Evaluating the influence of land cover on seasonal water budgets using Next Generation Radar (NEXRAD) rainfall and streamflow data

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1. Introduction

Understanding and evaluating water budgets in small to regional watersheds is critical for a range of resource management decisions. Water fluxes between different components of the hydrosphere change over a range of spatial and temporal scales due to variations in climatic conditions and landscape characteristics. Surface hydrological properties and processes such as soil moisture, runoff, and evapotranspiration are heavily influenced by land use and land cover characteristics, which we will refer to as land cover for simplicity. In addition, human activities and the accompanied land cover changes have the potential to significantly alter the local hydrology and cause long-term environmental changes [Dow and DeWalle, 2000; Walker et al., 2002; Costa and Foley, 2000; Pielke et al., 1998]. Despite this potential, our understanding of the interactions between land cover and hydrology has been limited by inaccurate data collection and integration at regional scales.

Runoff, evapotranspiration (ET), groundwater recharge, and changes in aquifer storage due to groundwater outflows and pumping are the main processes that redistribute precipitation in hydrologic systems in addition to snowmelt in colder regions. While runoff and aquifer storage can often be evaluated with a reasonable degree of accuracy, the most important components for watershed management, ET and groundwater recharge, are difficult to quantify. Commonly used methods including hydrograph separation, groundwater budget analysis, and tracer analysis coupled with groundwater models can be used to estimate recharge rates at various spatial scales [Scanlon et al., 2002]. However, large data requirements and other limitations have made it difficult for watershed managers and other decision makers to develop accurate estimates using such methods. Partly in response to these limitations, relatively simpler techniques using water balance models and Geographic Information Systems (GIS) have recently been introduced [e.g., Cherkauer and Ansari, 2005; Szilagyi et al., 2004]. Nevertheless, most such approaches do not describe the impact of land cover on watershed hydrology and groundwater recharge at short timescales. In regions such as Michigan, with distinct seasonal changes in land cover (vegetation) and spatially diverse land use practices, vegetation dynamics are a key component of any hydrologic analysis.

This paper examines the influence of land cover attributes on hydrologic fluxes at watershed scales on a seasonal basis. We use commonly available data sources to...
obtain watershed attributes and flux budgets for 40 watersheds, and we statistically link the flux budget characteristics with the watershed attributes. Since evapotranspiration (ET) is a key component of the water budget during the growing season and it is directly related to land cover characteristics [Mo et al., 2004; Finch, 1998], we also compare the streamflow and groundwater recharge differences of high-intensity and moderate-intensity agricultural systems. This analysis provides insight into the potential impacts of land use decisions on watershed hydrology.

2. Approach

[5] Seasonal analysis of the ratio between total water input ( precipitation) and outflows (streamflow and its components; overland flow and base flow) to a watershed during specified time intervals can provide insight into the mechanisms that redistribute moisture (e.g., runoff, recharge, ET). We evaluated correlations between streamflow:rainfall ratios and watershed characteristics (e.g., land cover, geologic materials, and soils) to help understand how these attributes influence hydrologic processes at watershed scales. We calculated the streamflow:rainfall ratios over the approximate peak growing season for 40 different watersheds using hourly Next Generation Radar (NEXRAD) precipitation data from the National Weather Service (NWS) and streamflow from U.S. Geological Survey (USGS) daily records. Prior to this analysis, the accuracy of NEXRAD data was evaluated by comparing it to observations from ground-based gauges, as described in more detail below in section 4.

[6] The July–September period was chosen for the water budget calculations both to minimize the effects of snowmelt recharge on the analysis and to capture the influence of vegetation on watershed hydrology. This period corresponds to both the low streamflow period based on USGS records and the peak growing season of the region based on mean leaf area index (LAI, one-sided green leaf area or projected needleleaf area per unit ground area). The LAI values for the region were obtained from the 1-km Moderate Resolution Imaging Spectroradiometer (MODIS) 8 day composite data product (version 4) from the National Aeronautic and Space Administration (NASA). We used the MODIS Reprojection Tool [USGS, 2004] to convert MODIS data in hierarchical data format (HDF) into Georeferenced Tag Image File Format (GEOTIFF) and ESRI grids. The spatial analyst extension and zonal statistics tools in ESRI ArcGIS software were used to extract mean LAI values for watersheds by overlaying a watershed boundary coverage on the LAI grids in ESRI ArcMap (version 9.1).

[7] The spatially averaged NEXRAD precipitation values for each study watershed were calculated using the ArcMap zonal statistics tool on 100 m resampled NEXRAD grid cells within each watershed boundary. Daily, monthly, and longer-period precipitation estimates were subsequently derived from the hourly precipitation estimates. We automated the hourly precipitation extraction process using custom scripts (included in the auxiliary material1) written in Visual Basic for Applications (VBA) integrated with ESRI ArcGIS, which load and unload data from ArcMap, and calculate mean watershed precipitation amounts with zonal statistics tools. This significantly improved the efficiency of processing ~2000 individual NEXRAD grids for each of the 40 watersheds. Correction coefficients obtained from the regressions between July–September monthly NEXRAD and monthly gauged precipitation were used to adjust for the bias from NEXRAD data before utilizing it in mass balance analyses.

[8] Total monthly base flow and overland flow volumes were estimated from the daily mean streamflow records using the PART computer program [Rutledge, 1998], which estimates base flow from daily streamflow records based on antecedent streamflow recession. This approach assumes spatially diffused recharge to the water table, uniform aquifer thicknesses, uniform hydraulic conductivities and storage characteristics as well as minimal regulation and diversion of streamflow within the gauged watershed. Although these assumptions are essentially never met in real aquifer systems, this provides an objective tool to evaluate base flow. In addition, heterogeneities in soil properties tend to be at a much smaller scale than that of the watersheds we analyzed in this study, thus the localized impacts likely average out. Base flow estimates obtained with PART have been shown to be comparable to that obtained with various other manual methods [Rutledge, 1998]. Linear interpolation of base flows during times that do not fit the antecedent criteria used in PART would lead to base flow estimation errors. However, errors resulting from the linear interpolation have been shown to be minimal for monthly or longer timescales [Rutledge, 1998].

[9] Land cover percentages (croplands, forests, urban areas, wetlands, etc.) for watersheds were calculated based on the National Land Cover Dataset (NLCD) [USGS, 1999] and Anderson level I classes [Anderson et al., 1976]. The forest cover percentage for each watershed was obtained by aggregating the deciduous, evergreen and mixed forest classes in NLCD. Pasture/hay, row crops, and small grain classes were combined to obtain the total percentage of agricultural uses. Total urban land cover percentages were obtained by combining low-intensity residential, high-intensity residential, and commercial/industrial/transportation classes.

[10] The distribution of Quaternary geologic materials was obtained from a digital coverage of Farrant and Bell [1982] (data available at http://www.mcgi.state.mi.us/mgdl/), and were aggregated in to five broad classes (glacial tills, end moraine tills, outwash sand and gravel, lacustrine clay and silt, and lacustrine sand and gravel) for each watershed. On the basis of State Soil Geographic (STATSGO) database for Michigan (available at http://www.nccg.ncrc.usda.gov/products/data_sets/statsgo/data/index.html), we also categorized the watershed soils into three different drainage classes that were expected to influence streamflow characteristics in the study region (extremely to somewhat extremely well drained, well to moderately well drained, and poorly to very poorly drained). Statistical correlations between watershed attributes (land cover, Quaternary geology, soil drainability, and watershed morphology) and the average 2002–2004 volume ratios (streamflow:rainfall, overland flow:rainfall, and base flow:rainfall) were evaluated using nonparametric Spearman’s correlations. The Kruskal-Wallis (nonparametric) test along with the chi-

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1Auxiliary material data sets are available at ftp://ftp.agu.org/apend/wr/2005wr004460. Other auxiliary material files are in the HTML.
square approximation for its two sided p value was used to compare base flow and recharge differences in high-intensity (>70%) and moderate-intensity (<50%) agricultural watersheds. Two sided p values at level 0.05 were used to test statistical significance. Nonparametric statistical methods were used in this study to minimize the effects of assumptions associated with parametric correlation methods. We also used stepwise multiple regressions and standard least squares fits as exploratory methods to evaluate variability of streamflow:rainfall and base flow:rainfall ratios between watersheds, and to explain the variability of the ratios in terms of land cover and other watershed attributes.

3. Study Sites

[11] Forty Michigan watersheds with drainage areas ranging from ~20 km² to ~1000 km² with an average of 312 km² (USGS station IDs and names are provided in the auxiliary material) were chosen that span a range of land cover characteristics and have sufficient data for our analysis (Figure 1). The primary land cover types in the selected watersheds are agriculture, forests, and urban, followed by the minor proportions of wetlands, grasslands, and open water. The percentage of agricultural land in the study watersheds ranges from about 6 to 85%, with a mean of 51%. Corn, beans, and alfalfa are the main crops cultivated in the state, which have growing seasons ranging from late April/early May to about mid-November. The percentage of forest cover in the study watershed ranges from about 8 to 55, with a mean of 26%; and nearly all of the forests in our study watersheds are deciduous. The amount of urban area in the study watersheds ranges from nearly 0 to 70%, with a mean of 11%. Urban and suburban land covers are more common in the southeastern part of the state with most of the forest land in the northwestern regions of Michigan’s Lower (or southern) Peninsula.

[12] Quaternary glacial advances and retreats shaped the regional geology of Michigan. The surficial deposits of the state are mostly glacial outwash and till deposited during the Pleistocene continental glaciation. Glacial outwash deposits are more abundant in the north/northwestern and southwestern portions of Michigan’s Lower Peninsula, while till deposits are prominent in the central and eastern half of the Lower Peninsula, extending from the Saginaw Bay area to the Ohio border. Lacustrine clays are common in the Saginaw Bay area and along the eastern fringe of the southern half of the state where artificial irrigation management practices, such as tile drains, are common. 78% of our study watersheds had less than 10% clay and only 17% had more than 20% clay.

4. Evaluation of NEXRAD Rainfall Data

[13] Starting in 1980, the National Weather Service (NWS) established the nationwide NEXRAD network of Doppler radar stations (Weather Surveillance Radar (WSR) –1988 Doppler (88D)). There are approximately 158 operational WSR-88D stations throughout the US, with some overseas locations. Information from these radar stations is commonly used to issue warnings of severe weather and flash floods to the public, and provide information for air traffic safety, water management, and outdoor activities.

[14] The detailed spatial and temporal coverage of NEXRAD data makes it a useful input to hydrologic models and provides an invaluable resource where ground-based rain gauges are scarce. The Army Corps of Engineers, U.S. Department of Agriculture, and National Weather Service all use radar data in hydrologic models. Within the research community, radar rainfall data have mainly been used to simulate streamflow response to storm events. Some examples include Neary et al. [2004], who used radar rainfall data to derive basin averaged hourly precipitation to simulate streamflow using a HEC-HMS model. Di Luzio and Arnold [2004] used the NEXRAD hourly grids in Soil and Water Assessment Tool (SWAT) model to predict hourly streamflow in response to storm events. In a similar manner, Carpenter et al. [2001] used NEXRAD precipitation data in a spatially distributed hydrologic model to simulate runoff and streamflow to evaluate the use of distributed hydrologic models in an operational environment. In this study, we are mainly interested in quantifying the influence of watershed characteristics on water balances, which could not be accurately evaluated based on ground-based gauges alone due to the general sparse nature of the rain gauge networks. We overcame this obstacle by calculating basin-averaged hourly precipitation rates from NEXRAD grids, which were then summed into monthly and growing season volumes for each study watershed.

[15] The primary radar rainfall product from the WSR-88D, called the Digital Precipitation Array (DPA), is generated by processing the radar information using a
Precipitation Processing System (PPS). The PPS is a set of algorithms that use information from two external functions for precipitation detection (effective within a 230 km radius from the radar station) and rain gauge data acquisition, and five internal functions for data preprocessing, radar to rainfall rate conversions, rainfall accumulation calculations, gauge-radar adjustments, and product generation [Fulton et al., 1998]. The hourly precipitation products used in this study have a 4 km spatial resolution and are generated from base Doppler radar data (reflectivity, mean radial doppler velocity and spectrum width) using the PPS.

There are several sources of systematic and random error associated with radar rainfall estimates [Seo et al., 1999]. The uncertainties in reflectivity (the quantity measured by the radar) to rainfall conversion, which is highly nonlinear, is recognized as one of the main sources of error [Neary et al., 2004]. Differences in radar instrument calibration from station to station, distance from radar stations or the range effect [Sharif et al. 2002], radar scan angles, local topography [Young et al., 1999], and climate conditions [Smith et al., 1996] can all cause significant error in radar rainfall estimates. We evaluated the accuracy of NEXRAD data calculated on the basis of the three WSR-88D weather radar stations in Michigan (Figure 1) relative to point observations of precipitation at NWS and other independent stations at daily and monthly timescales. This involved comparing 4 km spatial rainfall grids provided by the Michigan State University Geography Department to point rainfall data for 28 locations in Michigan’s Lower Peninsula with sufficient data from April to November of 2002–2004 (Figure 1). Root-mean-square differences (RMSD) between radar and direct measurements were computed for the radar and gauge pairs. We also assessed temporal variations in NEXRAD errors over monthly and growing season timescales.

Comparison of NEXRAD and ground-based precipitation data from May–November indicate that August has the largest monthly RMSD in the 2002 and 2003 data sets (Figure 2). This is mainly due to relatively large differences between NEXRAD and ground-based precipitation at a few gauge locations: Detroit, Bellaire, Grayling, and Ypsilanti in 2003; and Detroit, Bellaire, Grand Haven, Muskegon, and Howell in 2002. Nearly all of the monthly RMS differences remained below 25 mm throughout each of these growing seasons.

The largest percent absolute difference (calculated relative to gauged precipitation) between the radar estimated and gauged rainfall within the study region for the 2004 growing season (May–November) was 13% at the Grand Haven gauge location (Figure 3). This amounts to a 50 mm difference between the radar and gauge systems for the entire growing season. The largest absolute differences were concentrated in the northwestern corner of Michigan’s Lower Peninsula, where the highest errors ranged from about 25% to 38% in 2002 at five locations (North Port, Traverse City, Cadillac, Kalkaska, and Houghton). All watersheds from the northwestern region were thus excluded from this study. The lower absolute differences in the southern half of the state are partially due to the use of at least some of Grand Rapids, Lansing and Flint station data by the WSR-88D system for real-time corrections of the precipitation predictions. At most locations, NEXRAD estimates tend to be smaller than the precipitation recorded by the ground-based gauges.

Although most of the discrepancy between observed and NEXRAD precipitation is likely due to errors in radar estimates, some of the differences can also be attributed to

![Figure 2](image1.png)

**Figure 2.** RMS differences between NEXRAD and ground-based precipitation measurements at various sites with data spanning the 2002, 2003, and 2004 growing seasons.

![Figure 3](image2.png)

**Figure 3.** Map of the percent absolute differences (calculated relative to observed gauged precipitation) between the 2004 (April–November) gauge and NEXRAD rainfall data. The Grand Rapids, Lansing, Flint, and Alpena gauges are known to be used by the WSR-88D system for real-time calibration of radar rainfall estimates (Ann Arbor and Grayling are missing 1 month of data, Harbor Beach is missing 2 months, and Montague is missing 3 months, and thus these months were not used in this analysis).
inaccuracies in the ground-based precipitation observations. Mechanical failures associated with tipping bucket gauges often give rise to random errors, and the aerodynamic design of the gauges frequently result in systematic error in rainfall measurements [Sevruk, 1996; Heinemann et al., 2002]. Habib et al. [2001] have shown that sampling frequency, bucket size and precipitation characteristics also contribute to errors in tipping bucket rainfall data. Errors in ground-based observations discussed here would generally result in an under estimation of actual rainfall, particularly during heavy precipitation events. These errors contribute to a larger RMSD and would count the same as radar overestimates.

The accuracy of the NEXRAD estimates relative to ground-based observations for the eight gauges across the region with continuous precipitation records from 2002 to 2004 is shown in Figure 4 (see Figure 1 for locations). On the basis of this analysis, there does not appear to be any significant spatial trend in NEXRAD precipitation estimates except for the already mentioned larger error to the northwest corner of the Lower Peninsula. The Muskegon gauge was the only location that showed consistently higher RMSD values throughout the analysis period. In general there seems to be relatively higher variability at all gauge locations beginning in May and continuing through August. This may be due to intense precipitation events associated with convective weather systems that are relatively common during this period. Under such conditions, both ground-based gauges [Heinemann et al., 2002] and radar systems [Krajewski and Smith, 2002] are known to be less accurate, which contributes to the relatively large RMSD during such periods.

As is commonly the case, the total radar rainfall estimates for the evaluation period are generally lower than the ground-based precipitation recorded during the same period at the gauge stations. A limited evaluation of event scale data (hourly NEXRAD versus observed precipitation) showed that radar system performed poorly during very small precipitation events. However, only a small percentage of the differences in monthly precipitation totals between radar and gauge data in Michigan can be attributed to such small events. Another source of error is the comparison of precipitation derived from relatively large NEXRAD grid cells (4 km × 4 km) with point gauges. Event-scale NEXRAD data were not directly compared with ground-based gauge data in this study because of difficulty in obtaining hourly precipitation data for a sufficient number of ground-based gauges. The 2004 data show the highest degree of correlation between monthly gauge and NEXRAD rainfall from July to September, our main study period for water budget evaluations (Figure 5), while 2002 and 2003 also had reasonable correlations to gauged data. Data from the 2002 to 2004 period were used for water budget calculations in this study after adjusting for the bias in NEXRAD precipitation using correction coefficients shown in Figure 5.

5. Results and Discussion

A significant decrease in the July September streamflow:rainfall ratio was observed with increasing agricultural land cover above about 60% in all years (Figure 6). This
relationship has a smaller correlation in watersheds with lower-intensity agricultural land uses, likely due to the heterogeneity in land cover and morphological attributes that are characteristic of the lower-intensity agricultural systems, but it is still statistically significant across our 40 watershed sample according to the nonparametric correlation coefficients with a p value of $2.0 \times 10^{-4}$ (Table 1). Comparatively, high-intensity agricultural systems tend to be relatively homogeneous with respect to vegetation and morphology. An additional factor that could contribute to the low streamflow:rainfall ratio in intensively agricultural systems in some environments is the presence of tiled drains. However, such engineered drainage systems mainly exist in areas with significant proportion of clay rich soils. Only three watersheds with >30% clay rich soils were included in this analysis (circled on Figure 6), and two of these three have lower streamflow:rainfall ratios than other watersheds with similar agriculture percentages (Figure 6).

[23] An expected significant increase of overland flow in watersheds with urban land cover percentage is also evident from the correlation statistics (Table 1), even in this case where only 20% of the watersheds in this study had more than 10% urban land cover. A positive correlation was also observed between base flow:rainfall ratios in forested watersheds. The small p values (<0.05) in Table 2 indicate that the correlations between these land cover attributes and volume ratios in the analyzed watersheds are unlikely to be random. Other factors that show significant relationships with the volume ratios are the distribution of certain surficial glacial geologic materials and soil drainability classes. The amount of base flow is positively correlated with both the percent glacial outwash sand and gravel deposits and the extremely to somewhat extremely well drained soils, yet there was no statistically significant correlation between soil drainability and outwash deposits. Glacial outwash deposits were present in 90% of the investigated watersheds with varying degrees of abundances. Positive correlations also exist between glacial outwash deposits and forest cover percentages in the study watersheds, and between agricultural land uses and both poorly drained and low slope areas (Table 2).

[24] Seventy-three percent of the variability in the streamflow:rainfall ratio was explained by three watershed attributes (percentages of agriculture, open water, and glacial outwash sand and gravel) using a multiple linear regression analysis (Table 3). The proportion of agricultural land cover is the most significant attribute among the pool of watershed variables used for the exploratory multiple regression analysis. Poorly drained soils failed to explain a significant portion of the variability observed with streamflow:rainfall ratio, indicating that low streamflow conditions in watersheds with high-intensity agriculture is more likely related to the land use and cover attributes, rather than simply the soils. A negative coefficient for open water (lakes, ponds, wetlands etc.) indicates that these areas are associated with reductions in streamflow, which is likely associated with direct evaporation from open water surfaces. In a similar manner as the streamflow:rainfall ratio, 75% of the variability associated with base flow:rainfall ratio in the study watersheds was explained by four watershed attributes (Table 3). Agriculture, open water, and glacial outwash sand and gravel explained most of the variability in

### Table 1. Spearman’s Ranked Correlation Statistics for Mean July to September (2002–2004) Volume Ratios and Other Watershed Variables for the 40 Selected Watersheds

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spearman Rho p Value</td>
<td>Spearman Rho p Value</td>
<td>Spearman Rho p Value</td>
</tr>
<tr>
<td>Urban</td>
<td>0.28  7.7E-02(^a)</td>
<td>0.37  1.8E-02</td>
<td>0.04  8.0E-01</td>
</tr>
<tr>
<td>Forest</td>
<td>0.27  9.3E-02</td>
<td>-0.04  8.3E-01</td>
<td>0.44  4.5E-03</td>
</tr>
<tr>
<td>All agriculture</td>
<td>-0.56  2.0E-04</td>
<td>-0.46  2.9E-03</td>
<td>-0.38  1.6E-02</td>
</tr>
<tr>
<td>Agriculture&gt;60%</td>
<td>-0.86  1.8E-05</td>
<td>-0.29  2.8E-01</td>
<td>-0.83  6.3E-05</td>
</tr>
<tr>
<td>Extreme/somewhat extremely well drained soils</td>
<td>0.29  7.1E-02</td>
<td>-0.06  6.9E-01</td>
<td>0.44  4.7E-03</td>
</tr>
<tr>
<td>Outwash sand/gravel</td>
<td>0.22  1.6E-01</td>
<td>-0.07  6.5E-01</td>
<td>0.43  5.5E-03</td>
</tr>
<tr>
<td>Mean slope</td>
<td>0.18  2.5E-01</td>
<td>0.03  8.7E-01</td>
<td>0.31  5.4E-02</td>
</tr>
</tbody>
</table>

\(^a\)Statistically significance (p < 0.05) is indicated by bold typeface.

### Table 2. Spearman’s Nonparametric Correlation Statistics for Land Cover and Other Watershed Variables for the 40 Selected Watersheds

<table>
<thead>
<tr>
<th></th>
<th>Forest Percentage</th>
<th>Agriculture Percentage</th>
<th>Urban Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spearman Rho p Value</td>
<td>Spearman Rho p Value</td>
<td>Spearman Rho p Value</td>
</tr>
<tr>
<td>Mean slope</td>
<td>0.67  1.9E-06</td>
<td>-0.36  2.2E-02</td>
<td>-0.01  9.3E-01</td>
</tr>
<tr>
<td>Poorly drained soils</td>
<td>-0.34  3.2E-02</td>
<td>0.37  1.7E-02</td>
<td>-0.27  9.2E-02</td>
</tr>
<tr>
<td>Extreme/somewhat extremely well drained soils</td>
<td>0.43  6.2E-03</td>
<td>-0.03  8.7E-01</td>
<td>-0.25  1.2E-01</td>
</tr>
<tr>
<td>Well/moderately well drained soils</td>
<td>0.24  1.4E-01</td>
<td>-0.34  3.1E-02</td>
<td>0.30  5.9E-02</td>
</tr>
<tr>
<td>Glacial tills</td>
<td>-0.03  8.6E-01</td>
<td>0.29  6.8E-02</td>
<td>-0.31  4.9E-02</td>
</tr>
<tr>
<td>Outwash sand/gravel</td>
<td>0.47  2.3E-03</td>
<td>-0.22  1.8E-01</td>
<td>0.03  8.6E-01</td>
</tr>
<tr>
<td>Lacustrine clay/silt</td>
<td>-0.44  5.0E-03</td>
<td>0.03  8.3E-01</td>
<td>0.30  6.2E-02</td>
</tr>
</tbody>
</table>

\(^a\)Statistical significance is indicated by bold typeface.
base flow:rainfall ratio, followed by extremely to somewhat extremely well drained soils. One of the 40 watersheds was removed from the multiple regression analysis as an outlier due to unusually high streamflow conditions, likely related to urbanization effects since it was in the Detroit suburban area. Watersheds with high-intensity agriculture (>70%) tend to have lower base flows during the growing season than those with moderate-intensity (<50%) agriculture. Kruskal-Wallis tests had p values that indicate that April–June, July–September, and October–December base flow differences between high-intensity and moderate-intensity agricultural watersheds are statistically significant (Figure 7).

A considerable drop in base flow is evident during the peak growing season (July to September) in both classes of watersheds. However, the decline is relatively larger in watersheds with intense agriculture. Watersheds with over 10% high-intensity urban land uses (NLCD classifications “high-intensity residential” and “commercial/industrial/transportation”) were removed from the data set prior to the base flow:rainfall comparison in Figure 7, to minimize the urban effects that tend to be hydrologically different from forest and agricultural systems. High ET demands by active crops and anthropogenic abstraction of water for irrigation are two factors that could contribute to low base flow in high-intensity agricultural watersheds. However, the persistence of low base flow across the range of studied watersheds suggests that ET demand is a major component of the water budget during the growing season. According to U.S. Department of Agriculture (USDA) statistics, only a small percentage (~5%) of Michigan’s croplands are irrigated [Economic Research Service, 2004]. Countywide surface and shallow water withdrawals in 2000 were nearly uniform across the study watersheds, thus it is unlikely that anthropogenic abstraction of water for irrigation is the main cause of the observed lower streamflows associated with high-intensity agricultural watersheds.

The differences in annual base flow between high-intensity and moderate-intensity agricultural watersheds can also be attributed to early spring frozen soil conditions. High-intensity agricultural areas are more susceptible to frozen soils during the winter and early spring months, which would tend to lower the recharge rates during the important snowmelt period. In the absence of a persistent snowpack, soils in the region have been shown to freeze to about 5 cm depth even in warm winters [Isard and Schaetzl, 1998]. Intermittent snowpack conditions in winter months are more likely in bare and exposed farmlands resulting in a thicker frozen soil layer. An increasing trend in groundwater recharge toward the northwestern and western parts of the state reported by Holtschlag [1997] is consistent with the larger snowpack and denser forest cover along the northwestern and western fringes of the state as observed with mean January through May streamflow:drainage area ratio (Figure 8). Spatial patterns in volume ratios for watersheds in this study, however, did not show any specific east–west trend during the July to September period.

Culmination of the growing season, as depicted by a sharp decrease in mean monthly LAI in Figure 9, initiates a

![Figure 7](Image)

**Figure 7.** Average 2002–2004 quarter year base flow: drainage area ratios in high-intensity (>70%) and moderate-intensity (<50%) agricultural watersheds. The difference of the flows between the two types of watersheds are statistically significant (p value <0.05) in all quarters except January–March.

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**Table 3.** Multiple Regression Statistics for July September Mean (2002–2004) Streamflow:Rainfall and Base Flow:Rainfall Ratios and Watershed Attributes

<table>
<thead>
<tr>
<th>Parameter Estimates</th>
<th>Streamflow:Rainfall Response Variable</th>
<th>Base Flow:Rainfall Response Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term</td>
<td>Estimate</td>
<td>SE</td>
</tr>
<tr>
<td>Intercept</td>
<td>30.5</td>
<td>2.68</td>
</tr>
<tr>
<td>Agriculture%</td>
<td>-0.30</td>
<td>0.04</td>
</tr>
<tr>
<td>Open Water%</td>
<td>-2.63</td>
<td>0.41</td>
</tr>
<tr>
<td>Outwash sand/gravel%</td>
<td>0.26</td>
<td>0.05</td>
</tr>
<tr>
<td>Intercept</td>
<td>13.3</td>
<td>2.23</td>
</tr>
<tr>
<td>Extremely and somewhat extremely well drained soils</td>
<td>0.43</td>
<td>0.11</td>
</tr>
<tr>
<td>Agriculture percentage</td>
<td>-0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>Open water percentage</td>
<td>-1.88</td>
<td>0.34</td>
</tr>
<tr>
<td>Outwash sand/gravel percentage</td>
<td>0.31</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*aThe residuals from both fits were tested for normality with the Anderson-Darling test. Normality was not rejected; p values are 0.27 and 0.35, respectively.*
period of steady increase in base flow. Correspondence between the LAI and the base flow:watershed area ratio is consistent with the expectation that transpiration significantly reduces the recharge rates in this region during the summer period. The vegetation density associated with agricultural uses, calculated based on LAI, is significantly lower than that of forests, which is the most frequent land cover type in moderate-intensity agricultural watersheds. However, Figure 7 suggests that the high-intensity agriculture has a much more significant effect on hydrology than moderate-intensity agriculture during the peak growing season. The observed temporal changes in streamflow and volume ratios are also evident in the region’s groundwater system. Data from continuous water level transducers installed in a shallow aquifer in the Grand Traverse Bay Watershed located to the northwestern part of the state reveal a steady decline in water levels through late October followed by an increase thereafter (Figure 10). There is only minimal irrigation according to county statistics for the area where the wells are located, and the primary land cover within their watersheds is forest [Economic Research Service, 2004]. This is further evidence of low recharge rates during the growing months, which are too small to compensate for the deficit created by elevated water abstraction and transpiration by plants and base flow discharges to streams. Because of the damping effects of the subsurface materials, the lowest groundwater levels in the region are generally observed a few months after the peak growing period. This highlights the difficulty in using alternative approaches that analyze only groundwater levels and budgets to estimate transient groundwater recharge rates.

Figure 8. Average of 2002–2004 January to May streamflow:drainage area ratios (cm). Higher values likely indicate greater snowmelt influence on the watershed hydrology. The contour map was generated by kriging the ratio calculated from data at the 113 USGS streamflow gauges shown on the map.

Figure 9. The 2002–2004 monthly base flow:drainage area ratios and average monthly rainfall for 40 selected watersheds in Michigan. The peak growing season is clearly marked by higher leaf area indexes (LAI), which corresponds well with the decline in stream base flow during the same period.
The base flow:rainfall ratio for July-September period of each year was analyzed to evaluate differences in recharge between high-intensity and moderate-intensity agricultural watersheds in each of the years from 2002 to 2004. Base flow:rainfall ratio is a good measure of groundwater recharge given the base flow estimates are reasonably accurate. According to our analysis, the average growing season recharge from 2002–2004 in high-intensity agricultural watersheds was about 5% of the total rainfall compared to 15% in moderate-intensity agricultural watersheds (Figure 11). According to the Kruskal-Wallis test, the difference of the mean base flow:rainfall ratio between the two types of watersheds in each of the years is statistically significant (Figure 11). The above percentages amount to about 1.0 cm of growing season recharge in our high-intensity agricultural watersheds, compared to 3.0 cm in moderate-intensity agricultural watersheds (Table 4). The variability of recharge percent across the studied watersheds within a given year is likely related to both differences in land cover percentages and precipitation characteristics. The relatively higher ratios in 2004 are likely related to late spring snowmelt discharge effects and precipitation which contribute to higher streamflow conditions that sometimes extend to late June (Figure 12). In areas where times between recharge events and resulting discharge are relatively small (days to a few weeks), the ratio method presented in this paper could perhaps be applied at shorter temporal scales. Both the starting point and ending point for the analysis should include no significant rainfall events or recent increases in streamflow for several days to weeks, depending on the response time of the watershed of interest. However, larger uncertainties associated with both radar rainfall and base flow estimates at small time intervals would tend to increase the uncertainty in short time period recharge estimates with this approach.

### 6. Summary and Conclusions

Despite recent advances that have been made to quantify groundwater recharge rates, existing methods are generally limited by insufficient data. Increasing concerns over the likelihood of unsustainable water resources in many regions of the world emphasize the need for simple...
approaches that use readily available data for water budget assessment. Many of the existing approaches for groundwater recharge assessment require long-term monitoring, cumbersome and complex watershed models, accurate subsurface parameter estimates that are difficult to acquire, and significant time commitments. As a result these approaches often fail to deliver rapid water budget estimates for watersheds over critical time periods. To address these difficulties, we introduce a method that can be used to rapidly estimate water budgets and recharge rates over various temporal and spatial scales. We believe this approach can be adopted for rapid preliminary assessment of seasonal and longer term recharge conditions in most humid regions with relatively small unsaturated zones and no large artificial diversions of water. Data extraction and processing for this approach can be easily performed using GIS systems and simple database schemes.

We statistically analyzed ratios of streamflow, stream base flow and overland flow volumes to precipitation volume to examine factors that influence the water mass balances for 40 watersheds across Michigan during the growing season. Observed differences are primarily attributed to land cover characteristics. Our analysis indicates that there is minimal growing season recharge in all of the studied watersheds, with high-intensity agricultural watersheds receiving essentially one third of the growing season recharge of moderate-intensity agricultural watersheds. Low runoff and base flow conditions and low streamflow:rainfall ratios in agricultural watersheds provide insight into the significant growing season water demands for intensive croplands. While this has significant implications for managing water resources, further analysis is required to interpret and quantify the detailed processes leading to these trends in terms of ET and other forms of water use related to agriculture.

Statistical evaluation of streamflow and its component volumes (base flow and overland flow) as a percentage of total precipitation can be correlated with land cover and other watershed attributes. This provides a fairly simple and efficient approach to characterize watershed behavior across a range of temporal and spatial scales. When accurate precipitation and flow data are available for watersheds, they can be used to evaluate seasonal or longer-term potential recharge, ET, and runoff volumes. These estimated fluxes provide critical inputs to transient hydrologic models. Relatively large uncertainties associated with base flow estimates as well as radar rainfall estimates at event and other short timescales (i.e., daily, weekly), however, makes it difficult to apply the ratio method to evaluate flux budgets in watersheds over short time windows.

The use of radar-derived precipitation estimates can simplify and potentially improve the quality of water resource analyses for some watersheds. This is especially true when large watersheds are involved because there are often significant spatial and temporal variations in precipitation at these scales. Spatial characteristics of precipitation are extremely difficult to capture solely from ground-based gauges; thus use of NEXRAD data is likely to improve the accuracy of regional water mass balances. While there are numerous merits to using NEXRAD precipitation data in hydrogeological studies, the temporal and spatial accuracy needs to be evaluated for any study region due to the known uncertainties currently associated with these data. The continued effort of the National Oceanic and Atmospheric Administration (NOAA) to improve the accuracy of the radar rainfall estimates is likely to make NEXRAD an indispensable resource for many hydrologic applications.

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