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Simulating the Effects of Urbanization and Climate Change on Ground Water Recharging Using the Usgs Precipitation and Runoff Modelling System (PRMS)

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SIMULATING THE EFFECTS OF URBANIZATION AND CLIMATE CHANGE ON GROUND WATER RECHARGING USING THE USGS PRECIPITATION AND RUNOFF MODELLING SYSTEM (PRMS)

by

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ABSTRACT

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Ken Oanes

The University of Wisconsin-Milwaukee, 2020
Under the Supervision of Professor Shangping Xu

The Root River watershed, located in southeastern Wisconsin, was selected to be the subject of a study modeling the impacts of urbanization and climate change on groundwater recharge. Historical and projected (2035) land use data for the study area was sourced from the Southeast Wisconsin Regional Planning Committee (SEWRPC). The USGS Precipitation and Runoff Modelling System (PRMS) was selected to estimate recharge from a 35-year period of historical climate data (1980-2014). PRMS was run for the full 35-year time period under each land-use scenario and model outputs for evapotranspiration (ET), runoff, and recharge were calculated on a daily time-step.

Model simulations produced an average of 5.76 inches of annual recharge under the 2035 land use scenario compared to 5.70 inches of recharge for 1963 land use over the course of the 35-year simulation. The modest increase of simulated recharge coinciding with an increase in urbanization is the result of a combination of the removal of area that contributes to evapotranspiration (ET) and model simulations of runoff retention and infiltration in urban areas. The model input parameter related to infiltration rates for urban retention ponds had the strongest influence on the relationship between recharge and urban area.

This is dedicated to my supportive family and friends. I could not have done it without their unwavering support and push to finish. To my folks, Kyle and Terry, I cannot thank you enough for your support of my endeavors over the years, and I could not have done it without you.

This is also dedicated to my thesis adviser, Shangping Xu who stuck with me and helped me finish even after I left UWM.

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LIST OF ABBREVIATIONS

ANOVA	analysis of variance
BMP	best management practice
CBH	climate by hydrologic response unit
DEM	digital elevation model
ET	evapotranspiration
ETM	enhanced thematic mapper
ETM+	enhanced thematic mapper plus
GCM	global climate model
GIS	Geographic Information Systems
GUI	graphical user interface
HRU	hydrologic response unit
IPCC	Intergovernmental Panel on Climate Change
NHD	National Hydrography Dataset
PET	potential evapotranspiration
PRMS	Precipitation and Runoff Modelling System
RPA	Forest and Rangeland Resources Planning Act, 1974
SEWRPC	Southeast Wisconsin Regional Planning Committee

1. INTRODUCTION

Increases in urban area alter the natural hydrologic cycle. Urban area creates artificial pathways for precipitation received overland to bypass natural recharge and evapotranspiration routes. Rooftops, pavements, and artificial drainage features have the potential to transport precipitation and snowmelt away from natural groundwater recharge areas. Groundwater recharge is important in quality and quantity as an essential human resource for drinking water and is important to many ecosystems.

Estimating the impacts of urbanization on groundwater recharge requires the uncoupling of historical climate and land use data. This study attempts to accomplish that by running separate land use scenarios with 35 years (1980-2014) of historical climate data. The simulation of groundwater recharge was performed using a United States Geological Survey (USGS) program, Precipitation and Runoff Modeling System (PRMS).

The Precipitation-Runoff Modeling System is a deterministic, distributed-parameter, physical-process-based modeling system developed to evaluate the response of various combinations of climate and land use on streamflow and general watershed hydrology (USGS, 2015). The input parameter of interest for land use within PRMS is “hru_perc_imperv”, or the percentage of each Hydrologic Response Unit (HRU) that is composed of an impervious surface as the result of urbanization.

Historical land use data from the Southeast Wisconsin Regional Planning Committee (SEWRPC) was imported into ArcGIS to provide estimates of urban areas per HRU. Different multiplication factors were used to find the percentage of impervious surface for each type of urban area. The main goals of this study include: 1) to calculate conversion factors to apply to urban areas within the watershed to be used as model inputs as impervious area, 2) to run model simulations for historical land use and future forecasted urbanization, 3) to examine the effects of urbanization on groundwater recharge, and 4) examine model inputs that have the largest impact on simulated groundwater recharge through urban pathways.

2. SETTING

Study Area

The Root River watershed is located within the Great Lakes drainage basin in southeast Wisconsin. The watershed contains a drainage area of approximately 500 square kilometers and discharges into Lake Michigan at Racine, Wisconsin. The Root River watershed has reaches in Kenosha, Milwaukee, Racine, and Waukesha counties.

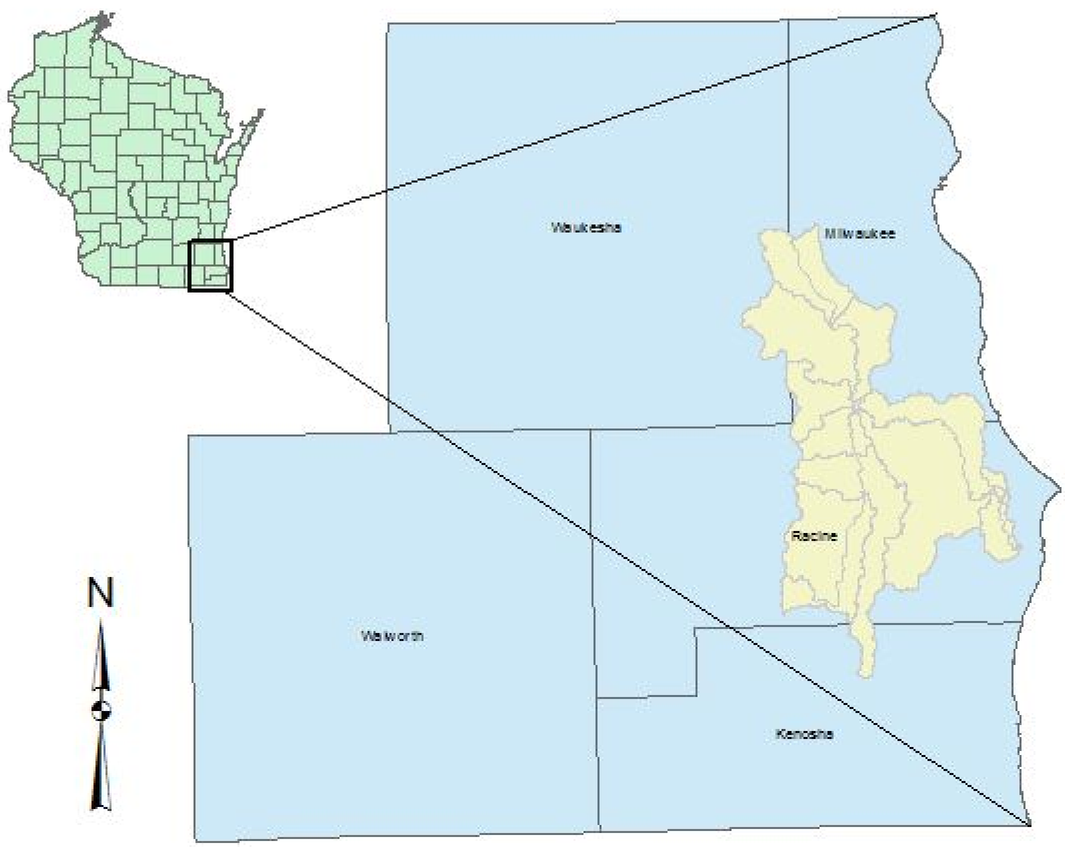


Figure 1. The map of the Root River watershed that is consistent to the Racine, WI gauging station.

The western edge of the Root Rover watershed is bounded by the subcontinental divide, which separates the Great Lakes drainage basin from the Mississippi River drainage basin.

Topography is predominantly influenced by the most recent glaciation, the Wisconsin, approximately 11,000 years ago. The study area is gently sloping to a dendritic stream drainage pattern. Elevations range from a high of 963 feet in the northwest region of the watershed, to a low of 580 at the eastern region.

There are three gauging stations within the root river watershed. Gaging station 04087240 is located at 42°45’05” latitude and 87°49’25” longitude. This gage is located in the city of Racine, WI, and is the outlet gaging station for the Root River watershed. Gauging stations 04087214 and 04087220 are located further upstream and were also used for calibration of the model.

Climate and Precipitation

Climate data was retrieved from the USGS National Hydrography Dataset for the time period from 1980-2014. The Climate-by-HRU Distribution Module used for this model requires daily climate data inputs for each HRU. The average annual precipitation is 36.1 inches over the course of the simulation, and daily temperature minimum and maximums are 38.9 and 56.6 degrees Fahrenheit, respectively.

Bedrock Geology

The Root River watershed lies atop Silurian and Devonian age sedimentary rocks. The Silurian rocks consist primarily of dolomite with minor beds of shale interspersed. The Ordivician-aged formations, which are dolomite with interbedded shales, and a dolomitic sandstone formation, underlie the Silurian dolomites. Cambrian sandstones lie at depths in excess of 800 feet below the topographic surface. The bedrock geology beneath the Root River watershed has been tectonically quiet for nearly a billion years and contains no known major fault system. The dip of the bedding is gentle to the east-southeast.

The surface of the bedrock geology in the region is irregular, having been carved by repeated glaciations. The depth to bedrock for most of the region is 100 feet to 150 feet. The unconsolidated materials that make up this depth are quaternary glacial deposits comprised predominantly of silt and clay tills.

Hydrostratigraphy

The Root River watershed lies overtop of two separate aquifer systems. The unconfined aquifer system is comprised of the Quaternary glacial deposits and the Silurian dolomite bedrock formations. This aquifer is connected to the water table and provides the water for most domestic wells. The deeper, confined aquifer system is capped by the Maquoketa Formation. The Maquoketa formation consists primarily of a green to gray shale that is locally mixed with shaly dolomites. The Maquoketa formation is approximately 130 feet to 150 feet thick beneath the Root River watershed in Racine County. The confined aquifer is predominantly Ordivician sandstones.

3. LITERATURE REVIEW

The effect of urbanization on recharge

The impacts of urbanization on groundwater recharge can be broken down into two different pathways: natural and anthropogenic. The natural hydrologic cycle involves interception, evapotranspiration, runoff, infiltration, and recharge. The urban or anthropogenic hydrologic cycle bypasses or alters the natural hydrologic cycle to the extent that it can be thought of as its own system. Evapotranspiration (ET) is largely diminished, as well as is infiltration. The urban hydrologic cycle also has different modes for recharge which include leaky sewer and water distribution networks, septic systems, and stormwater retention or soakway ponds. Water supply networks typically leak at rates of 10% of supply, or more, and rates of up to 50% have been reported. This can account for meters per year of potential recharge (Lerner, 1986).

Replacing forests and native vegetation with impervious surfaces can lead to a higher runoff ratio, a faster response time in streamflow, an increase in peak flow of streams, and the degradation of stream water quality (Rose and Peters, 2001). Precipitation inputs in streamflow can be broken down into three levels: surface runoff, subsurface flow, and groundwater flow. Impervious surfaces limit the amount of water that is allowed to penetrate the vadose zone and contribute to streamflow via the two comparatively slow routes, subsurface and groundwater flows. Subsequently, a greater fraction of the precipitation received by an area becomes surface runoff, which leads to faster stream response times and higher peak flows. The removal of flora also eliminates the interception of precipitation before it reaches the ground surface, allowing a greater portion of the overall precipitation to reach the stream network.

Stormflow recession is also affected by increasing the impervious surface area of a watershed. The return of a stream to baseflow after an increased flow event or stormflow becomes much quicker due to lesser contributions to streamflow from subsurface and groundwater flow. A study done across eight watersheds in northern Georgia showed that an artificial storm drainage system present in more urbanized watersheds produced a recession period 1-2 days shorter than non-urbanized watersheds (Rose and Peters, 2001). The USGS published a study in 2001 on the modeled impact of urbanization on a watershed in south-central Wisconsin which simulated an increase in mean annual streamflow of 54 percent and a reduction in base flow of 14 percent with the addition of urban area to the basin (Steuer and Hunt, 2001).

The degree of impact of urbanization on groundwater recharge is relative to the climate of the region. In more arid climates, leaking septic and water distribution networks, combined with over-irrigation, can often exceed natural recharge rates. An example of this is Doha in Qatar where groundwater levels have been raised to the surface in low lying areas as the result of over-irrigation (Lerner, 1988). In the urban area of Merida, Yucatan, Mexico, it was found that recharge beneath the city from anthropogenic sources significantly exceeded that which would have occurred from excess rainfall alone (Graniel et al, 1999).

The impact of urbanization is also affected by the type of urbanization and the sources of water used by humans. In less commercial areas, where people rely upon private water and septic systems, the anthropological impact is minimalized because water is not transmitted into or out of the basin (Cherkauer and Ansari, 2005). In areas where water is brought in from an external source, all leakage and wastewater become a net recharge gain. The nature of the urbanization can also have a different impact. Changes in land use from row crop to low-density residential development may increase recharge rates (Harbor, 1994), while land use changes from woodland to high density residential and commercial may decrease infiltration.

The effect of climate change on groundwater recharge

The Intergovernmental Panel on Climate Change (IPCC) has estimated that the global mean surface temperature will increase by 2 to 4 degrees Celsius over the next 100 years. The hydrologic cycle will be directly impacted by the predicted warmer temperatures, as well as more frequent occurrences of droughts, storms, and floods. Coupled atmosphere and ocean global climate models (GCMs) are used to estimate changes in climate. A statistical downscaling technique should be applied to model the simulated climate impacts on a smaller scale (Singh and Kumar, 2015). Statistical downscaling uses empirical relations between features reliably simulated by a GCM at grid scale and surface predictands at the sub-grid scale (Markstrom, 2011).

The variability of timing and intensity of forecasted precipitation events makes them more difficult to predict. The increase in average temperature, on a broader scale, has a more predictable effect on groundwater recharge. Increases in average temperature will cause increased amounts of evapotranspiration (ET) by increasing the potential evapotranspiration (PET) and lengthening the growing season. A study was done on 14 watersheds in the United

States using PRMS and forecasted climate data from 3 greenhouse gas emission scenarios. This study (Hay et al, 2011) concluded that temperature increases were the most reliable prediction from the GCMs and, therefore, changes in evapotranspiration, timing of snowmelt, and changes in the type of precipitation based on temperature (snow versus rain) were predicted with higher confidence. These changes could indicate an earlier snowmelt resulting in earlier peak flows. The increase in temperature will also lead to a decrease in volume of the snowpack resulting from a larger portion of precipitation falling as rain. The study also stated that a change in the volume and timing of snowmelt may lead to increased water scarcity (Hay et al, 2011).

Estimating impervious surface area from urbanization

The Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 mandates a periodic assessment of the conditions and trends of the United States' renewable resources (Wear, 2011). This assessment is driven by estimates for wildlife, timber, and recreation but also generates estimates for urbanization. Forecasts are made at the county level by economic models that use historical data for population and income. These models establish growth rates based upon different income and population scenarios. The 2010 RPA Assessment (Wear 2011) projects between 60 and 86 million acres of rural land to be developed between 1997 and 2060.

A land use study that focused on Minnesota, Michigan, and Wisconsin (Mauldin and Plantinga, 1999) projected an increase of urban land by 127 hundred thousand acres for the state of Wisconsin from the year 2000 to 2050, an increase of approximately 12 percent. The study also stated that area of urban land in the Lake States (MI, MN, WI) has increased twofold since the 1950's while population grew by 50 percent during the same time span. The Southeastern Wisconsin Regional Planning Commission (SEWRPC), which encompasses 7 counties in the greater Milwaukee area of Wisconsin, produced a land use plan that projected an increase of urban area by 13 percent for the region (SEWRPC, 2006). The focus area of this projection includes the Root River watershed.

A study published in *Sensors* (Chormanski et al, 2008) detailed a method for deriving the percent of impervious area for different classifications of urban land use from high-resolution and medium-resolution satellite imagery. High-resolution Ikonos imagery (4 meter multi-spectral, 1 meter panchromatic) from the city of Brussels was used to calibrate sub-pixel resolution from medium-resolution (30 meter) Landsat ETM+ data. Values for six different types of urban area were generated: low density build-up, high density build-up, city center, infrastructure, roads/highways, and industrial. A fully-distributed rain-fall runoff model (WetSpa) was used to evaluate the high-resolution and medium-resolution estimates of impervious surfaces under three scenarios for runoff calculation. The first scenario used a non-distributed approach, which assigned an average value of impervious surface derived from Ikonos data to all types of urban areas. The Ikonos degree of imperviousness was 44%, which produced peak discharges 10-20% higher than the default value for WetSpa of 30%. The second scenario used a semi-distributed approach based on six different classifications of urban area (described above) and produced increases of 5-10% peak discharge versus the non-distributed approach. The third scenario used fully-distributed values for each pixel derived from the high-resolution Ikonos data, which produced 15% increases in peak discharge vs the non-distributed approach.

The University of Minnesota, in conjunction with the Minnesota Pollution Control Agency, conducted a study on increases in impervious surfaces using Landsat Enhanced Thematic Mapper Plus (ETM+). The study included an accuracy assessment of the calibrated Landsat ETM+ by picking 25 points to verify on location. The accuracy assessment showed the medium-resolution imagery to be within 10% for most cases, with the greatest difficulty occurring when differentiating bare soil from impervious surface, and also when tree canopy area overlapped impervious area. They then applied the calibrated impervious surface regression model to the entire state of MN for 1990 and 2000 data. They found that impervious surface area across the state increased by 44%, with 20 of 81 major watersheds exhibiting a 100 percent or greater increase in impervious surface area (Bauer et al, 2007)

4. OBJECTIVE

The main objectives of this study are 1) to develop a conversion factor for estimating impervious surface area from different types of urban land use; and 2) to estimate the impacts of increased impervious surface area on groundwater recharge, runoff and evapotranspiration simulated in PRMS through the uncoupling of historical land use and climate data.

5. METHODS

GIS

The delineation of Hydrologic Response Units can be performed using GIS. HRU delineation was done by creating 19 sub-watersheds within the Root River drainage basin. From a Digital Elevation Model (DEM), the surface sinks are filled, and flow direction is calculated using ArcMap. The flow direction calculation creates a stream network within the basin that can be compared to high-resolution aerial imagery for verification. Nodes along each stream are chosen, and the program uses the flow direction surface to create HRUs as sub-watersheds.

Land use data was delivered from the Southeast Wisconsin Regional Planning Commission in ¼ section township and range format. ArcMap 10.3.1 was used to orient the land use data spatially so that it could be summarized and prepared as input for the Precipitation and Runoff Modelling System (PRMS). The state of Wisconsin ¼ section grid was imported and drawn into ArcMap. The SEWRPC land use data was altered in Excel to create a common coordinate designation per grid, and the land use table was joined to the Wisconsin ¼ section grid. The Root River watershed with HRU's was used to clip the Wisconsin ¼ section map to the area of interest, and the extract by mask and summarize within tools were used to generate percent urban area specific to each HRU. Once the ¼ sections were extracted to each HRU, the data had to be manually compiled in Excel in order to accurately normalize the percentage of urban area for the number of grid squares that were cut by the irregular HRU boundaries. This was done so that a partial ¼ section grid did not carry the same weighted area into the overall urban area of the HRU as a fully contained ¼ section.

Impervious Surface Area from Urban Land Use Area

The land use data from SEWRPC, 2012, included seven sub-categories of urban area. The six semi-distributed values of impervious surface area derived from the high-resolution Ikonos remotely sensed data used in the *Sensors,* 2008, article were applied to the seven sub-categories of the SEWRPC for each data set. The percent of impervious surface area of urban area ranged from a high of 38 percent of the 1963 land use data to a low of 35 percent for the 2035 projected land use data. Averaging the values of total impervious area for each dataset gave an overall average of 36 percent impervious surface area per unit urban area. This value was applied to the urban area contained within each HRU and used as the input for the model.

PRMS

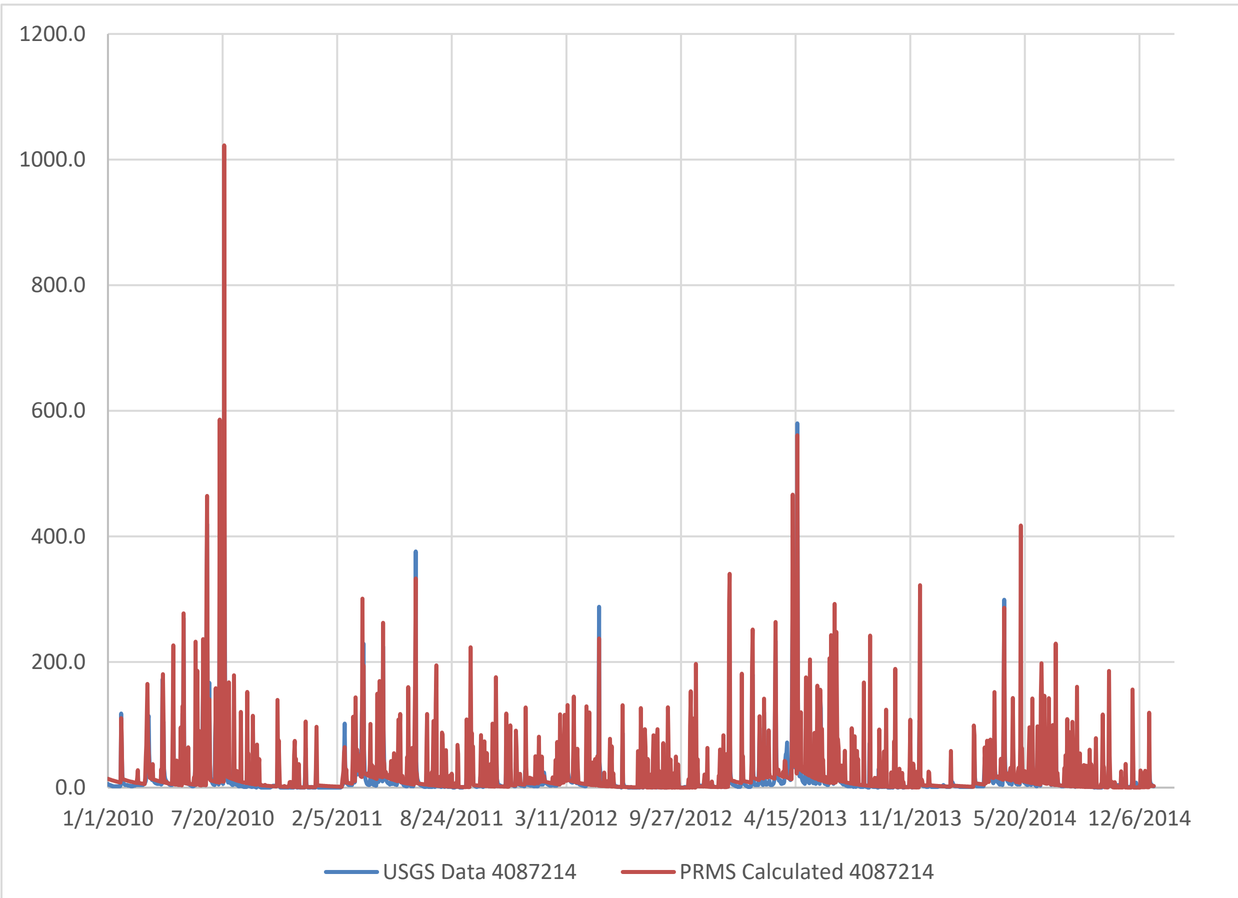
The USGS Precipitation and Runoff Modelling System (PRMS), is a distributed-parameter physical-process-based hydrologic model developed to evaluate the response of various combinations of climate and land use on streamflow and general watershed hydrology. PRMS version 4 was used for the simulations in this study. PRMS requires that the watershed be delineated into hydrologic response units (HRUs). Discretization allows for spatial variability for model parameters and climate inputs.

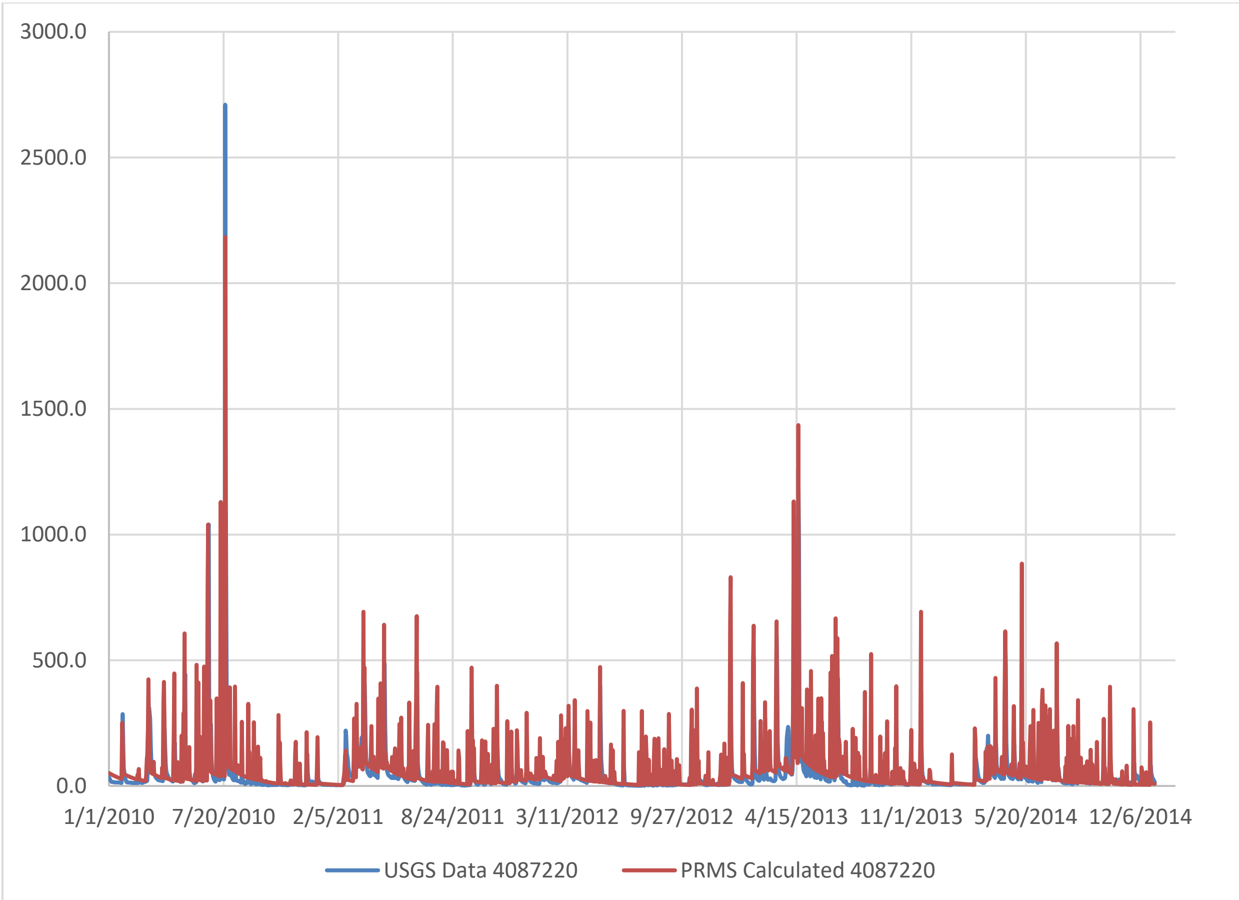
Inputs to the hydrologic model are daily time-series values of precipitation, minimum and maximum temperature, and short-wave solar radiation. The program requires the user to write climate inputs for each HRU when using the Climate-by-HRU (CBH) module. This allows for spatial variability throughout the watershed and a higher resolution of climate data to be used. Historical climate data (1980-2014) by HRU was downloaded from the National Hydrography Dataset (NHD). Also available from the NHD is stream gage data for three stream gages in the Root River watershed. The historical stream gage data is compared to simulated runoff and stream data generated by the model in calibration.

Inputs of energy in the form of short-wave radiation and air temperature drive the processes of evaporation, transpiration, snowmelt, and sublimation. Daily short-wave radiation can be estimated internally by the program if it is not assigned by the user. Four input files are required for a simulation: a Control File, a Data File, a Parameter File, and a Climate by HRU File. The Control File is used to specify the input and output file names, content of output files, simulation start and end dates, and the active modules. The Data File (and Climate by HRU Files) contains the climate inputs for the model in daily time series, written for each HRU. The Parameter File contains the values for the parameters that are specified for each module. The parameters do not change over the course of the simulation.

The Statistics Variable File is a text file that provides selected output variables in a time series output. The variables chosen for the Statistics Variable Files for the purpose of this study were basin evapotranspiration, basin recharge, and basin surface runoff. The daily time series for the outputs allowed the data to be manipulated in Excel to determine temporal variability of the hydrologic sinks simulated by the program.

The PRMS IV program can be executed with or without a graphical user interface. The graphical user interface (GUI) also allows the user to make changes to the control file and creates a running graph of simulated streamflow versus observed streamflow at each stream gage. Because model simulations run through the GUI required orders-of-magnitude longer runtimes, most of the simulations in this study were run without the GUI.

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7/20/2010
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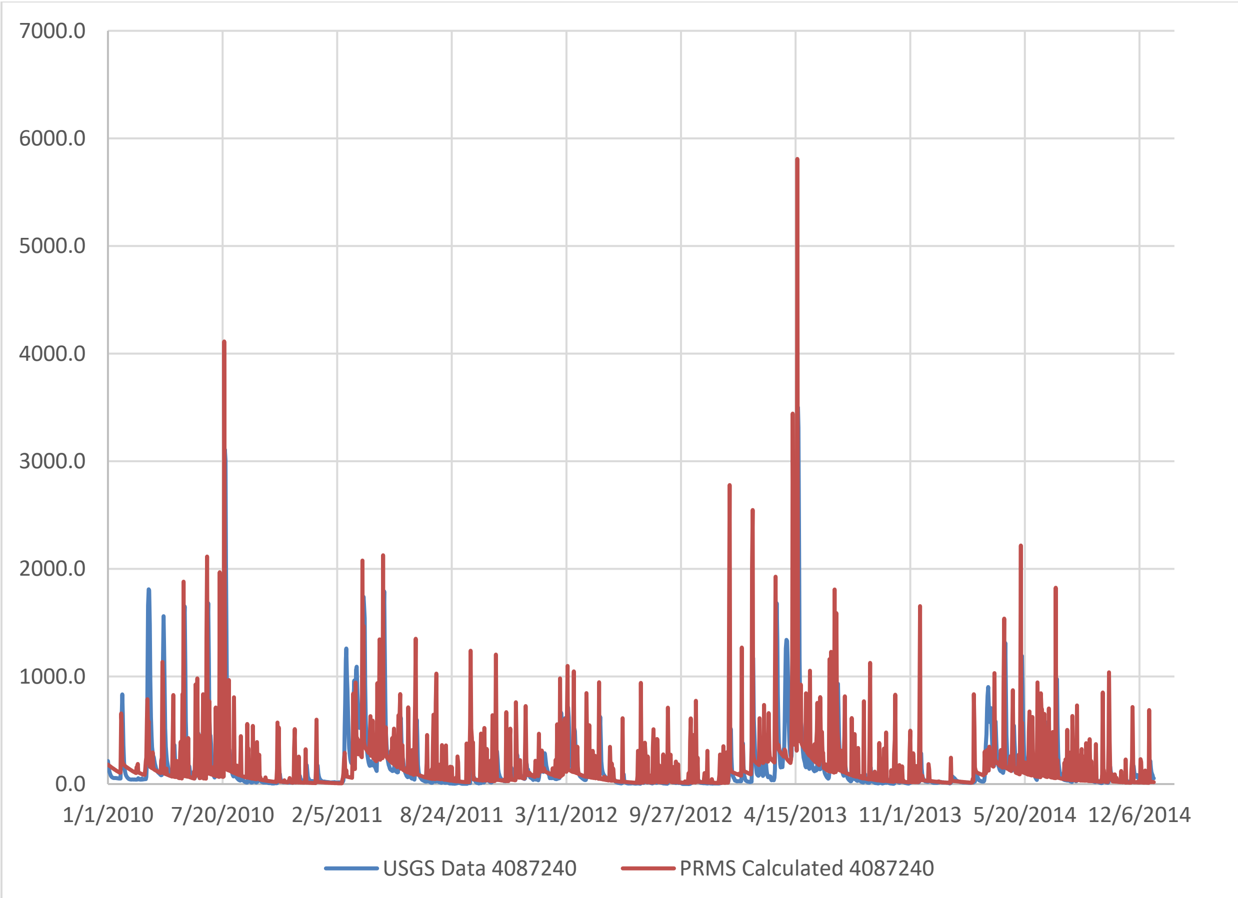

Figure 2. Example comparison of simulated stream flow and USGS gauging stream flow (2010 to 2014) unit: cubic feet per second (cfs). Each graph represents model calculated runoff vs stream gauge data at three locations in the Root river watershed.

Simulations were run for the entire time series for each set of land use data (1963, 1970, 1975, 1980, 1985, 1990, 1995, 2000, 2010, and forecasted 2035). The analysis was particularly focused on the two extremes: 1963 and 2035 land use. All inputs and parameters remained constant except for the "hru_percent_imperv" parameter, which was changed to represent the calculated impervious area for the respective land use scenario being tested.

6. RESULTS AND DISCUSSION

GIS Urbanization Area Results

The total urban area for the Root River watershed increased from 25,035 acres in 1963 to 47,800 in the 2035 forecasted land use scenario. The percentage of urban area for the Root River watershed increased from 20% in 1963 to 39% in 2035. The categories of urban area, in descending order of percentage of total, include: Residential; Transportation, Communications, and Utilities; Recreational; Commercial; Government and Institutional; Industrial; Unused Urban Land. Residential land use experienced the largest increase while unused urban land decreased steadily throughout the period covered by the datasets.

LAND USE (ACRES) WITHIN THE ROOT RIVER WATERSHED:
EXISTING 1963 TO 2010 AND PLANNED 2035

Land Use Category	1963	1970	1975	1980	1985	1990	1995	2000	2010	2035 Plan
Single-family residential	11,447	14,203	15,432	16,640	17,081	17,876	19,154	20,195	22,137	--
Multi-family residential	357	555	719	846	931	1,186	1,338	1,613	1,883	--
Residential Subtotal	11,804	14,758	16,151	17,486	18,012	19,062	20,492	21,808	24,020	27,069
Commercial	632	931	1,123	1,286	1,407	1,544	1,684	1,810	2,058	2,808
Industrial	333	524	607	689	757	889	1,022	1,219	1,453	1,786
Government and Institutional	1,117	1,523	1,622	1,647	1,674	1,709	1,796	1,942	2,070	2,027
Transportation, Communications, and Utilities	7,270	8,299	8,520	8,720	8,816	8,987	9,770	10,706	11,281	12,144
Recreational	1,845	2,473	2,626	2,706	2,778	2,862	3,013	3,201	3,317	3,401
Unused Urban Land	4,467	3,588	3,176	2,740	2,657	2,504	2,582	2,792	2,420	1,360
Urban Land Subtotal	27,468	32,096	33,825	35,274	36,101	37,557	40,359	43,478	46,619	50,595
Agricultural	82,978	77,606	76,068	74,172	73,143	70,541	67,506	63,686	58,246	57,174
Woodland	5,451	5,207	5,162	5,085	5,036	5,176	5,061	4,894	4,862	4,827
Wetland	5,888	6,030	6,064	6,223	6,233	6,589	6,704	6,945	9,307	6,945
Water	594	794	880	908	916	934	983	1,001	1,434	1,001
Other Open Land	3,674	4,319	4,054	4,392	4,625	5,265	5,444	6,067	5,613	5,531
Nonurban Land Subtotal	98,585	93,956	92,228	90,780	89,953	88,505	85,698	82,593	79,462	75,478
Total	126,053	126,052	126,053	126,054	126,054	126,062	126,057	126,071	126,081	126,073

NOTE: Planned 2035 land use is based on year 2000 data and may not reflect development that occurred between 2000 and 2010.

Table 1. Summary of root river basin land use data by category (source: SEWRPC).

The largest impact of urbanization on non-urban land uses came at the expense of agricultural land, which decreased by a total area greater than the increase in urban acreages, also losing area to increases in wetland and other open land areas. Agricultural land decreased from approximately 66 percent of the total area of the Root river watershed in 1963, to 45 percent in the simulated 2035 land use.

After converting the urban areas by sub-category to percent impervious, the total impervious area for the Root river watershed increased 6.4 percent from 8.8 percent in 1963 to 15.2 percent with the 2035 forecasted land use. Total impervious acreage for the watershed was approximately 9,000 in 1963 and 17,000 for the 2035 data.

Fraction of Area Impervious - by HRU

HRU	1963	1970	1975	1980	1985	1990	1995	2000	2010	2035
3734	0.230	0.250	0.256	0.267	0.270	0.267	0.279	0.286	0.287	0.269
3740	0.214	0.233	0.244	0.252	0.255	0.257	0.262	0.271	0.284	0.281
3744	0.098	0.155	0.158	0.173	0.173	0.175	0.178	0.182	0.190	0.200
3755	0.048	0.063	0.063	0.071	0.073	0.076	0.076	0.083	0.086	0.099
3760	0.020	0.025	0.029	0.031	0.031	0.031	0.034	0.036	0.042	0.038
3763	0.027	0.034	0.035	0.037	0.038	0.040	0.044	0.047	0.054	0.059
3772	0.022	0.027	0.030	0.031	0.032	0.033	0.042	0.046	0.050	0.052
3774	0.040	0.052	0.056	0.059	0.060	0.062	0.070	0.075	0.085	0.095
3775	0.020	0.022	0.023	0.024	0.025	0.026	0.031	0.034	0.040	0.037
3778	0.014	0.016	0.016	0.016	0.016	0.041	0.064	0.131	0.134	0.145
3781	0.044	0.057	0.062	0.066	0.069	0.073	0.082	0.104	0.116	0.130
3784	0.036	0.042	0.044	0.045	0.046	0.044	0.046	0.048	0.053	0.132
3796	0.128	0.160	0.169	0.176	0.180	0.184	0.199	0.223	0.244	0.259
3801	0.124	0.140	0.150	0.159	0.169	0.180	0.199	0.220	0.235	0.261
5667	0.308	0.324	0.325	0.327	0.331	0.337	0.336	0.337	0.334	0.340
5670	0.018	0.025	0.027	0.029	0.030	0.031	0.034	0.038	0.046	0.042
5730	0.204	0.254	0.261	0.272	0.276	0.302	0.325	0.333	0.326	0.338
5733	0.026	0.031	0.033	0.036	0.036	0.038	0.042	0.047	0.051	0.052
5790	0.045	0.053	0.046	0.047	0.049	0.049	0.049	0.055	0.057	0.055

Table 2. Calculated values for fraction of HRU as impervious surface. These represent the input values for the "hru_percent_imperv" parameter required by the PRMS model.

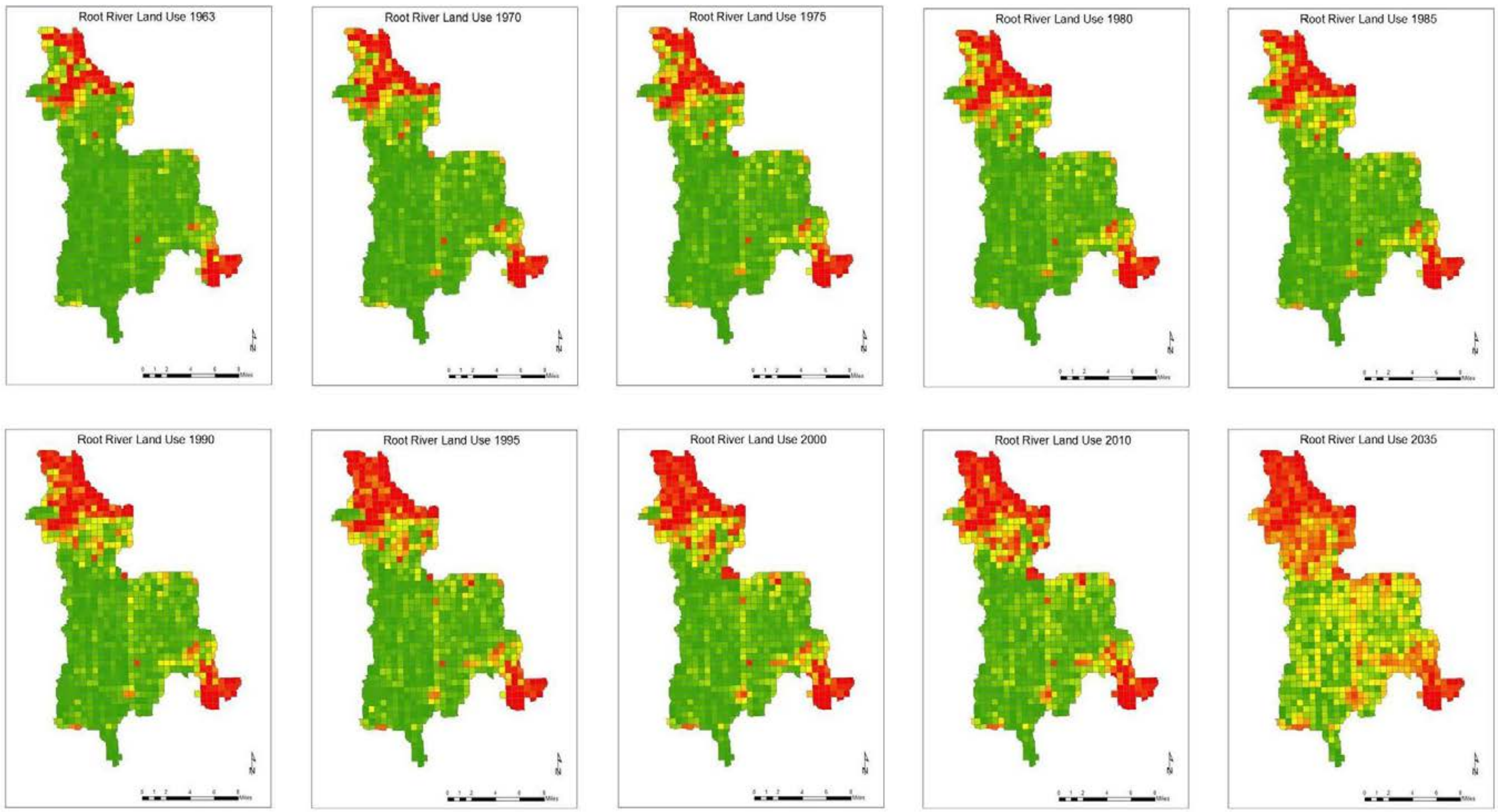

Figure 3. The set of images shown shows the distribution and density of urban area in the root river watershed. The Root river watershed spans from the southern portion of the greater Milwaukee area to the north to the city of Racine, located to the southeast. Each ¼ section within the watershed is shaded on a green to red scale, with green indicating non-urban and red indicating 100 percent urban area. The vertical band of urban area that appears to bisect the watershed is the Interstate 94 corridor.

PRMS Results

The climate data for the watershed from 1980 to 2014 produced an average precipitation of 35.7 inches per year, with a maximum of 43.2 inches in 2008 and a minimum of 25.8 inches in 2005. Monthly averages for precipitation range from less than one inch for the month of January to 4.4 inches in June. The mean annual water budget for the Root River watershed across all land use scenarios is:

35.7 inches precipitation = 7.0 inches runoff + 23.0 inches ET + 5.7 inches recharge.

Three output variables were identified to compare the simulations.

basin_actet – Basin area-weighted average actual ET

basin_sroff – Basin area-weighted surface runoff to the stream network

basin_recharge – Basin area-weighted average recharge to groundwater reservoirs

These output variables are calculated at a daily time-step for each HRU, then combined in an area-weighted average for a basin total of the Root River watershed. These three output variables account for over 98% of the basin area-weighted precipitation inputs. Runoff is the most strongly correlated with precipitation (R^2=0.90), while recharge and ET are loosely correlated with precipitation (R^2=0.50 and R^2=0.56, respectively).

PRMS Results – by Year

To evaluate the effects of land use change on the hydrological responses (i.e., runoff, evapotranspiration and groundwater recharge), the PRMS model was run using the available land use data (1963, 1970, 1975, 1980, 1985, 1990, 1995, 2000, 2010, 2035) and the 35 years of available weather data. The PRMS-generated annual runoff, evapotranspiration and groundwater recharge were summarized by year for each land use scenario.

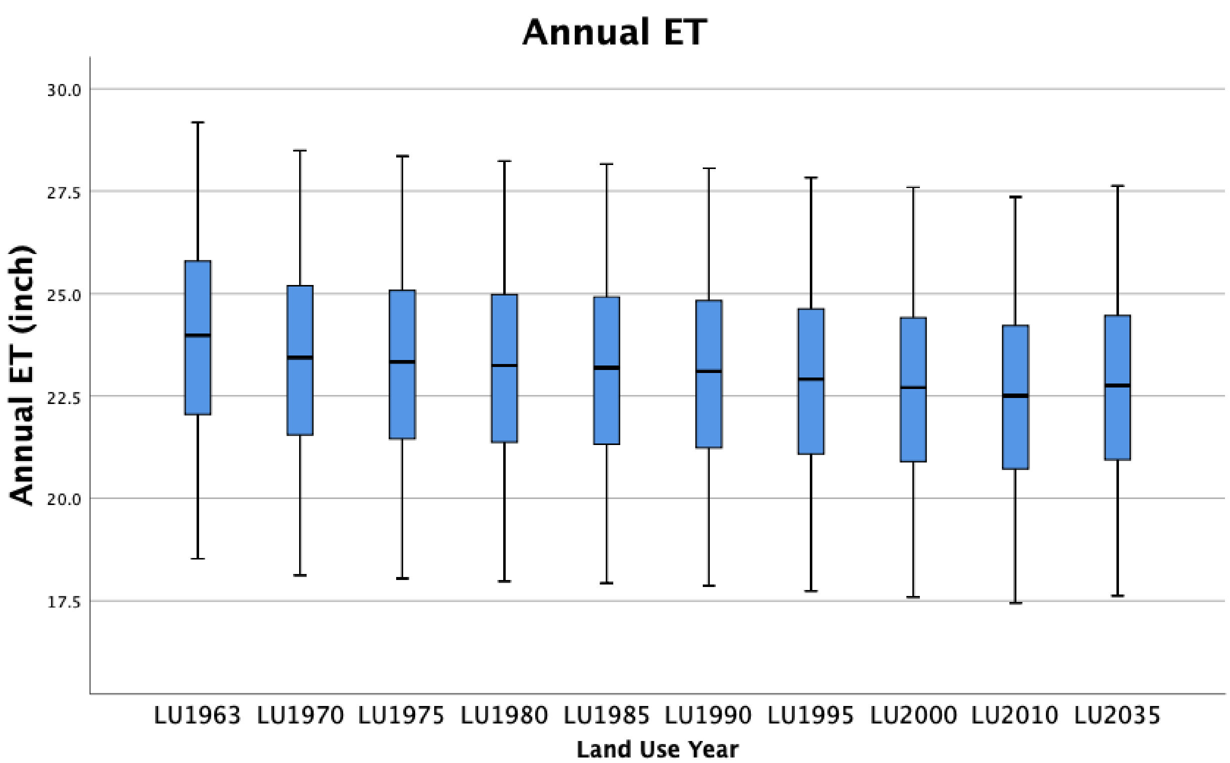

Figure 4. Box-Whisker plots of annual evapotranspiration (ET) rate using land use data for the years between 1963 and 2035.

Figures 4 through 6 are Box-Whisker plots of the annual ET, runoff, and recharge by land use scenario. The median value is in the center of the box which extends to the 25th and 75th percentile values. The whiskers, or T-bars, extend to the minimum and maximum values for each scenario. Figure 4 summarizes model simulated annual evapotranspiration totals for the 10 land use scenarios. On average, the increase in urbanization led to ~5% decrease in annual ET. The result from one-way analysis of variance (ANOVA) showed that the effect of land use on annual ET was insignificant. However, when paired Student-t test was performed for the results from 1963 and 2035 land use scenarios, there was statistically significant ($p<0.05$) difference between the annual ET rates. On average, the urbanization led to the loss of agricultural-forest land and subsequently decrease in annual ET (~5%).

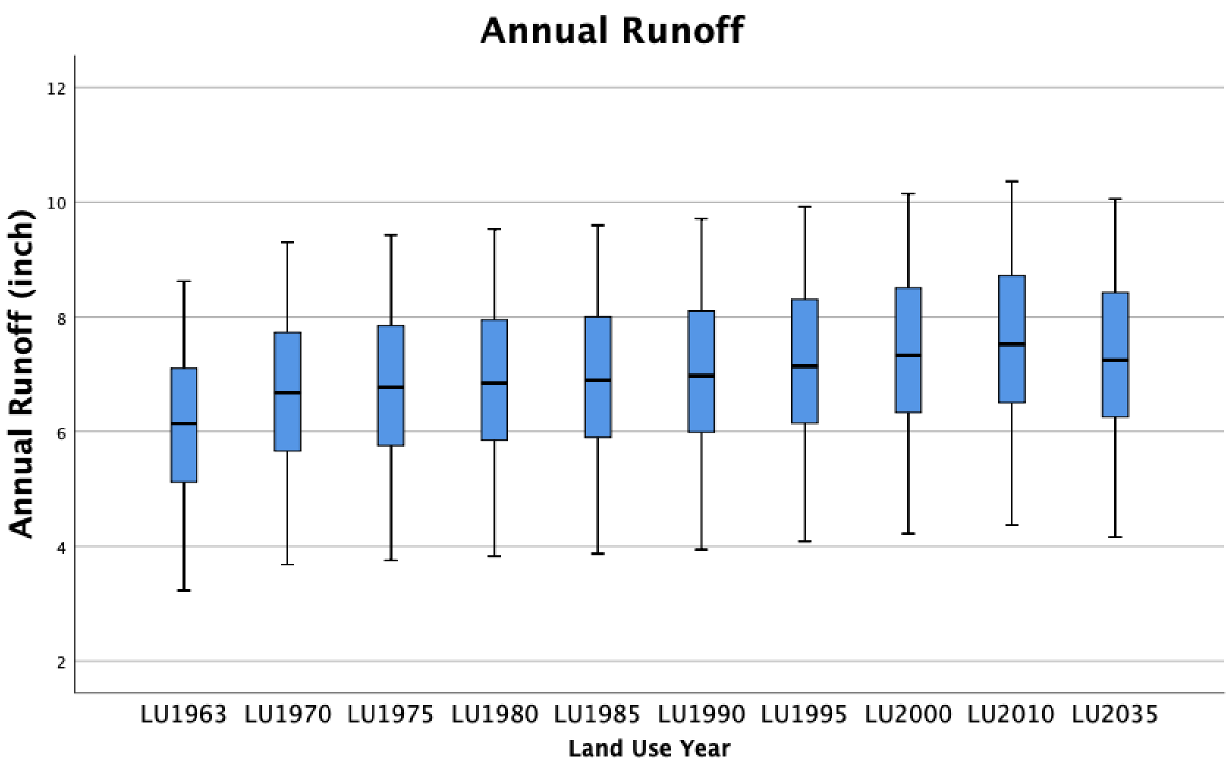

Figure 5. Box-Whisker plots of annual runoff rate using land use data for the years between 1963 and 2035.

Simulation results for the annual runoff showed that the urbanization within the Root River watershed led to a clear trend in runoff as the p-value from the one-way ANOVA was less than 0.01 (Figure 5). Overall, the results showed that urbanization during 1963 and 2035 will increase runoff by an average of 19%.

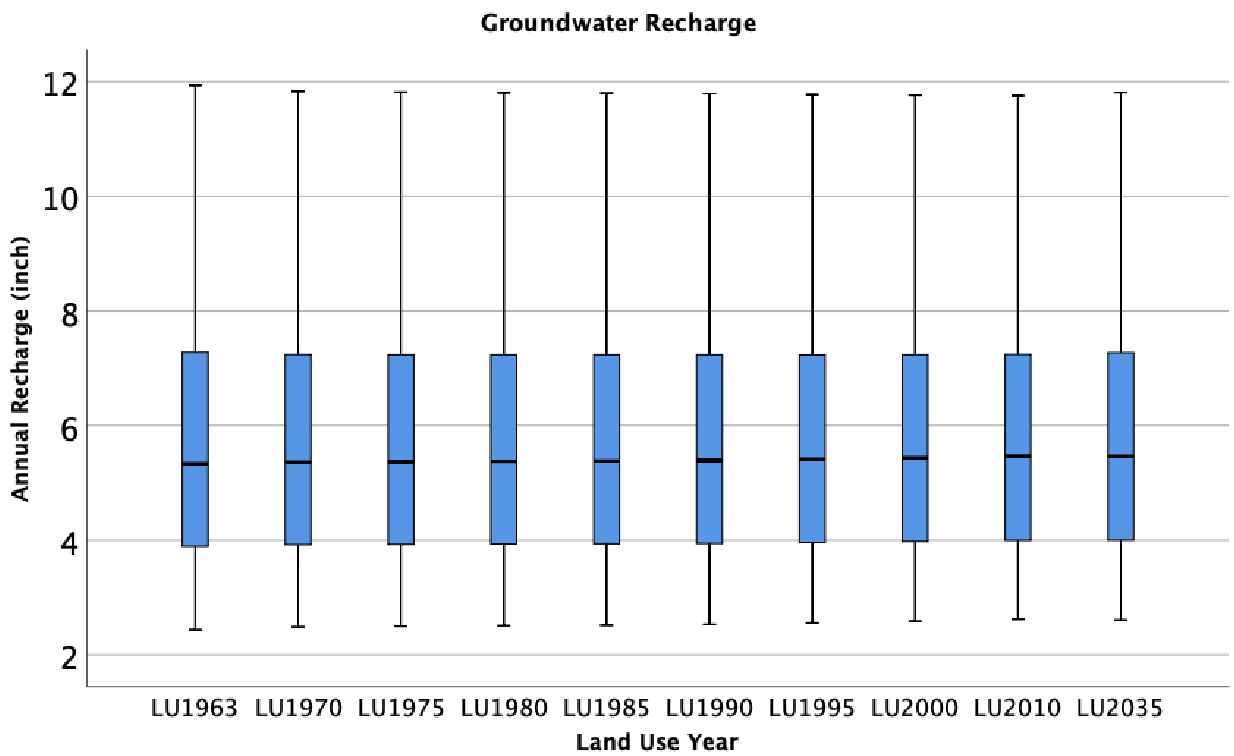

Figure 6. Box-Whisker plots of annual groundwater recharge rate using land use data for the years between 1963 and 2035.

Figure 6 shows the simulated annual recharge under various land use scenarios. Overall, there were small variations in annual groundwater recharge which was confirmed by one-way ANOVA ($p>0.05$). Comparison for the 1963 land use and 2035 projected land use through paired Student-t test, however, did show that there was statistically significant ($p<0.05$) *increase* in groundwater recharge due to urbanization, which seemed counter to the original hypothesis that increasing impervious area would decrease recharge. The original hypothesis was based upon the idea that the model would simulate runoff directly to streamflow as a loss of precipitation available for recharge. Going line-by-line through model input parameters revealed parameter “sro_to_dprst_imperv”. This input parameter accounted for the fraction of impervious surface runoff that was routed to surface depression storage. Model inputs for this parameter are on a 0.0 to 1.0, with values for the HRUs in the Root River model ranging between 0.0 to 0.327. Eleven of the 19 HRUs had value of 0.0. The parameter that then calculated seepage rates from depression storage (“dprst_seep_rate”) was approximately 0.35 for all HRUs. This is how the model accounted for runoff retention ponds in urban areas. Routing surface runoff to retention ponds and allowing it to contribute to recharge while in storage effectively bypasses a large portion of precipitation that can be lost to evapotranspiration. This is how the model can calculate increases in groundwater recharge with increases in impervious area.

Close inspection of the recharge data also revealed that Climate year 2008 produced recharge totals of approximately 11.8 inches for both land use scenarios with an annual precipitation of approximately 43.5 inches while climate year 2000 produced recharge totals of just over 5 inches for both land use scenarios with an annual precipitation total of approximately 43 inches. These variations are likely due to changes in the timing and intensity of precipitation events.

PRMS Results – by Month

In this section, model simulations for 1963 land use and 2035 forecasted land use were summarized by month to examine the effects of seasonal climate variations on calculated groundwater recharge, ET and runoff. The model predicted decreases in recharge for the 2035 land use scenario for the months of January through March, and December. The model calculated increases in recharge for the remaining 8 months. This shift from loss in model calculated recharge to gain in model calculated recharge coincides with the growing season in southeastern Wisconsin, roughly May through September.

Category - Land Use Scenario	Model Calculated Distribution of Precipitation (%)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Runoff - 1963	18	8.9	13	19	16	17	14	17	19	19	27	26
Runoff - 2035	22	13	16	21	19	21	18	21	23	22	31	29
ET - 1963	21	43	58	67	78	75	82	76	72	71	49	26
ET - 2035	20	41	55	64	74	71	78	72	68	67	46	24
Recharge - 1963	61	48	29	14	6.5	7.8	3.7	6.7	8.3	11	24	48
Recharge - 2035	58	46	29	15	7.0	8.3	4.4	7.2	8.9	11	24	46

Table 3. Model calculated runoff, ET, and recharge by month, shown as percent of monthly total precipitation

Recharge accounts for less than 10 percent of precipitation during the growing season while evapotranspiration accounts for greater than 60 percent of precipitation during that period. Table 3 shows the distribution of precipitation by percent of total, per month. Runoff, as a percent of total precipitation, is higher during each month of the year for the 2035 land use scenario than the 1963 land use scenario. However, evapotranspiration is higher for the 1963 land use scenario for all 12 months.

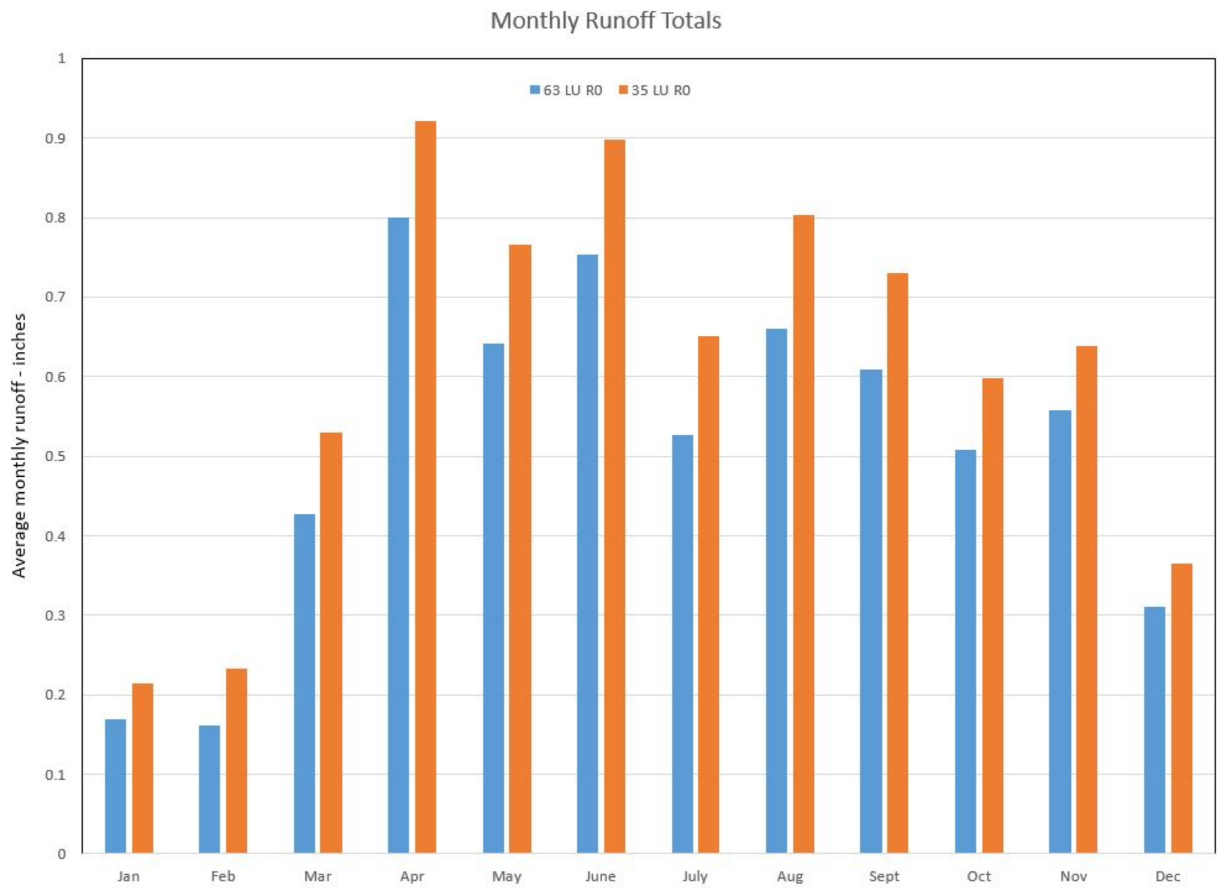

Figure 7. Model calculated runoff average by month. Student *t* tests showed that the difference was statistically significant (p<0.05) for every month.

Figure 7 shows average runoff by month for the 1963 land use scenario and the 2035 projected land use scenario. Model calculated runoff is greater for all 12 months when totaled by month for the 35-year simulation. The increase in runoff for the 2035 land use scenario is greater during growing season months when vegetation plays a greater role in interception, the capture of precipitation before it reaches the ground surface, and evapotranspiration.

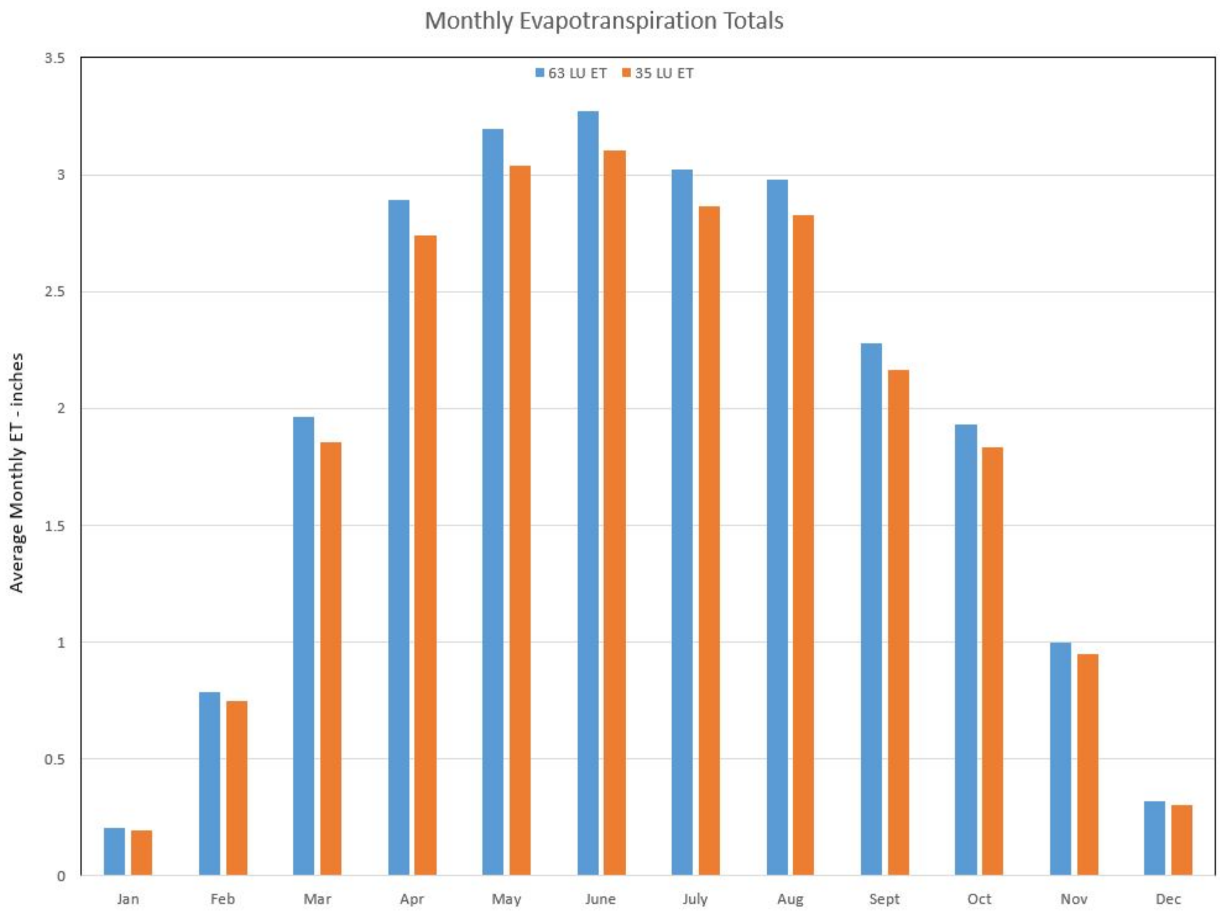

Figure 8. Model calculated evapotranspiration average by month. Student *t* tests showed that the difference was statistically significant ($p<0.05$) for every month.

Figure 8 shows average evapotranspiration by month for the 1963 land use scenario and the 2035 project land use scenario. Evapotranspiration is greater for all 12 months. The decrease in calculated ET for the 2035 land use scenario is greater during the growing season. The month with the greatest difference in calculated ET was July, with approximately 0.25 inches in total difference. The model calculated decreases of greater than approximately 0.15 inches for the months between April and September. Model calculated decreases in evapotranspiration for the 2035 land use scenario are greater than model calculated increases in runoff during that same growing season timeframe.

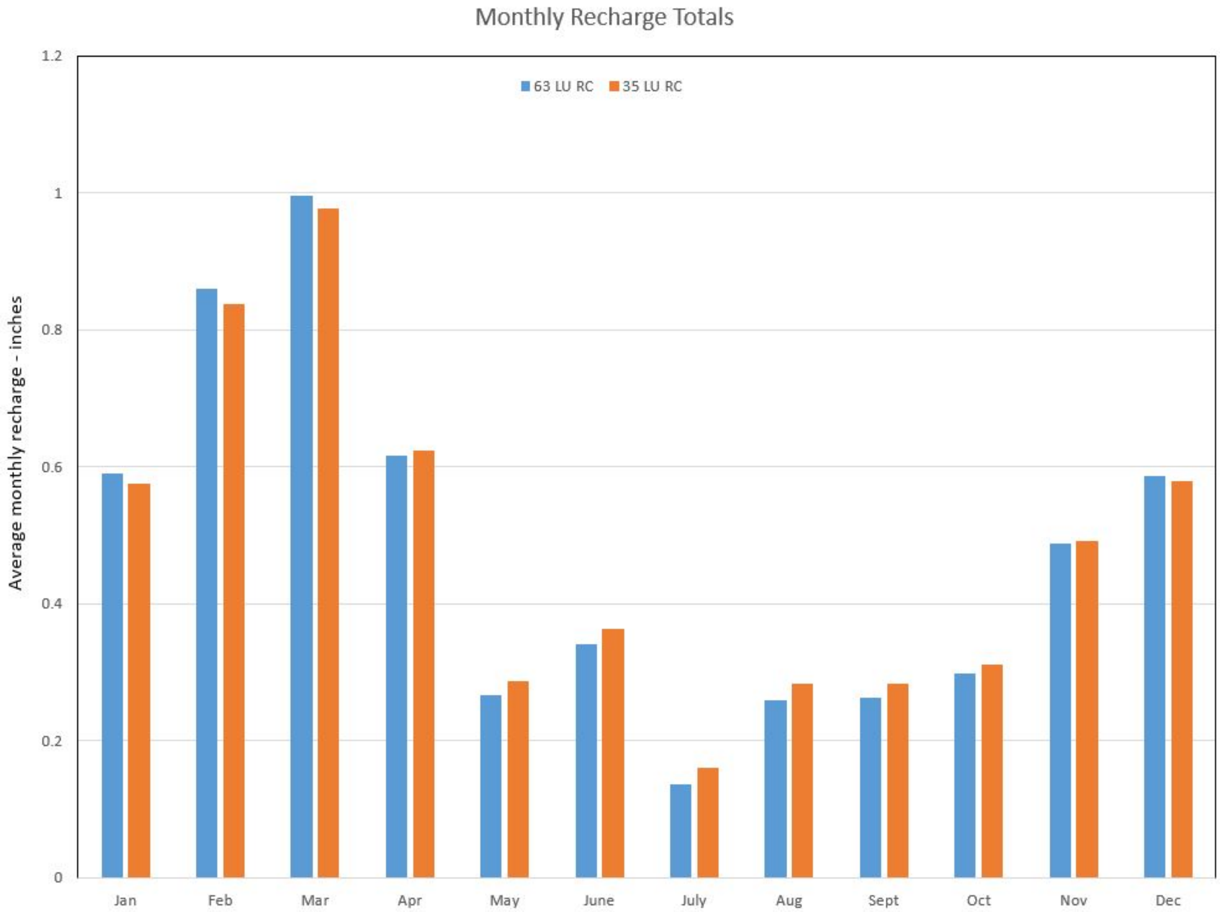

Figure 9. Model calculated recharge average by month. Student *t* tests showed that the difference was statistically significant ($p<0.05$) for the months of January, February, March, and the growing season months (May, June, July, August, September and October).

Figure 9 shows average recharge by month for the 1963 land use scenario and forecasted 2035 land use. Model calculated recharge is greater for the 1963 land use scenario for the months of January, February, March, and December. The model calculated recharge for forecasted 2035 land use is greater in the months of April through November. Model calculated recharge for the 2035 land use scenario was greater for the month of July in every year of the 35-year simulation, indicating that an increase in recharge during the heart of the growing season can be expected through varying climate possibilities. However, model calculated recharge for the month of March was only greater for the 1963 land use scenario for 22 out of 35 simulated years of climate. This distinction is important because it demonstrates the higher degree of certainty with which we can predict increases in recharge during the growing season than we can the decreases in recharge during the non-growing season.

Land Use	Runoff Average - by Month (inches)											
Scenario-Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1963	0.17	0.16	0.43	0.80	0.64	0.75	0.53	0.66	0.61	0.51	0.56	0.31
1970	0.19	0.20	0.48	0.86	0.70	0.82	0.59	0.73	0.67	0.55	0.60	0.34
1975	0.19	0.20	0.49	0.87	0.71	0.83	0.60	0.74	0.68	0.56	0.60	0.34
1980	0.20	0.21	0.49	0.88	0.72	0.85	0.61	0.75	0.69	0.57	0.61	0.35
1985	0.20	0.21	0.50	0.88	0.73	0.85	0.61	0.76	0.69	0.57	0.61	0.35
1990	0.20	0.22	0.51	0.89	0.74	0.86	0.62	0.77	0.70	0.58	0.62	0.35
1995	0.21	0.23	0.52	0.91	0.75	0.88	0.64	0.79	0.72	0.59	0.63	0.36
2000	0.22	0.24	0.54	0.93	0.77	0.91	0.66	0.81	0.74	0.60	0.64	0.37
2010	0.23	0.25	0.55	0.95	0.79	0.93	0.68	0.83	0.76	0.62	0.66	0.38
2035	0.21	0.23	0.53	0.92	0.77	0.90	0.65	0.80	0.73	0.60	0.64	0.37

Table 4. Model calculated average runoff by month for each land use scenario.

Land Use	Evapotranspiration Average - by Month (inches)											
Scenario-Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1963	0.21	0.79	1.96	2.89	3.20	3.29	3.03	2.97	2.28	1.93	1.00	0.32
1970	0.20	0.77	1.91	2.82	3.11	3.20	2.94	2.91	2.23	1.89	0.98	0.31
1975	0.20	0.77	1.91	2.81	3.11	3.20	2.94	2.89	2.22	1.88	0.97	0.31
1980	0.20	0.76	1.90	2.80	3.09	3.17	2.91	2.89	2.21	1.87	0.97	0.31
1985	0.20	0.76	1.89	2.79	3.09	3.17	2.91	2.89	2.20	1.87	0.97	0.31
1990	0.20	0.76	1.89	2.78	3.09	3.14	2.91	2.86	2.19	1.86	0.96	0.31
1995	0.20	0.75	1.87	2.76	3.06	3.11	2.89	2.86	2.18	1.85	0.96	0.31
2000	0.20	0.75	1.85	2.73	3.03	3.09	2.86	2.82	2.16	1.83	0.95	0.31
2010	0.19	0.74	1.84	2.71	3.00	3.09	2.83	2.79	2.14	1.82	0.94	0.30
2035	0.20	0.75	1.86	2.74	3.03	3.11	2.86	2.83	2.16	1.83	0.95	0.31

Table 5. Model calculated average evapotranspiration by month for each land use scenario.

Land Use Scenario-Year	Recharge Average - by Month (inches)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1963	0.59	0.86	1.00	0.62	0.27	0.34	0.14	0.26	0.26	0.30	0.49	0.59
1970	0.58	0.85	0.99	0.62	0.27	0.35	0.14	0.27	0.27	0.30	0.49	0.58
1975	0.58	0.85	0.98	0.62	0.27	0.35	0.15	0.27	0.27	0.30	0.49	0.58
1980	0.58	0.84	0.98	0.62	0.27	0.35	0.15	0.27	0.27	0.30	0.49	0.58
1985	0.58	0.84	0.98	0.62	0.28	0.35	0.15	0.27	0.27	0.30	0.49	0.58
1990	0.58	0.84	0.98	0.62	0.28	0.35	0.15	0.27	0.27	0.31	0.49	0.58
1995	0.57	0.84	0.97	0.62	0.28	0.36	0.15	0.28	0.28	0.31	0.49	0.58
2000	0.57	0.83	0.97	0.62	0.29	0.36	0.16	0.28	0.28	0.31	0.49	0.58
2010	0.57	0.83	0.97	0.62	0.29	0.37	0.16	0.29	0.28	0.31	0.49	0.57
2035	0.58	0.84	0.98	0.63	0.29	0.36	0.16	0.28	0.28	0.31	0.49	0.58

Table 6. Model calculated average recharge by month for each land use scenario.

Table 4, Table 5, and Table 6 show the model calculated average monthly runoff, evapotranspiration, and recharge, respectively. The averages show a relatively linear response in model calculated totals for each land use scenario. The 2035 forecasted land use scenario, while increasing overall urban area and area of impervious surface, changes the distribution of urban area in some HRU's. This explains the departure from the trends in some months.

7. CONCLUSIONS

This study shows that the USGS Precipitation and Runoff Modeling System (PRMS) is suitable for estimating the impact of urbanization on groundwater recharge. Focusing on the PRMS output variables for runoff, evapotranspiration, and recharge accounted for over 98 percent of precipitation inputs. The application of Ikonos high-resolution imagery derived values for impervious surfaces in different types of urban area resulted in an average conversion factor of 0.36 for the Root River watershed. Applying this value to the SERPC land-use data provided a reasonable estimate for the PRMS input parameter "hru_perc_imperv".

The data produced by the modeling simulations in this study provided estimates for the distribution of precipitation into three bins: runoff, evapotranspiration, and recharge. The data demonstrated that evapotranspiration was the dominant force in the Root River watershed, accounting for an average of approximately 65 percent of the total annual precipitation, followed by runoff at approximately 19 percent and recharge at approximately 16 percent. The impacts of increased urban area and impervious surfaces were most pronounced on model calculated evapotranspiration and runoff. Recharge increased by approximately 0.2 percent as a total of annual precipitation with increased impervious surface area.

The increase in model calculated recharge was counter to the original hypothesis that increasing impervious area would decrease recharge. This was mainly caused by the routing of surface runoff to retention ponds and allowing it to contribute to recharge while in storage effectively bypasses a large portion of precipitation that can be lost to evapotranspiration. The USEPA considers the use of runoff retention features, such as retention ponds, to be a best management practice (BMP). Existing or historic urban areas have little room for the construction and implementation of retention ponds. Newly constructed urban areas are more likely to include runoff retention features as part of the overall design, leading to a predicted increase in the percentage of impervious surface runoff captured and allowed to infiltrate to become recharge.

While the increase in model calculated recharge with increases in urbanization are modest, approximately 0.1 inches per year on average for the Root River watershed, this result is import for urban planning. This study did not incorporate other anthropogenic impacts on groundwater recharge. Impacts such as water distribution network leaks, sanitary sewer network leaks, irrigation, and roof systems that retain precipitation, also have the potential to increase groundwater recharge. Furthermore, implementation of other stormwater BMPs such as bioswales and pervious paving techniques can further allocate precipitation that might have been evapotranspirated to groundwater.

This result is also important with respect to climate change. Climate change is expected to result in lengthening of the growing season and increases in extreme precipitation events. If this is true, these elements would be expected to compound the results of this study. Increases in precipitation received as snow will be managed differently than snow falling on a non-urban land surface. The use of road-salt to melt snow, allowing it to infiltrate through cracks in paved surfaces, and the piling of snow in parking lots, also have the potential to change the amount of precipitation that becomes groundwater. Further studies that focus on the impacts of forecasted climate change and, on a smaller scale, anthropogenic inputs to the groundwater system are warranted.

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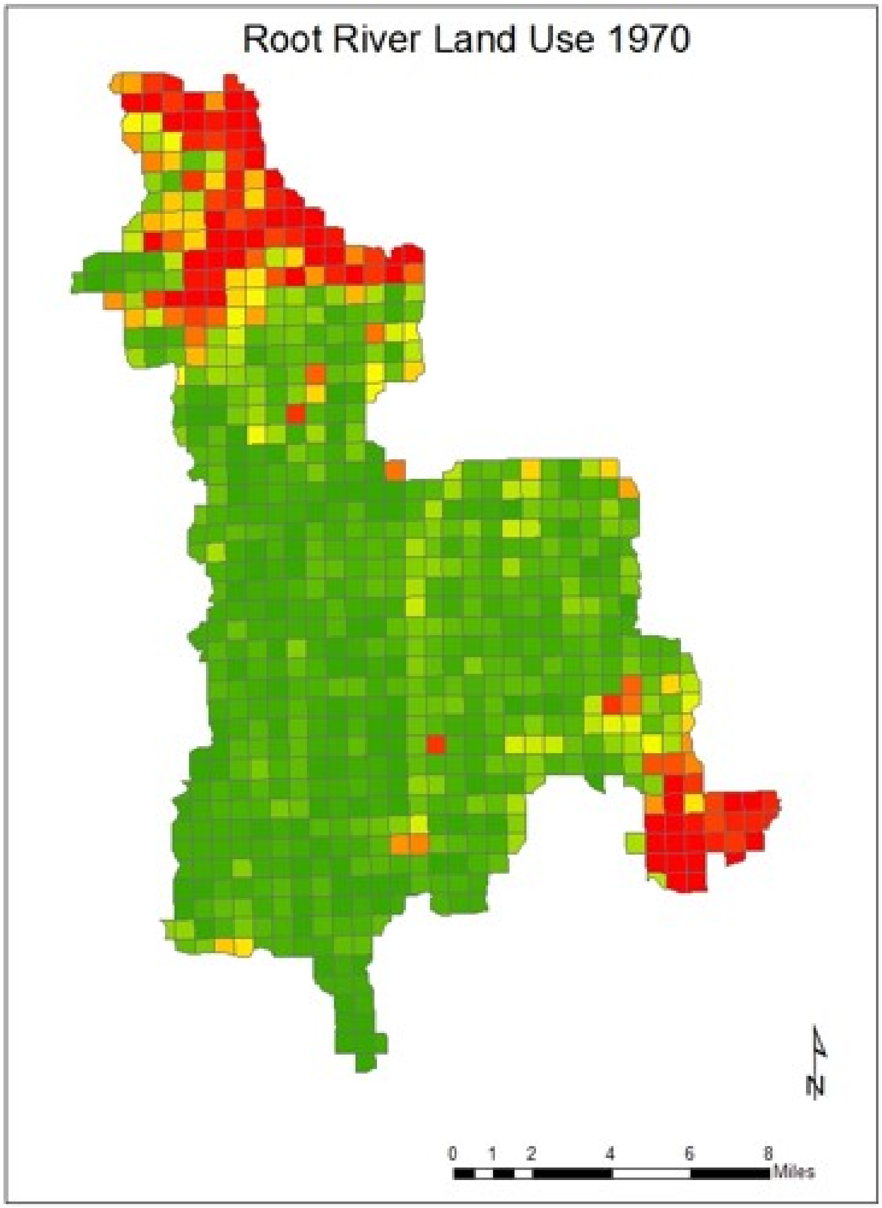
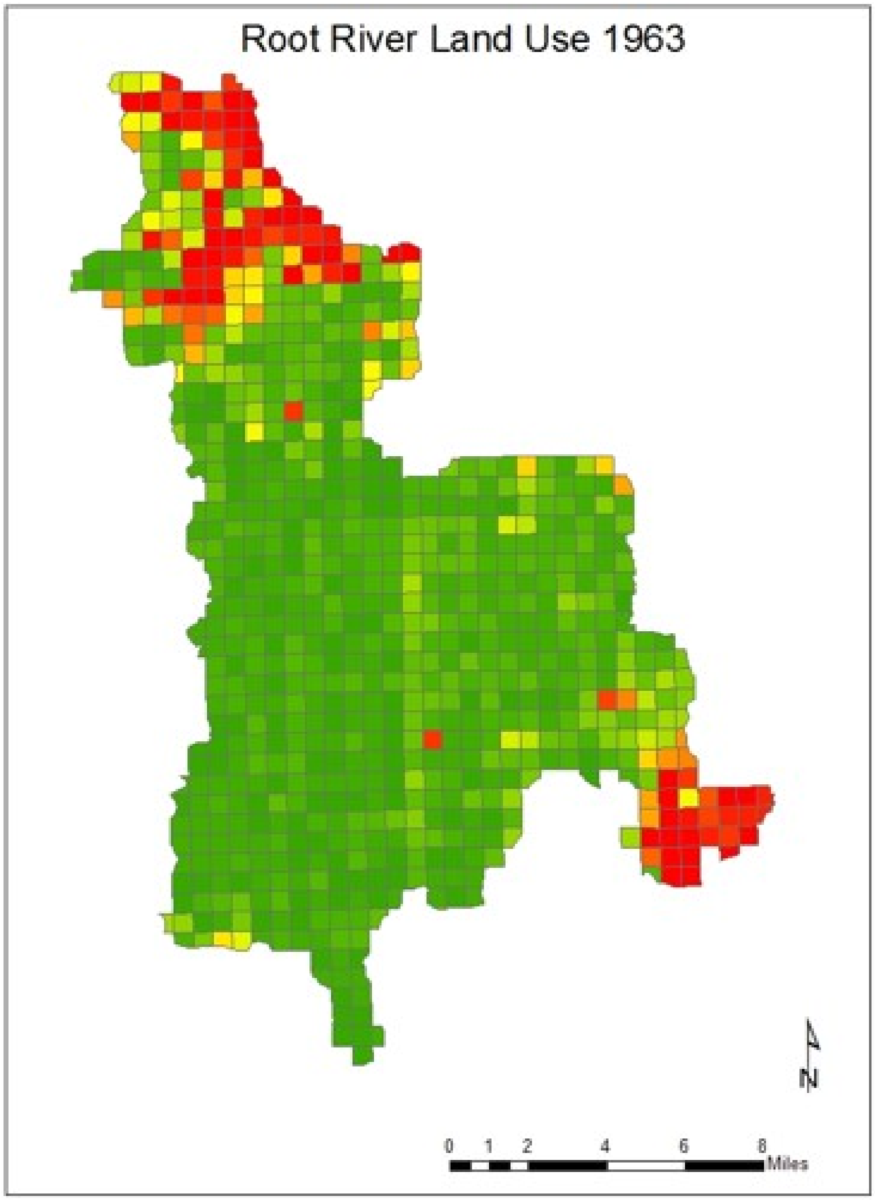
APPENDIX A:

Land Use Maps

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N
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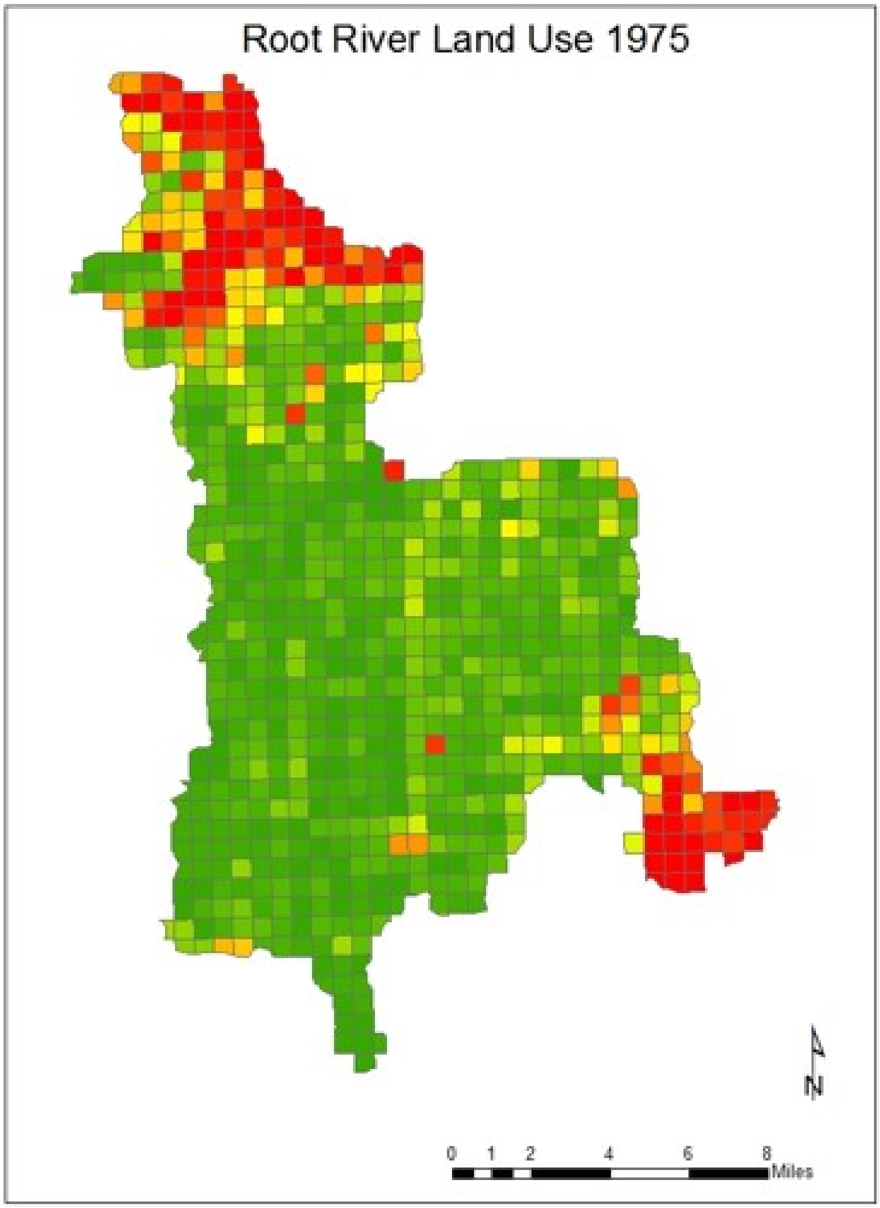
Miles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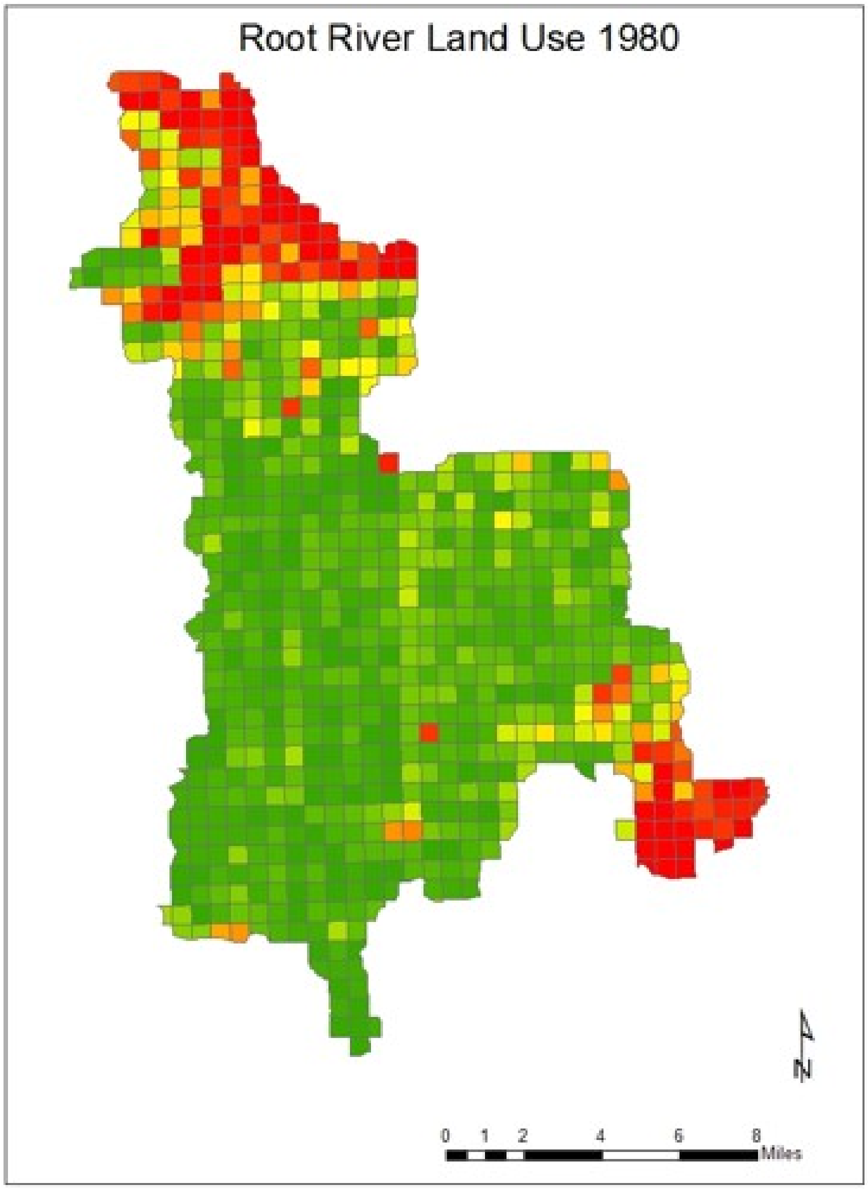
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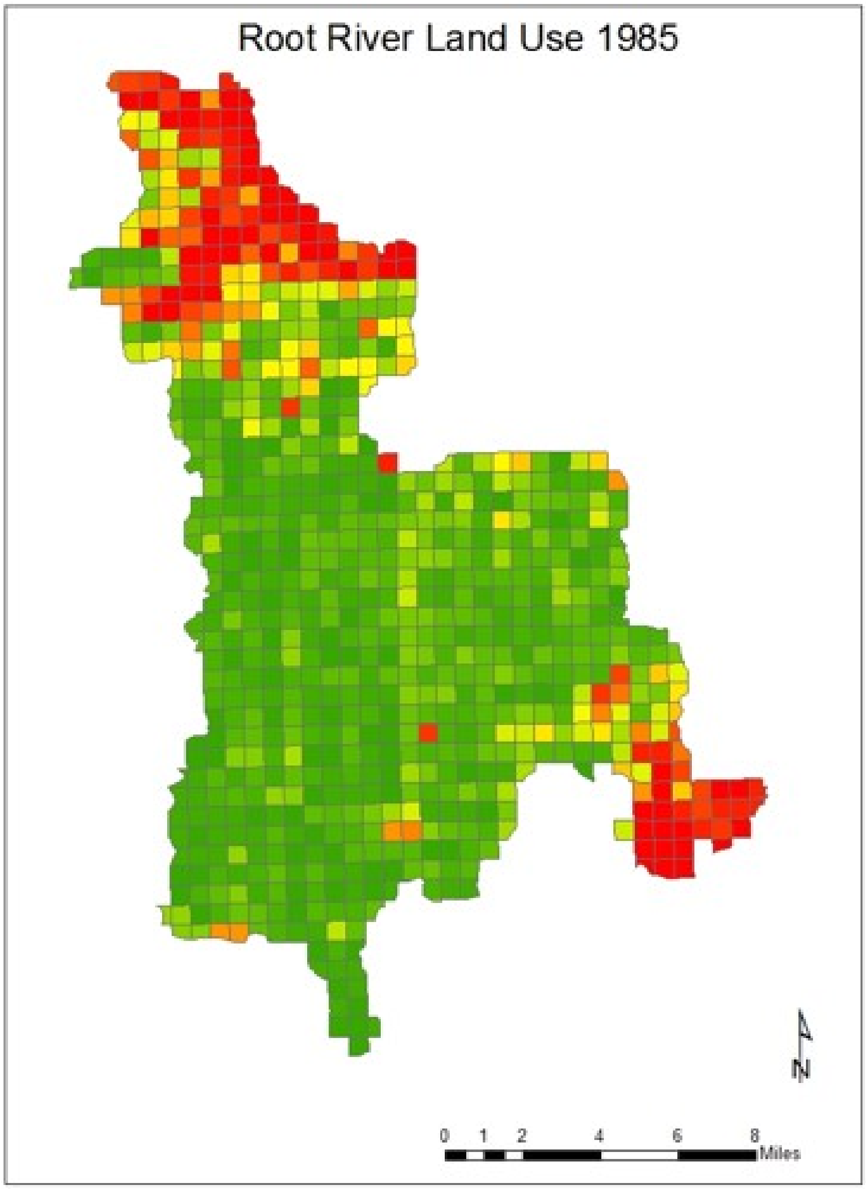
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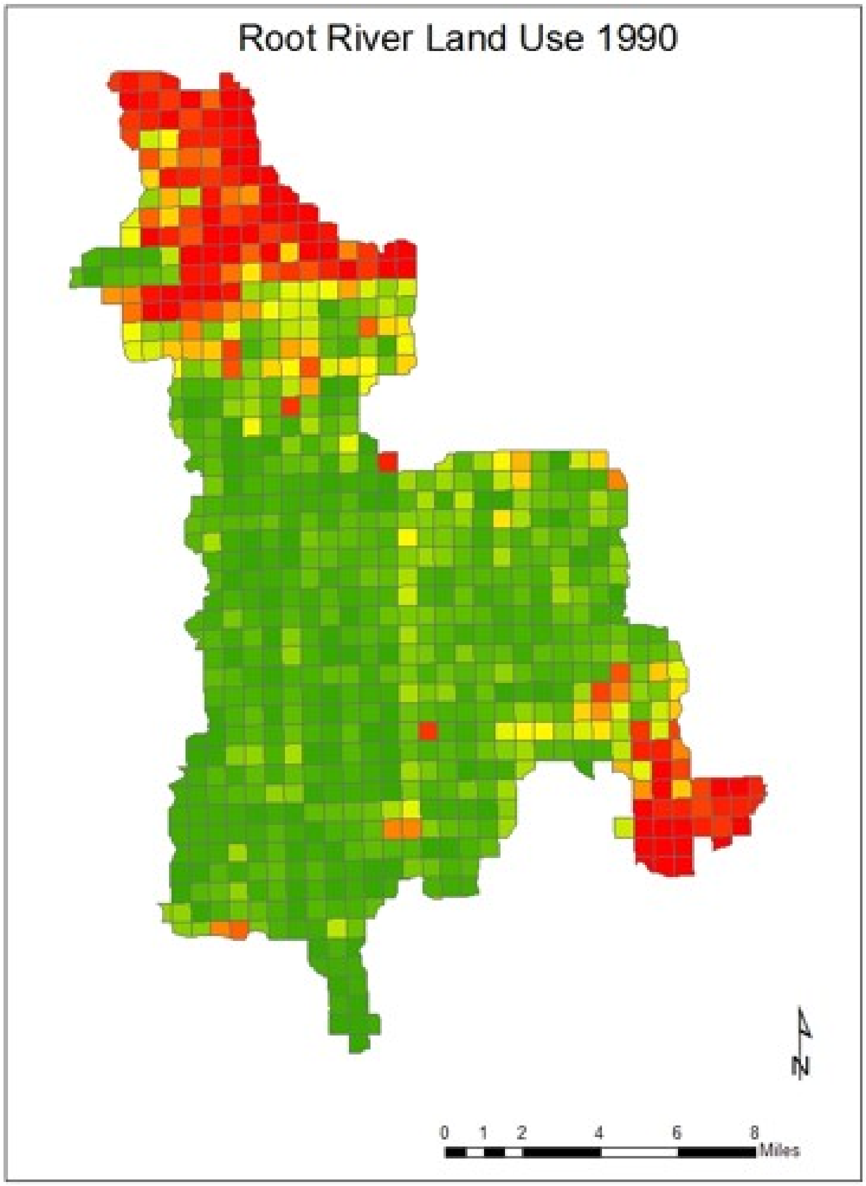
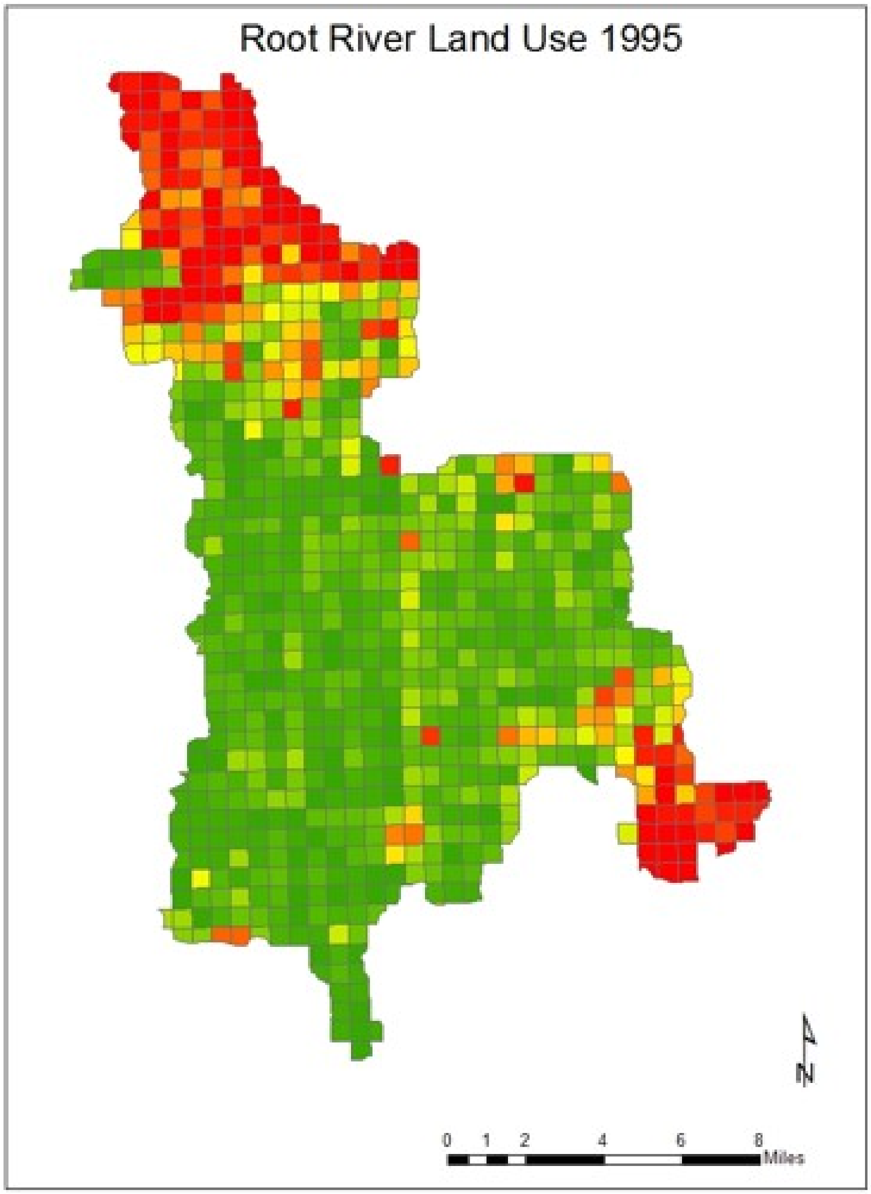
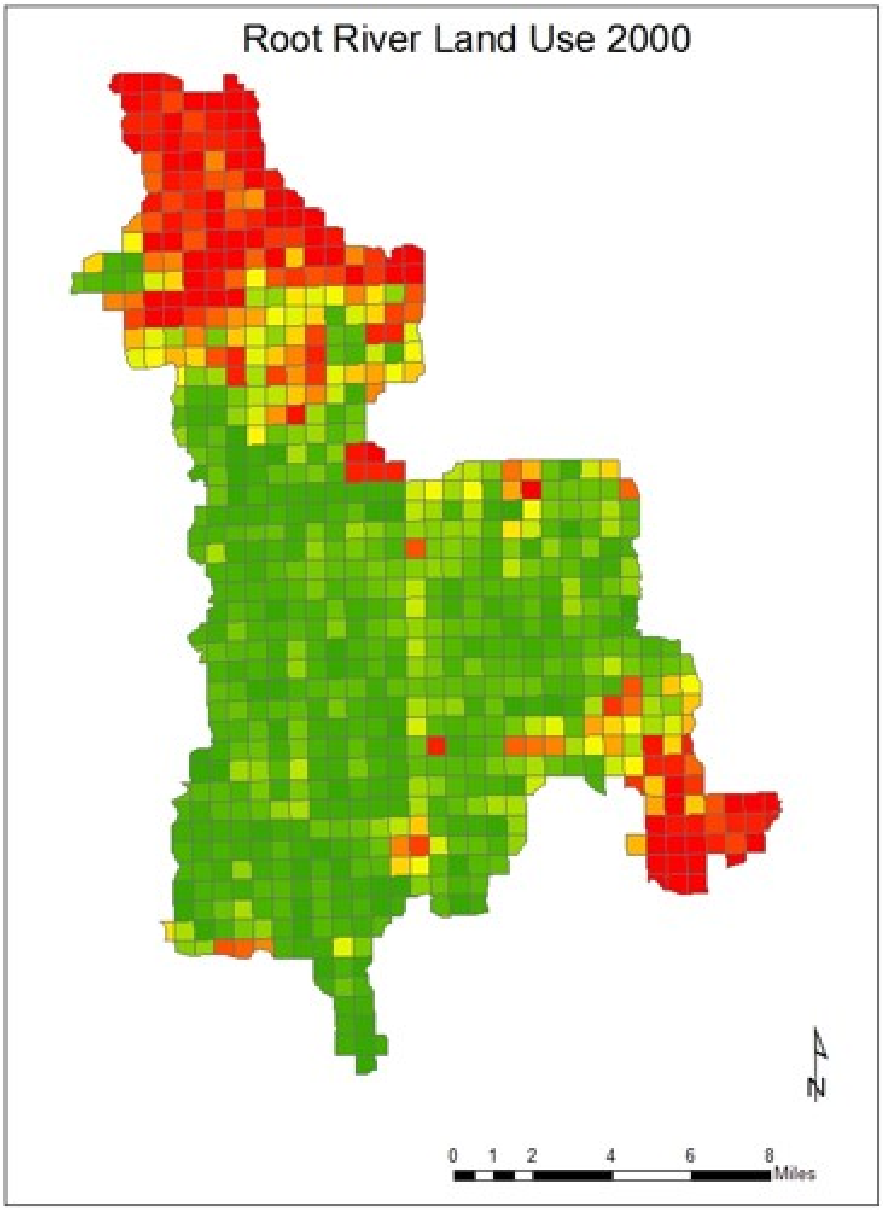
Miles


Root River Land Use 1990
N
0 1 2 4 6 8
Miles


Root River Land Use 1995
N
0 1 2 4 6 8
Miles


Root River Land Use 2000
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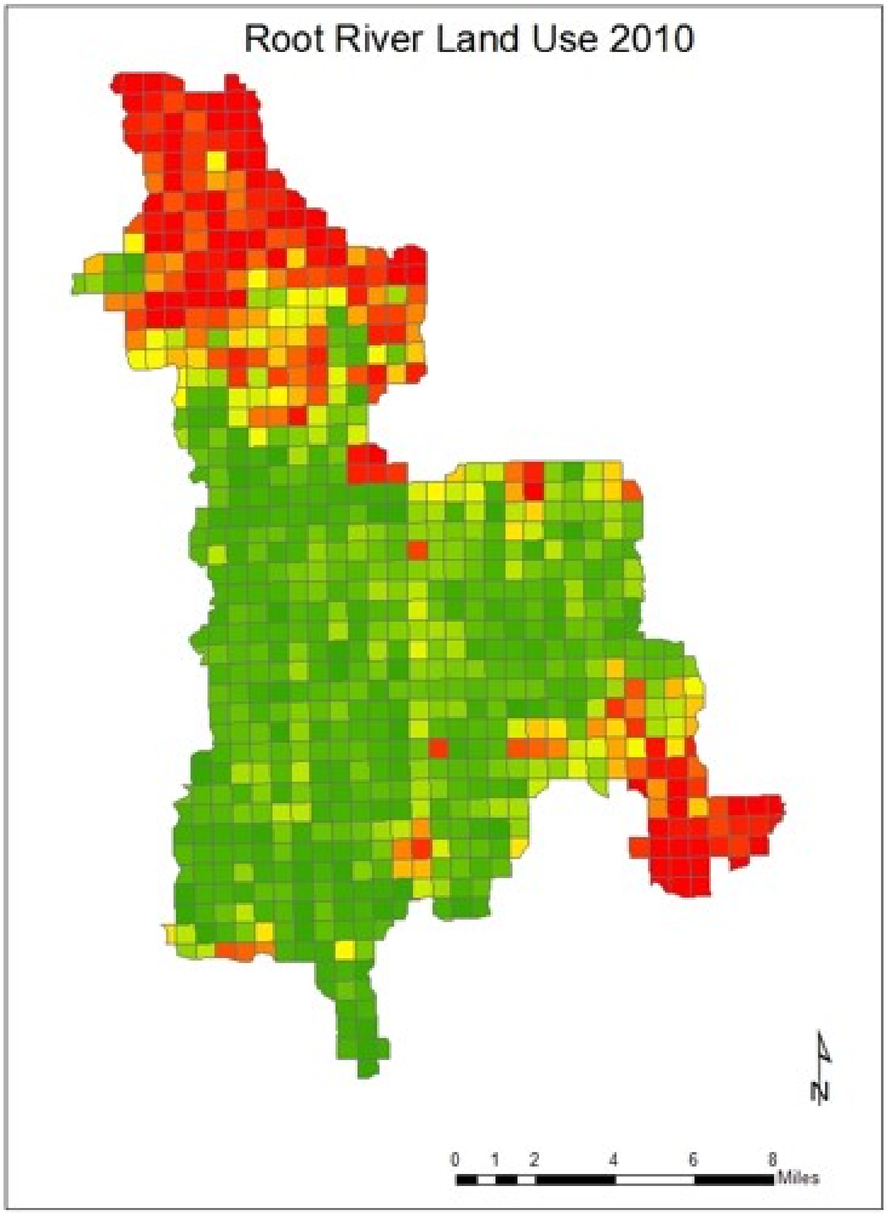
Miles


Root River Land Use 2010
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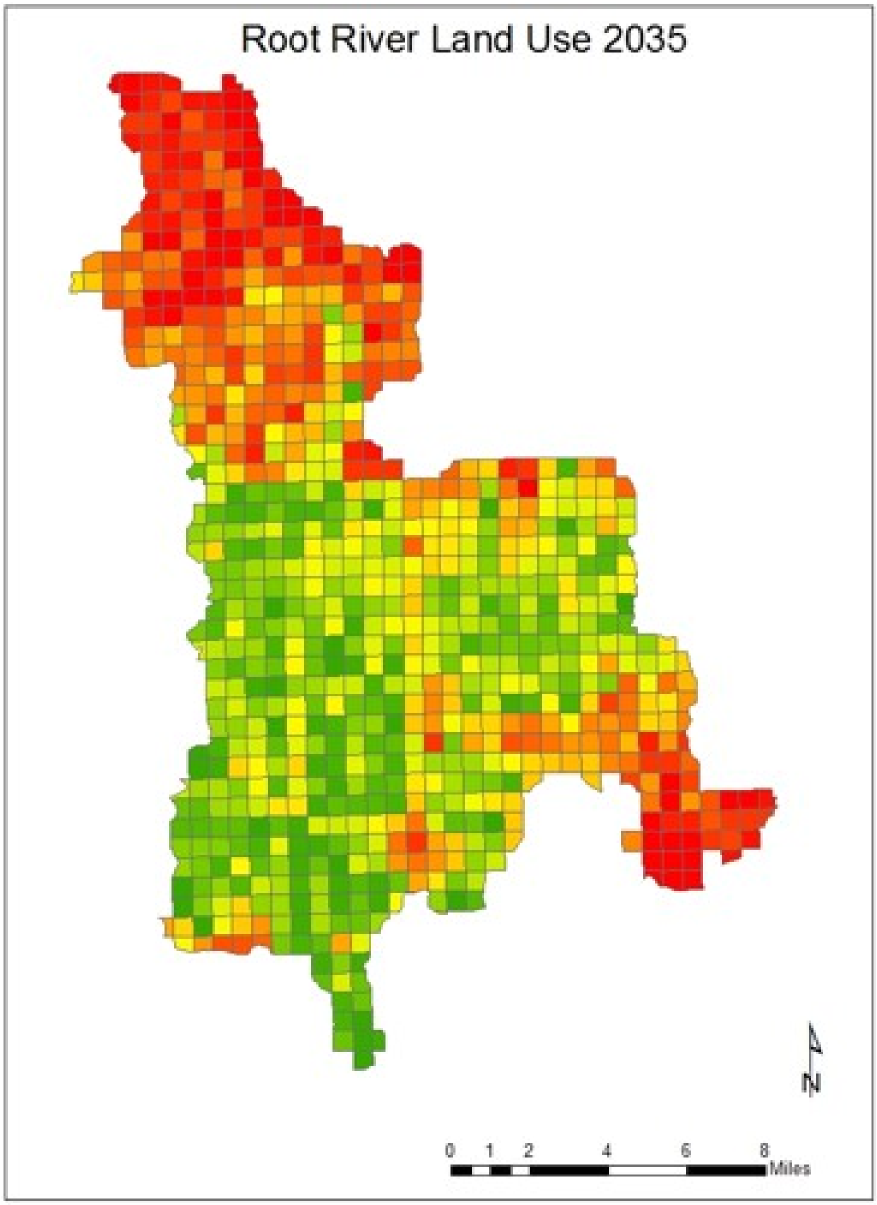
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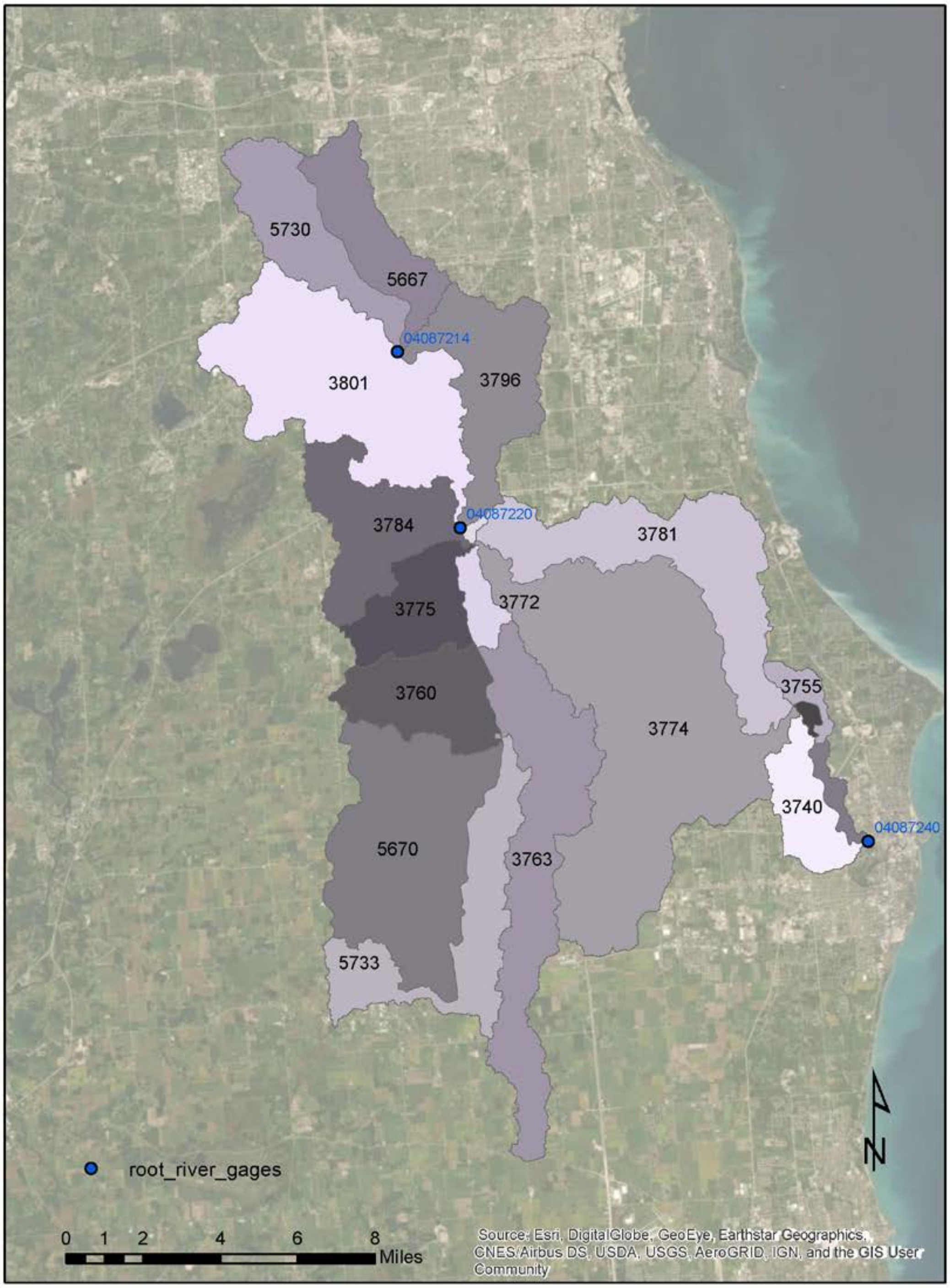
Miles

APPENDIX B:

Root River HRUs



APPENDIX C:

Sample Control File to run PRMS

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PRMS_IV

####

dprst_flag

1

1

1

####

aniOutON_OFF

1

1

0

####

aniOutVar_names

2

4

swrad

potet

####

ani_output_file

1

4
```

./output/animation.out

####

capillary_module

1

4

soilzone

####

data_file

1

4

./input/data

####

dispGraphsBuffSize

1

1

1

####

dispVar_element

6

4

9

1

7

2

6

3

####

dispVar_names

6

4

seg_outflow

runoff

seg_outflow

runoff

seg_outflow

runoff

####

dispVar_plot

6

1

1

1

2

2

3

3

####

end_time

```
6
1
2014
12
31
0
0
0
####
et_module
1
4
potet_jh
####
executable_desc
1
4
PRMS 4
####
executable_model
1
4
../../bin/prmsNHM
####
```

gravity_module

1

4

soilzone

####

init_vars_from_file

1

1

0

####

initial_deltat

1

2

24

####

model_mode

1

4

DAILY

####

model_output_file

1

4

./output/model.out

####

naniOutVars

1

1

2

####

ndispGraphs

1

1

3

####

nstatVars

1

1

4

####

param_file

1

4

./input/params

####

precip_module

1

4

climate_hru

####

save_vars_to_file

1

1

0

####

solrad_module

1

4

ddsolrad

####

soltab_module

1

4

soltab

####

srunoff_module

1

4

srunoff_smidx

####

start_time

6

1

1980

1

1

0

0

0

####

statVar_element

4

4

1

1

1

1

####

statVar_names

4

4

basin_cfs

basin_potet

orad

runoff

####

stat_var_file

1

4

./output/statvar

####

statsON_OFF

1

1

1

####

stats_output_file

1

4

./output/stats.out

####

strmflow_module

1

4

strmflow_in_out

####

summary_module

1

4

basin_sum

####

temp_module

1

4

climate_hru

####

tmax_day

1

4

./input/daymet_tmax_1980_2014.cbh

####

tmin_day

1

4

./input/daymet_tmin_1980_2014.cbh

####

precip_day

1

4

./input/daymet_prcp_1980_2014.cbh

####

var_init_file

1

4

init_vars

####

var_save_file

1

4

save_vars

####

csv_output_file

1

4

.\output\prms_summary.csv

####

csvON_OFF

1

1

1

####

print_debug

1

1

0

####

parameter_check_flag

1

1

0

####

cbh_check_flag

1

1

0