions. Digital elevation models (DEM’s) are developed using the elevation point files.

Project Site

Rochester is located in Central Olmsted County, in Southeastern Minnesota. It resides 80 miles south of the Twin Cities metropolitan area, along the Interstate 90 corridor. Rochester is the third largest city in the state. It occupies 40 square miles of area and has a total population density of 2,170 people per square mile. A majority of the economy is supported by educational, health, and social service jobs. Employment among retail, manufacturing, construction, and professional administrative work are also common.

Hadley Valley Watershed is selected because it falls within Rochester’s urban growth area and occupies land inside the city limits (Figure 1). It is northeast of the city, and contains 312 acres that empty into the Zumbro River. The eastern portion of this watershed is flat and comprised mostly of cropland and pastures managed by single family, rural, residential farmsteads. Steep, forested slopes make a horseshoe shape following the northern and southern fringes and meet in the center. The flat western edge moves into the city where impervious land use increases (Figure 2).

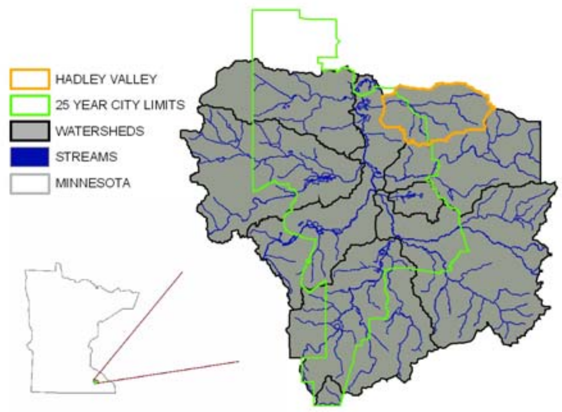

Figure 1. Watersheds of Rochester, Minnesota.

Figure 2. Clipped 2005 Mr. SID Image.

Potential Infiltration Model

The three primary influences of ground water infiltration are percent impervious surface, permeability of the soil, and percent slope. Potential infiltration may be calculated through a weighted overlay process of land use, soils, and slope. Each of these layers contributes one-third to the model. It is assumed that all three layers of the model equally influence infiltration at all locations.

Land Use

100 percent coverage of a land use layer is not available for the City of Rochester. A new layer is developed through heads-up digitizing (Figure 3). Current land use, zoning, survey descriptions, and aerial photography were loaded into an ArcMap project. On-screen editing of the existing land use data reshapes polygons based on percent coverage of impervious structures. The features are then attributed by percent infiltration, or the difference of the impervious value from 100 (Appendix A). For example, a land use classified as 'institutional' (a church or school) has a percent impervious value of 45, and an infiltration value of 55. The boundary of the institutional property is outlined, and the entire polygon receives a 55 in the field for potential infiltration.

Figure 3. Digitized Land Use from Image.

Since the data was created in-house, a quality assurance plan is implemented to validate the data. Polygons overlayed on imagery are panned through checking for errors. In the attribute table, the select by attribute function verifies infiltration values and land use classes. The edited land use layer is reviewed for structural connectivity. Topology identified gaps and overlaps in the linework and the inconsistencies are rectified.

The land use layer does not take into account vast areas of impervious surfaces such as large buildings, parking lots, and roads. These structures need to be edited separately before adding to the land use data. Buildings and parking lots displayed in the impervious surfaces shapefile are imported to the land use database and given an infiltration value of zero. Centerlines for transportation lines are found in one road .dwg file. These are extracted into separate feature datasets; roads buffered by 25 feet and highways by 40 feet using Proximity Analysis Tools. This buffer represents the compact area adjacent to the concrete or asphalt street known as the right-away. An infiltration value of zero is entered in the table. A master polygon is auto-completed around all features found in the new roads, highways, and impervious surfaces layers and the infiltration value is one. These three files are imported to the land use geodatabase.

Roads, highways, impervious surfaces, and land use are meshed into one dataset. All four layers are separately converted from features to grids with ten-meter cells using Spatial Analyst. The outputs are based on potential infiltration values and masked to the Hadley Valley watershed. Using Raster Calculator the four datasets are merged into one final impervious land use layer (Figure 4).

[LandUse] * [Impervious] * [Highways] *[Roads] = FinalLandUse. Locations where impervious=1, highways=1, and roads=1 will retain the original land use infiltration value, example 55*1*1*1 = 55, institutional. Any location where impervious=0, highways=0, or roads=0, the output cell=0 and is a 100 percent impervious surface.

Figure 4 illustrates percent impervious land uses. Dark blues indicate natural vegetation and low impact. Light blues are heavy human influence and more impervious. Red shows roads, parking lots, and buildings.

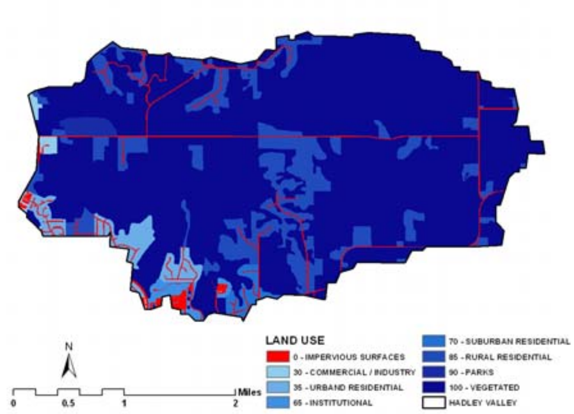

Figure 4. Land Use Percent Impervious Surface.

Soils

Three new fields are added to the SSURGO shapefiles, HydrologicGroup, Test, and Infiltration. The spatial shapefile then joined to the Component table through the MUSYM field. This allows access to the hydrologic properties of the soil data. The HydrologicGroup field is calculated to equal the existing HydrGrp field. The values found in this field are listed in Appendix A under Hydrologic Soils. After the field was populated the join is removed and the shapefile is exported to a geodatabase as a feature using ArcCatalog.

The infiltration field is calculated as follows: A=100, B=67, C=33, D=0, A/D=0, and B/D=0. The test field is calculated as A=1, B=1, C=1, D=0, A/D=3, and B/D=3. The features are converted to two grids at a ten-meter cell size and masked to the Hadley Valley watershed. The infiltration grid is based on the Infiltration field, and the BMP grid is based on the Test field (Figure 5).

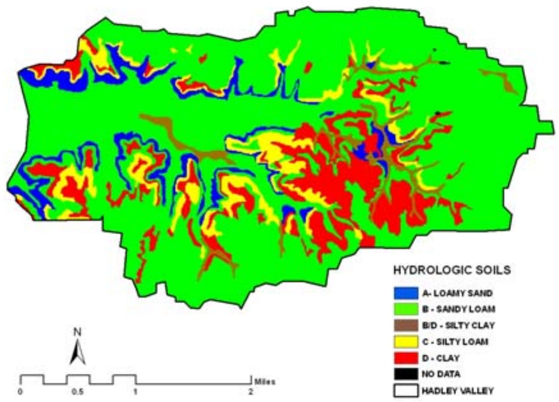

Figure 5. SSURGO - Hydrologic Soils Grid.

Slope

Global positioning system, (GPS) points are collected by the City of Rochester and stored as AutoCAD files. These are exported from .dwg to features with Conversion Tools. This feature dataset then is interpolated to raster by Kriging and masked by the Hadley Valley watershed using Spatial Analyst. A 200-meter DEM best represents the contour lines as shown in Figure 6.

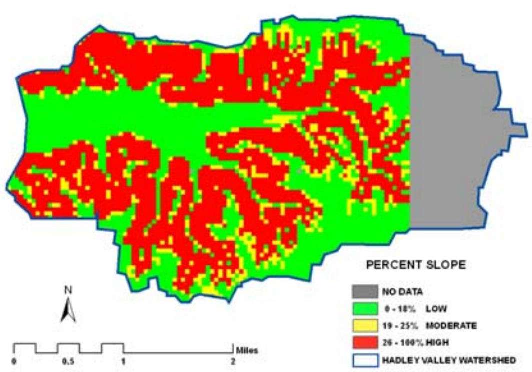

Figure 6. Percent Slope DEM.

Original slope values range from zero – 100 percent slope and require manual breaks of zero – 18 percent, 18 – 25 percent, and above 25 percent. These values correspond to low, moderate, and high percent slope. The percent slope DEM is then reclassified to coordinate with the infiltration model values. Low slope equates to 100, moderate 50, and high zero infiltration. The final slope DEM is converted to a ten-meter cell raster and masked to the Hadley Valley watershed.

Construction personal geodatabase and geodataset titled Restrictions is created. Shapefiles of rivers, streams, wetlands, sinkholes, DWSMA's, and soils are imported to the database. A new field titled infiltration is added to all six tables. Proximity Analysis Tools buffers the streams, rivers, wetlands, and sinkholes features by 100 feet. The buffered polygons are given a value of zero in the infiltration field, as BMP construction is restricted in these sites. A master polygon is auto-completed around these restricted features in each of the six sets of data. An infiltration value of one is entered representing BMP construction is permitted.

In addition, the soil features list a test value of three for both A/D and B/D soils, while all other soils receive a value of one. For construction of a BMP to be permitted soil testing is required in clay mix soils. Also, the DWSMA layer is assigned infiltration values of zero inside the one-year time of travel, two within the DWSMA, and one outside the DWSMA. Locations inside the DWSMA, but outside the one-year time of travel also require testing. The six layers restricting BMP construction are converted to grid using Spatial Analyst. The output rasters are in ten-meter cells and masked to the Hadley Valley watershed.

Runoff Model

A new geodatabase titled Analysis and geodataset titled Runoff are created. Spatial Analyst converts the land use, soils, and slope grid to features. This vector data, in addition to streams and contours is added to the geodatabase using ArcCatalog.

Overlay Analysis Tools intersects soil features and the land use layer (Figures 7 and 8). New fields called Soils_Landuse, Runoff, and Runoff_Rank are added to the table. All features with the same land use and soil are merged. The final infiltration grid is converted to vector and Infiltration_Rank is added to the attribute table.

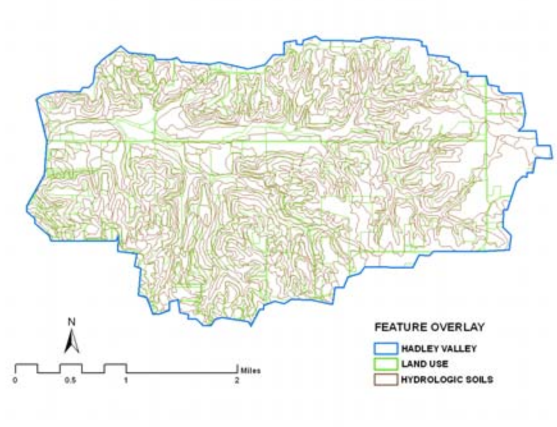

Figure 7. Overlay of Soils and Land Use.

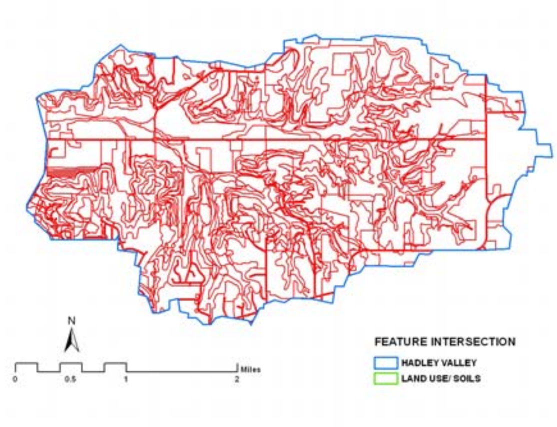

Figure 8. Intersection of Soils and Land Use.

Analysis

Infiltration

The Potential Infiltration Model is developed using Model Builder (Appendix B). To finalize the land use grid the four initial rasters are merged. An overlay is first processed on the buffered roads, buffered highways, impervious surfaces, and digitized land use layers. Wherever a road, highway, or impervious surface polygon intersects the land use layer, the infiltration value of the final land use becomes zero.

The Weighted Overlay Tool of Spatial Analyst creates the final output, a Potential Infiltration Model (Figure 9). Land use, soil, and slope each receives an influence weight of one-third and develops the final potential infiltration grid. The overlay is based on percent of 100, so in actuality the soils and slope receive 33 percent of weight and land use 34 percent.

The final potential infiltration model is a ten-meter cell raster. The grid is masked to the Hadley Valley watershed. As displayed in Figure 9, regions in red indicate a restriction in infiltration due to an impervious surface such as road, highway, parking lot, or building, a clay soil of the D hydrologic property, or a steep slope over 25 percent. Potential infiltration values have a range of 70, from 30 to 100. Infiltration of 100 represents a crop or vegetated land use, low slope, and a sandy, A soil. Infiltration values decrease as humans increase impact on land uses, soils decrease in porosity and permeability, or slope increases. These values are depicted by dark blues in Figure 9 and are found on the farmed outskirts of the steep slopes and along the creek moving west and entering the

Zumbro River. 30 is the lowest possible infiltration value and represents an industrial or commercial site, of moderate slope, with a C hydrologic soil property. These values are pictured in light blue and are concentrated in the southwest portion of Hadley Valley moving into the city limits.

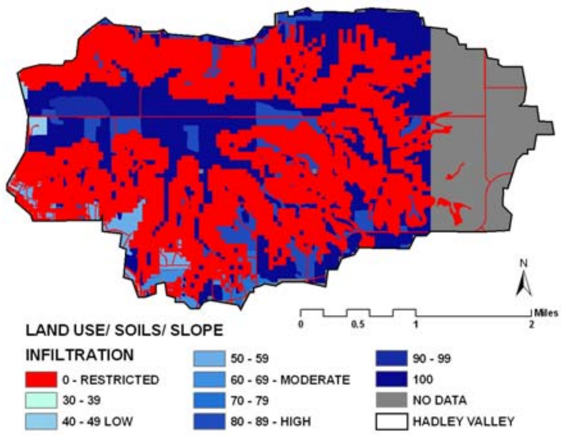

Figure 9. Potential Infiltration Overlay Model.

A large area in Eastern Hadley Valley is colored grey, indicating no data. Elevation points are not present east of the border between the dark blue and grey, therefore one element of the three-part model is missing. The potential infiltration model recognizes this and identifies as no data.
As pictured, areas of red indicating impervious roads and D soils are still represented as restricted throughout the no data polygons. Values of zero, or restricted variables are set as highest priority in the model.

BMP Construction

The BMP model indicates areas where best management practices may be constructed (Figure 10). BMP site analysis displays where construction is restricted. 100-foot buffers of rivers, streams, other wetlands, sinkholes, and the one-year time of travel within a DWSMA are pictured in red. Areas displayed in blue require drinking water monitoring while areas in brown are clay mixtures that require soil testing. Areas in yellow require both tests. The region in green represents permissible construction of BMP's.

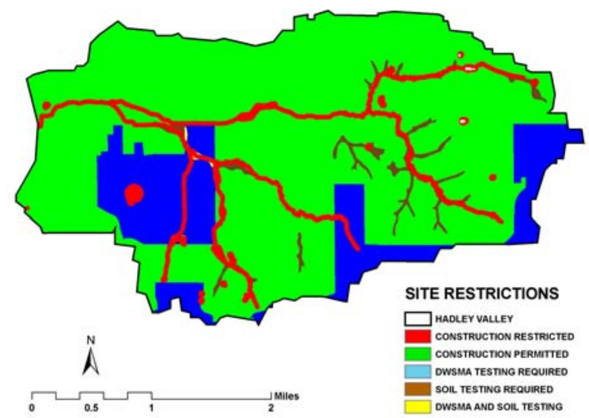

Figure 10. BMP Construction Model.

The closing infiltration analysis includes final overlay of the Potential Infiltration Model and the BMP Model, which further reduces areas where infiltration construction may occur (Figure 11). This location and proximity analysis displays areas of green where BMP construction is permitted. Areas in red display no natural infiltration according to the Potential Infiltration Model. Ground water recharge does not occur in these areas due to impervious land uses, clay soils, or steep slopes. The grey area in the eastern portion of Hadley Valley lacks GPS points for the slope analysis. Polygons in black represent buffered hydrologic structures where BMP construction is restricted. The blue zones require groundwater testing of the DWSMA, brown needs extensive soil testing, and yellow entails both tests.

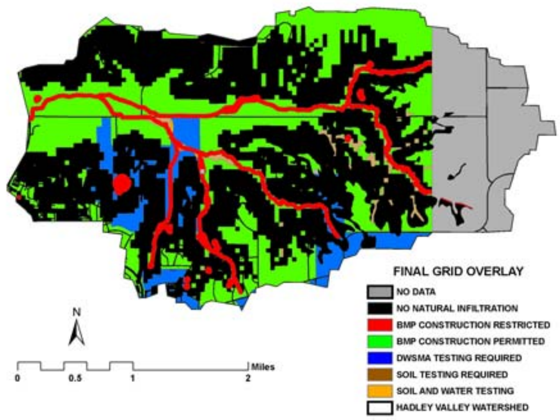

Figure 11. BMP and Infiltration Overlay.

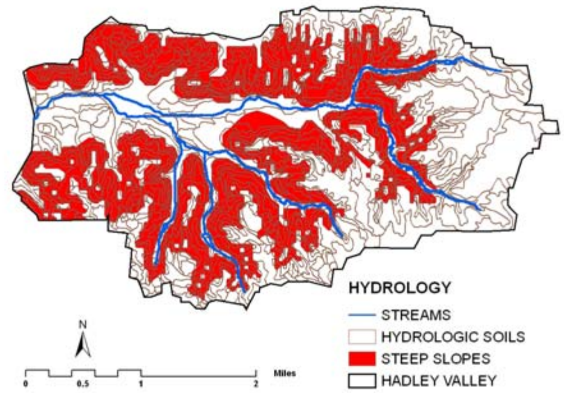

Figure 12. Hydrology of Hadley Valley.

Runoff

The Kirpirch Method is a developed formula for predicting time of concentration in a watershed. The formula indicates where t_c is the time of concentration in minutes, L is the maximum hydraulic flow length in feet, and H is the difference in elevation in feet between the outlet of the watershed and the hydraulically most remote point in the watershed.

With a maximum elevation of 1150 feet and minimum of 977 feet, Hadley Valley's longest stream channel is 27,926 feet. The average slope is .62 percent (Figure 12). The stream length is calculated using the shape length of National Wetland Inventory (NWI) linear features. Elevation is calculated by locating entry and exit points of the stream overlayed with contours. The total time to concentration is 14.64 minutes according to the Kipirch Method.

$$t_c = 0.0078\ L^{0.77}\ (L / H)^{0.385}$$

Most watersheds contain more than one soil type with multiple land uses and slopes. It is necessary to determine a CN or runoff curve number that best represents this variability. Polygons of the land use soil intersection map are attributed with individual curve numbers (Appendix C). C_i is the runoff coefficient applicable to the area A_i (Figure 13). Blue represents wetland complexes and open water, with a runoff value of 0. Impervious areas are colored red, with a value of 98. The lighter the shade of green the lower the runoff coefficient and greater infiltration.

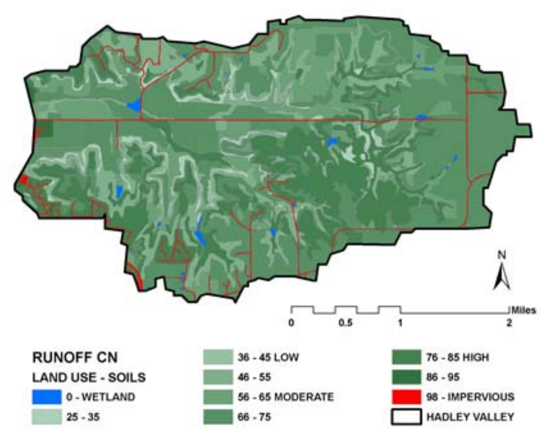

Figure 13. Runoff Curve Numbers.

38 hydrologic soil and land use combinations exist in Hadley Valley (Appendix D). Runoff coefficients range from 25 in forested A soils to 98 for impervious structures. The 312-acre

basin has an average CN of 67.29 calculated by the formula below.

$$CN = \sum C_i A_i \; / \sum A_i$$

This curve number can be used to calculate S, the maximum soil water retention parameter. Hadley Valley has a maximum soil water retention parameter of 4.861.

$$S = ((1000 / CN) - 10)$$

An accumulated runoff volume, Q in inches, may be computed for a particular storm event. In Rochester, Minnesota these are Type II precipitation events. This is a connective, high intensity storm occurring in inland areas. This method estimates total runoff and factors in infiltration losses, I_a. Losses also include initial abstractions from interception due to vegetation and surface storage.

$$Q = (P - I_a)^2 / P - I_a + S$$

$$I_a = .2S$$

Total precipitation, P must be larger than I_a. These formulas are influenced by AMC, or antecedent moisture. AMC I is a dry condition where little or no precipitation occurs prior to the calculated event. A rainfall of 3.0 inches under these conditions in Hadley Valley watershed produces .60 inches of runoff.

Figure 14 depicts locations with highest potential for runoff in Hadley Valley watershed. No runoff occurs in black wetlands. Yellow shows minimal runoff in permeable soils and naturally vegetated areas. As humans influence through residential living or commerce and as the porosity of the soil decreases runoff increases. It moves up the fire scale to orange, red, purple and finally blue impervious structures.

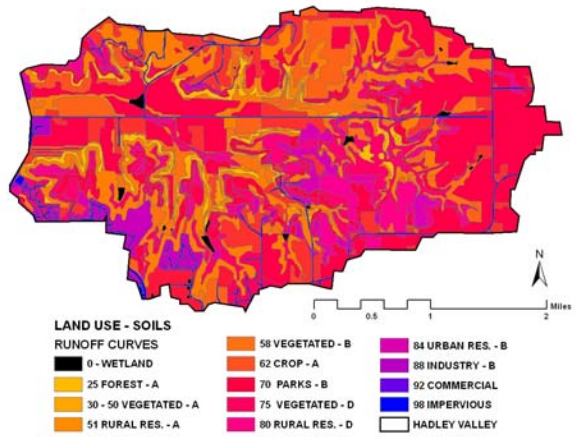

Figure 14. Land Use and Soils Runoff.

Conclusion

Both the infiltration and runoff models have values with a range of 70. A simple rank and comparison between the two models is completed. Where runoff is high because of impervious land use or clay soil it is expected that infiltration is low. It is discovered that after the two models are intersected with Overlay Analysis tools this is not always the case (Figure 15).

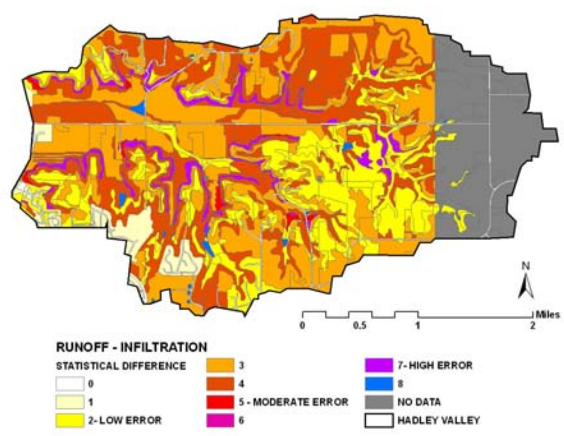

Figure 15. Infiltration / Runoff Rank.

New fields titled RunoffRank and InfiltrationRank are added to the two models respectively. Where infiltration is highest based on land use, soils, and slope the rank is seven and decreases to one. Wetlands are eight and impervious features are zero. Ranks are opposite for the runoff features. The lowest runoff is one, increasing to seven. Wetlands receive a value of zero and impervious surfaces eight. If the two models are equal, the two ranks should add up to eight and the difference between the two ranks equals zero.

The greatest inconsistency is found in soils with the A hydrologic property (Appendix E). Blue bars of the A soils represent most discrepancies between the infiltration and runoff models. Interestingly, as the hydrologic conditions of the soil decrease so does the variability between the two models. The runoff and infiltration models depicting C and D soils largest rank difference is three, and the B soil property is never larger than four. In addition, as human influences increase, the more synonymous the two models become. Areas with commercial, industrial, or urban residential housing never have a rank difference of more than two, regardless of soil type. As permeability and porosity of soil or infiltration of land use increases the higher the conflict between the acknowledged runoff model the potential infiltration model.

Several conditions promote this outcome. The runoff and infiltration model both use the same impervious surfaces layer. Road, highway, building, and parking lot features correspond in both models when intersected. A rank difference of zero is anticipated to occur in high impervious areas. Runoff should increase as infiltration decreases due to the complete overlap of the man-made structures in both models.

The elements of nature become more difficult to replicate. The runoff model simply states that a curve number is associated with the intersection of soil and land use. Slope only affects the time it takes surface water to runoff or infiltrate. The infiltration model takes all three parameters into account. The infiltration model shows 100 percent runoff in steep slopes and complete infiltration in low slopes, when soils textures are A and vegetated.

Figures 16 and 17 display the impact slope has on the difference between the infiltration and runoff models. Where slope is steep, 83 percent of error is considered high; this is when the rank difference between the infiltration model and the runoff model values are six, seven, or eight. Only 17 percent of highest error is derived from low to moderate slopes.

Figure 17 represents both moderate and high error, rank differences of four to eight. 90 percent of moderate to high error is represented by one of the extremes, either low or steep slope. Moderate slope yields only 10 percent of this error.

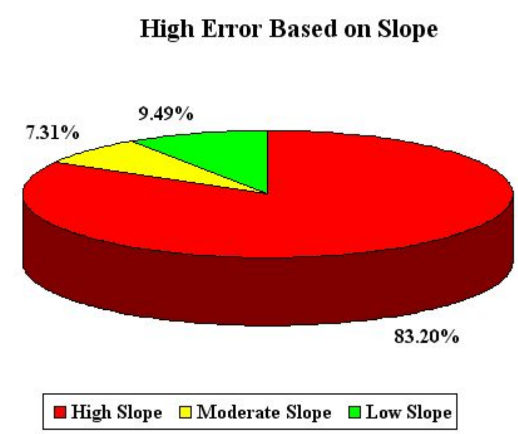

Figure 16. High Error between Infiltration and Runoff Models.

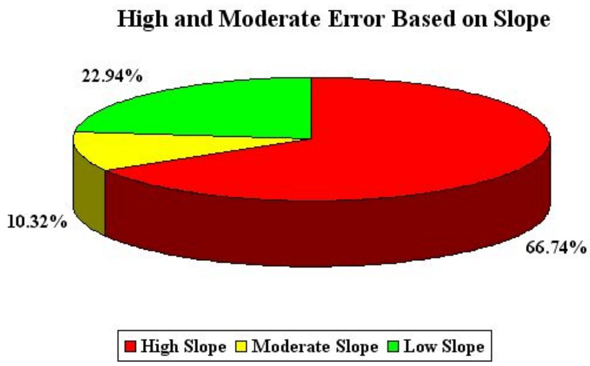

Figure 17. High and Moderate Error between Infiltration and Runoff Models.

The runoff model states even though an area has high infiltration some runoff still exists. Additionally, the runoff model allows for small amounts of infiltration to occur despite steep slopes. The accepted runoff model requires field-testing based on slope in order to permit construction of BMP's. No construction in areas over 20 percent slope is permitted. Whereas the infiltration model dictates no infiltration occurs on slopes over 25 percent.

Secondly, the infiltration model does not take initial abstractions into account. This includes surface storage by wetlands and water retention on leaves and buildings. Neither model accounts for evapotranspiration of rainfall. These conditions vary based on region, season, weather, and time of day. The Potential Infiltration Model is not designed to account for these temporal variables.

A possible solution to better map potential surface water infiltration is a compromise between the two models. Since most error in the infiltration model is derived from slope the inverse of the runoff model can determine where infiltration does or does not occur. Two separate intersections of steep slopes and impervious surfaces extracts restrictions in infiltration on the Runoff Model to indicate levels of potential infiltration.

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Appendix A. Potential Infiltration Model Weights.

Land Use	Impervious %	Non-Impervious %	Infiltration 100%	Model 34%
Crop	0	100	100	34
Pasture	0	100	100	34
Forest	0	100	100	34
Grass	0	100	100	34
Shrub	0	100	100	34
Park	10	90	100	30.6
Undeveloped	10	90	90	30.6
Rural Residential	15	85	85	28.9
Suburban Residential	30	70	70	23.8
Institutional	45	55	55	22.1
Urban Residential	65	45	45	15.3
Industrial	70	30	30	10.2
Commercial	70	30	30	10.2
Roads	100	0	0	0
Highways	100	0	0	0
Buildings / Parking lots	100	0	0	0
No Data	No Data	No Data	No Data	No Data

Slope	Grade	% Slope	Infiltration 100%	Model 33%
Low	Flat	0 - 18	100	33
Moderate	Steady	19 - 25	50	17
High	Steep	26 - 100	0	0
No Data	No Data	No Data	No Data	No Data

Hydrologic Soils	Texture	Permeability	Infiltration 100%	Model 33%
A	Sand / Loam	High	100	33
B	Silt / Loam	Moderate	67.7	22
C	Sand / Clay / Loam	Low	33.3	11
D	Clay	None	0	0
A/D	Clay Mix	No Natural	0	0
B/D	Clay Mix	No Natural	0	0
No Data	No Data	No Data	No Data	No Data

Values of 0 are Restricted in the Potential Infiltration Model

Scenario 1:	*Scenario 2:*	*Scenario 3:*	*Scenario 4:*	*Scenario 5:*
Crop	*Grass*	*Rural Residential*	*Heavy Commercial*	*Forest*
Low Slope	*Moderate Slope*	*Low Slope*	*C Soils*	*High Slope*
A Soils	*A Soils*	*B Soils*	*Moderate Slope*	*C Soils*
100% Infiltration	*84% Infiltration*	*79% Infiltration*	*38% Infiltration*	*0% Infiltration*

Appendix B. Potential Infiltration Weighted Overlay Model using Model Builder 9.1.

Appendix C. Runoff Curve Numbers for Selected Land Uses and Soil (NRCS, 2004).

		Hydrologic Soil Group		
Land Use Description	A	B	C	D
Cultivated Land				
Without Conservation Treatment	72	81	88	91
With Conservation Treatment	62	71	78	81
Pasture or Rangeland				
Poor Condition	68	79	86	89
Good Condition	39	61	74	80
Meadow	30	58	71	78
Woodland or Forest				
Thin stand, poor cover, low mulch	45	66	77	83
Good cover, no grazing or litter	25	55	70	77
Open Spaces, parks, and cemeteries				
Good Condition, 75% grass	39	61	74	80
Fair Condition, 50-75% grass	49	69	79	84
Commercial and Business	89	92	94	95
Industrial Districts	81	88	91	93
Residential, Average Impervious %				
65	77	85	90	92
38	61	75	83	87
30	57	72	81	86
25	54	70	80	85
20	51	68	79	84
Paved parking lots and buildings	98	98	98	98
Highways and Roads				
Paved with curb and gutter	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89

Appendix D. Average Runoff Curve Numbers for Hadley Valley Land Use Soil Intersection.

Land Use	HydroGroup	Area sq. Meters	CiAi Curve Number	Runoff
Wetland	H	1264233.81	0.00	0
Crop	B	60693138.31	4309212820.09	71
Pasture	C	536391.48	39692969.84	74
Pasture	B	11595758.69	707341279.85	61
Pasture	D	3134111.53	250728922.37	80
Crop	A	2527965.29	156733848.18	62
Pasture	A	559888.51	21835652.04	39
Crop	C	520263.87	40580581.86	78
Shrub	B	1034069.51	68248587.89	66
Shrub	C	215276.05	16576255.65	77
Grass	C	2854472.32	202667534.88	71
Grass	B	13609741.52	789365008.13	58
Institutional	B	3083732.80	212777563.04	69
Shrub	D	392900.84	32610769.68	83
Crop	D	7317789.66	592740962.51	81
Shrub	A	293291.93	13198137.03	45
Rural Residential	D	7274310.98	611042122.18	84
Rural Residential	B	21532874.89	1464235492.37	68
Rural Residential	C	3862547.49	305141251.36	79
Park	B	2140389.91	130563784.51	61
Grass	A	1506842.11	45205263.20	30
Grass	D	7513065.95	586019144.28	78
Forest	B	37054522.21	2037998721.31	55
Forest	C	9095340.48	636673833.39	70
Forest	A	6826921.91	170673047.67	25
Forest	D	12855558.13	989877975.87	77
Industry	A	277455.12	22473864.96	81
Industry	B	1001985.94	88174762.97	88
Impervious	None	6035759.15	591504396.51	98
Suburban Residential	B	2226995.37	167024653.02	75
Urban Residential	A	900194.51	69314977.48	77
Urban Residential	C	130370.89	11733380.25	90
Urban Residential	D	100729.58	9267121.23	92
Rural Residential	A	1206041.59	61508120.84	51
Industry	C	7410.48	674353.44	91
Commercial	B	42613.71	3920461.76	92
Commercial	D	5556.57	527873.71	95
Urban Residential	B	5796594.00	492710490.24	85
Sum		237027107.08	15950575985.60	**67.29**

Appendix E. Infiltration / Runoff Difference.
(Legend is read horizontally.)