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THE EFFECTS OF SUBURBAN LAND-USE CHANGE AND
CLIMATE ON WATERSHED HYDROLOGY IN
OAKLAND COUNTY, MICHIGAN, 1975-2005

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THE EFFECTS OF SUBURBAN LAND-USE CHANGE AND CLIMATE
ON WATERSHED HYDROLOGY IN
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By

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ABSTRACT

THE EFFECTS OF SUBURBAN LAND-USE CHANGE AND CLIMATE ON WATERSHED HYDROLOGY IN OAKLAND COUNTY, MICHIGAN, 1975-2005

By

Stephen Scranton Aichele

Oakland County, Michigan, is a rapidly growing area northwest of Detroit. Previous studies have determined that as much as 25 percent of the total area of several watersheds in the county has been converted to urban land uses during the period from 1980 to 2000, yet little overall change in streamflow characteristics has been observed. An impervious surface dataset was developed using automated classification of digital imagery, and compared to parcel-based land-use data. Impervious surface percentages were calculated for parcels of different sizes based on the year the parcel was developed. The results suggested substantial variation in impervious surface for residential parcels less than 1 acre (0.404 ha), ranging from less than 10 percent to more than 30 percent of parcel area, with an increasing trend through time in impervious surface even within parcels with similar size and use. However, because the number of small, highly impervious parcels has dropped as a fraction of total housing starts, the rate of impervious surface growth has slowed. Analysis of streamflow records for six selected sites within the county showed little change in annual flow characteristics, and some decrease in spring season flows as a percentage of annual flow. The Soil Water Assessment Tool (SWAT) simulation model

was used to test the effects of land-cover renderings, land-use change and climate on the Paint Creek Watershed. The results indicated that parcel and hand-digitized land-use data were not a good surrogate for land-cover data, and tended to overestimate runoff and underestimate recharge. The effects of land-use change on stream-flow were more than offset by the effects of climate, but both land-use and climate tended to reduce ground-water components of the hydrologic budget. These results were partially confirmed by calculating the total evapotranspiration for the six watersheds based on the difference between annual precipitation and annual streamflow. Records from a nearby long-term monitoring well also suggest a long-term decline in ground-water levels in the region.

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INTRODUCTION

Overview

The interaction of humans with their environment is a central theme of the geography discipline. Although these interactions have many dimensions, the expectations for environmental, and particularly hydrologic, changes associated with urbanization are well documented. As early as the late 1700s, Benjamin Franklin expressed concern the urbanization was reducing recharge in the City of Philadelphia (Smyth, 1907, p.506):

> And, Having considered that the covering of a groundplot of the city with buildings and pavements, which carry off most of the rain and prevent its soaking onto the Earth and renewing and purifying the Springs, whence the water of wells must gradually grow worse, and in time be unfit for use, as I find has happened in all old cities.

Although Franklin may have been one of the first, he was by no means the last to express concern over the physical impacts of urbanization. Hundreds of studies have been published, and countless more commissioned for internal use, to evaluate the effects of land development on hydrologic systems. However, the implicit assumption is almost always that land development is the sole change to an otherwise static system. In fact, climate varies over time, as do government regulations, economic considerations, and societal preferences.

During the last thirty years, since the enactment of the Federal Water Pollution Control Act of 1972 and the amendments of 1977 resulted in what is widely known as the Clean Water Act, a variety of regulatory and engineering practices have been employed to try to mitigate the adverse effects of development. At the same time, the transportation considerations that encouraged clustering in cities have been substantially reformed, such that access to a highway interchange might be more valuable than a downtown address. Finally, the social preference for urban living has largely been inverted since Franklin's time. More importantly, these shifts are not events but processes and evolutions, continuously ongoing. The patterns of development we see in suburban areas today are the result of a current set of economic and social conditions, which may well change if infrastructure or transportation conditions change.

The effects of modern suburban (subdivision) and exurban (individual large lot) development practices and patterns, as well as the effect of climate change, on hydrologic systems are poorly understood. Oakland County, a suburban area northwest of Detroit, provides an excellent setting to evaluate some of these effects, as well as some of the subtleties of how we characterize the changes.

Study Area

Oakland County is located in Southeast Michigan, and the city of Pontiac is the county seat. Oakland County provides a cross-section of urban and suburban development, including both older urban industrial cores in Pontiac, a number of smaller cities and villages such as Milford and Rochester, and a variety of suburban developments ranging from inner-ring suburbs of the 1950s in the southeastern part of the county to exurban 'sprawl' on multi-acre lots in the northern and western parts of the county. The distinction between 'suburb' and 'exurb' is not well defined, although they do have specific connotations. For the purposes of this study, suburbs are areas within established residential/commercial zones, with organized development occurring in subdivisions or other multi-house units, generally on lots of less than 1 acre. In contrast, exurbs (or more often, exurban) will denote the leading edge of the 'crabgrass frontier' (Jackson, 1987) typified by conversion of land to residential use in large parcels, and development on a parcel by parcel basis. This general definition is drawn from Theobald's (2005) survey of suburban and exurban landscapes.

Oakland County, as well as the rest of the Detroit metropolitan area, is served by the Southeast Michigan Council of Governments (SEMCOG), which has produced a land use map for the region based on visual inspection of aerial imagery every year since 1985. Prior to 1985, the Michigan Department of Natural Resources (MDNR), Michigan Resources Information System (MIRIS) produced a similar land use dataset. These datasets are great assets for assessing landscape change that are seldom available in other areas of the country. Areas of Oakland County defined as "urban" in 2000 by SEMCOG are shown in Figure 1.

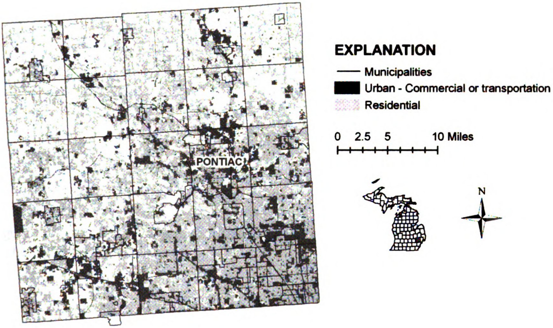

Figure 1: Urban land use of Oakland County, Michigan in the year 2000. Land-use data courtesy of Southeast Michigan Council of Governments (Burns, written communication, 2003)

The population of Oakland County has grown steadily throughout the 20th century (Figure 2), from approximately 100,000 people in 1920 to just over 1.2 million in 2000. Rates of population change have been heavily dependent on economic conditions, particularly in the manufacturing sector. A rapid increase in population during the initial expansion of the auto industry almost halted during the Great Depression of the 1930s. During the 1950s and 1960s, population expanded rapidly, growing from almost 400,000 to about 1,000,000 by 1980, with a slowing during the 1970s and early 1980s. Following the recession of the early 1980s the population has grown by about 10,000 persons per year.

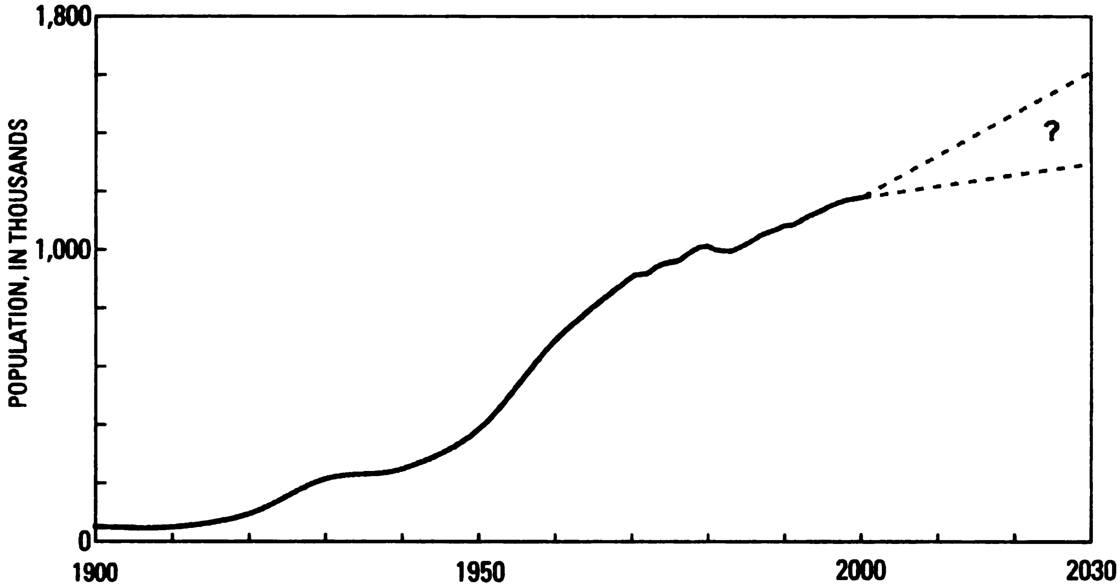

Figure 2: Population growth in Oakland County, Michigan, 1900-2030 (modified from Aichele 2005b).

The geology of Oakland County is strongly influenced by the Wisconsinan glaciation, when the Saginaw Lobe and the Huron-Erie Lobe of the ice sheet met across the center of the county (Figure 3), along a line running roughly from Oxford, west of Pontiac, to Milford (Winters et al., 1985). Along this division, the glaciers constantly deposited material, advanced and retreated across the deposits, and discharged huge volumes of melt water. The resulting surficial deposits are up to 400 feet thick (Twenter and Knutilla, 1972) and form a complex assemblage of primarily morainal and outwash deposits, ranging from coarse sand and gravel to clay-rich tills varying both horizontally and vertically.

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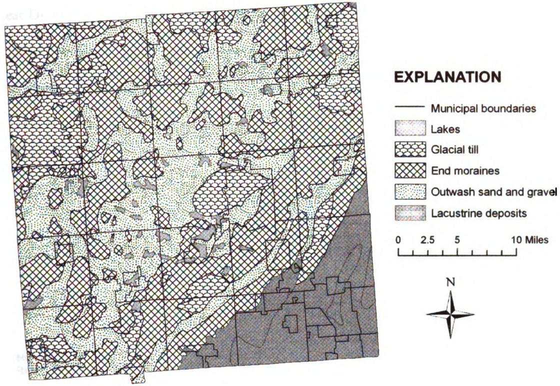

Figure 3: Surficial geology of Oakland County, Michigan (modified from Aichele, 2005b)

Six watersheds are of particular interest in Oakland County, in that each has more than 30 years of continuous daily streamflow data (Blumer et al., 2005), a well-behaved rating curve (LeuVoy, personal communication 2007), relatively few in-channel lakes, and are either entirely or almost entirely within the county. All drain the morainal and outwash materials stretching across the center of the county, and all but the Huron drain south and east. The Huron flows to the southwest from Oakland County to Livingston County, before turning to the south and east in Washtenaw County. The six watersheds are: the Huron River, gaged at Milford, Michigan, draining to Lake Erie; the Upper River

Rouge, gaged at Farmington, Michigan, draining to the Detroit River; the River Rouge, gaged at Birmingham, Michigan, draining to the Detroit River; Sashabaw Creek, gaged near Drayton Plains, Michigan, a tributary of the Clinton River which drains to Lake St. Clair; Paint Creek, gaged at Rochester, Michigan also a tributary of the Clinton River; and Stony Creek, gaged near Romeo, Michigan another tributary of the Clinton River.

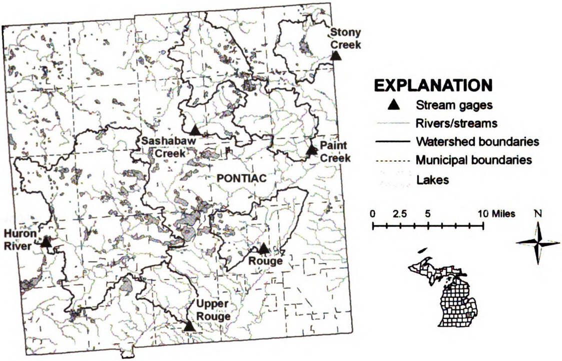

Figure 4: Map showing six watersheds in Oakland County, Michigan, with gage locations.

Previous research in the area has documented the rate of land-use change (Table 1) and population change (Table 2) in each of these watersheds (Aichele, 2005a). Land-use change in this case was based on a rasterized version of the manually digitized SEMCOG land-use data (1985-2000) or MIRIS (1978). Population estimates are based on dasymetric mapping of census population to residential land-use classes, as described by Aichele (2005a).

Table 1: Land use of selected watersheds in Oakland County, Michigan, 1980-2000. Modified from Aichele (2005a).

Watershed (Station number)	Year	Total Built	Total Unbuilt
Sashabaw Creek (04160800)	1980	24.9	75.1
	1990	33.9	66.1
	2000	50.2	49.8
Paint Creek (04161540)	1980	26.3	73.7
	1990	34.6	65.4
	2000	52.4	47.6
Stony Creek (04161580)	1980	11.7	88.3
	1990	20.5	79.5
	2000	30.2	69.8
River Rouge (04166000)	1980	69.8	30.2
	1990	78.8	21.2
	2000	86.3	13.7
Upper River Rouge (04166300)	1980	48.2	51.8
	1990	64.5	35.5
	2000	79.8	20.2
Huron River (04170000)	1980	27.8	72.2
	1990	34.7	65.3
	2000	48.9	51.1

[1] Undifferentiated urban land, not clearly identified as commercial or residential.

Table 2: Population characteristics of selected watersheds in Oakland County, Michigan, 1980-2000. Modifed from Aichele (2005a).

Watershed (Station number)	Year	Residential acres	Residential (square miles)	Estimated population	Residential population density (persons per acre)
Sashabaw Creek 04160800	1980	1,488	2.33	11,000	7.39
	1990	1,856	2.90	12,200	6.57
	2000	2,746	4.29	18,033	6.57
Paint Creek 04161540	1980	5,119	8.00	38,900	7.60
	1990	7,141	11.16	49,200	6.89
	2000	11,369	17.76	66,500	5.85
Stony Creek 04161580	1980	955	1.49	3,720	3.89
	1990	1,727	2.70	3,940	2.28
	2000	2,179	3.40	4,980	2.29
River Rouge 04166000	1980	7,689	12.01	71,500	9.30
	1990	8,505	13.29	76,600	9.01
	2000	9,266	14.48	82,400	8.89
Upper River Rouge 04166300	1980	2,078	3.25	20,100	9.67
	1990	3,145	4.91	32,200	10.24
	2000	3,876	6.06	41,600	10.73
Huron River 04170000	1980	10,425	16.29	76,143	7.30
	1990	13,527	21.14	83,900	6.20
	2000	18,255	28.52	103,000	5.64

As can be seen in Table 1, land uses classified as urban increased by approximately 100 percent in area in four of the six watersheds. The rate of urban land-use change is inversely related to the level of urbanization in the watersheds in 1980, with the most urbanized watershed experiencing the least change. This change came almost entirely at the expense of agriculture and a less well defined "open space" category, described as "grass and shrubland" (SEMCOG, 2004) representing primarily fallow agriculture, but also other unclassified, non-forested categories. Forest, water, and wetland areas remained relatively unchanged except in the heavily urbanized watersheds.

Climate

The humid continental climate in Oakland County is typical of the Upper Great Lakes, with four distinct seasons and precipitation in every month, although more precipitation tends to fall in summer months than in winter months. Monthly normal precipitation data (1971-2000) are shown in Figure 5. Monthly normal temperatures are shown in Figure 6.

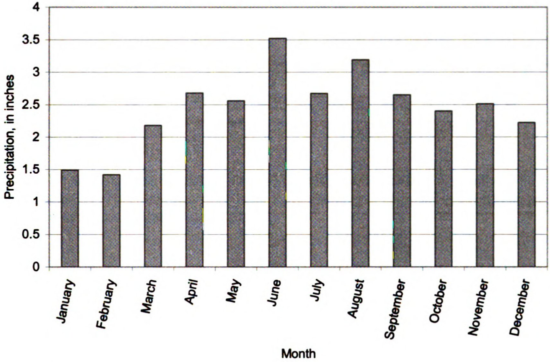

Figure 5: Normal monthly precipitation at Pontiac, Mich., 1971-2000. (data from 1971-2000; Peter Kurtz, Michigan Climatological Resources Program, written communication, 2003).

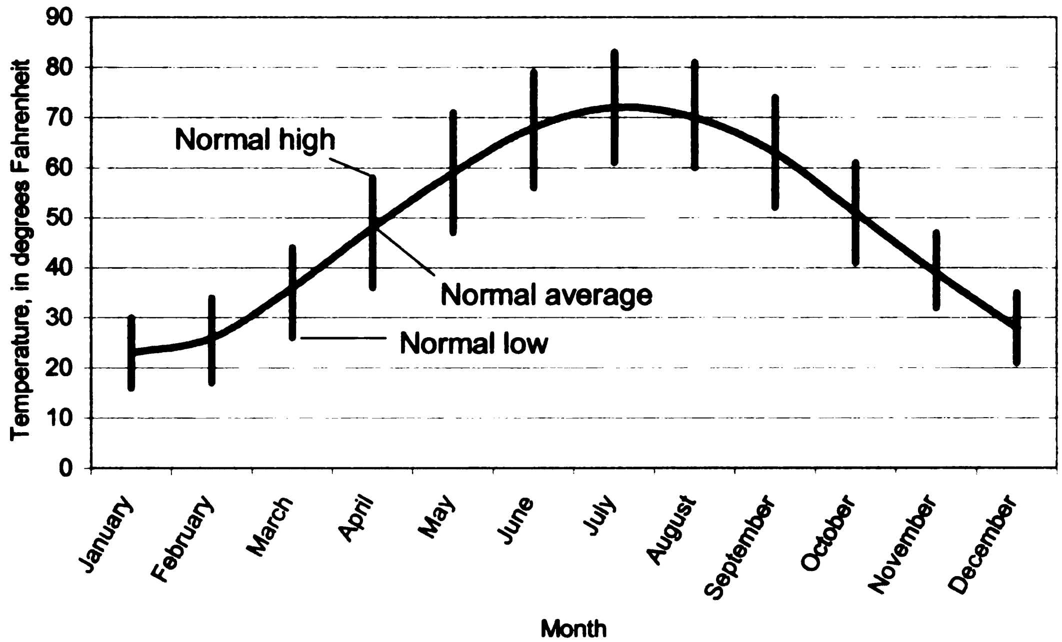

Figure 6: Normal daily maximum, minimum, and mean temperatures by month at Pontiac, Mich., 1971–2000 (data from Peter Kurtz, Michigan Climatological Resources Program, written communication, 2003).

Several temporal climatic trends are also evident in Oakland County. Total annual precipitation has increased by approximately 35mm over the last 30 years based on local gage records. However, Hodgkins et al. (2007) noted a decrease of 41.6mm (1.64 inches) in annual precipitation for the period 1955 to 2004 at Owosso, Michigan, just north and west of Oakland County. Over the same period, precipitation during February, March, and April decreased by 28mm (1.1 inches).

Winter temperatures have increased since approximately 1975, but have increased most dramatically since 1997 (Aichele, 2005b) and during overnight hours (Andresen and Winkler, 2009). Seasonal and annual variability in weather patterns, as well as long-term climatic trends, interact with changes in land cover to affect the water budget of streams and aquifers in Oakland County.

Given profound landscape and land use changes in Oakland County during the past several decades and expectations for hydrologic changes based on existing literature, this research will focus on an examination of hydrologic records and the general relationship between land use change and hydrology in the region. Three principal areas will be considered:

1) A better understanding of land-cover changes associated with observed land-use changes;
2) an explicit examination of the area's stream flow record for evidence of change; and
3) development of a suite of watershed models to investigate the effects of land-use and climate change on streams and aquifers in Oakland County.

Problem

A recent study of watersheds undergoing rapid development in Oakland County, Michigan (Aichele, 2005a; Aichele, 2005b) searched for, but did not find, the anticipated hydrologic effects of urbanization in a temporal analysis, despite relatively high rates of land use change over the period from 1980-2000. This suggests that some of our assumptions regarding the effects of urbanization on hydrologic systems, particularly modern patterns of urbanization, are less well understood and certain than generally believed.

Review of relevant literature

There are three major bodies of literature surrounding this proposed study. The first examines the effect of impervious surface on hydrologic systems. The second addresses the methods of quantifying of impervious surface area. Finally, the third addresses the application of hydrological models and other modeling approaches to small watershed studies such as those proposed above.

EFFECTS OF IMPERVIOUS SURFACE ON HYDROLOGIC SYSTEMS

The expectations for environmental, and particularly hydrologic, changes associated with urbanization are well documented. As noted previously, the effects of paving and building on the landscape have been a concern to some for centuries. However, these concerns came to the fore in the 1950s and 1960s. Ven Te Chow (1952) reported on the increases in peak flow associated with urbanization in the Boneyard Creek watershed near Champaign-Urbana, Illinois. However, pre-development flow data were somewhat lacking (Chow, 1952). In 1961, Savini and Kammerer published a comprehensive report on the effects of urbanization on hydrologic systems, including runoff, erosion, land subsidence, water quality, and water availability, as those topics were understood at the time. Their discussion of studies of urban runoff is slightly more than one page. In the concluding section of the report, they identify effects of human occupancy and modification of the land as an area lacking research and understanding.

Carter (1961) described changes to peak flow volume and timing in response to suburban development in the Washington D.C. area. This document provides the early empirical underpinnings of the widely-used SCS Curve Number method (NRCS, 1986).

The SCS Curve Number method is an empirically-derived calculation incorporating precipitation, initial abstraction (I_a; the filling of storage, such as closed surface depressions), and retention after runoff begins, S. The curve number (CN) is based on a combination of cover type, condition, and hydrologic soil group. The CN is then used to estimate the initial abstraction and retention characteristics, with the overland runoff (Q) being the excess beyond the initial abstraction and retention. Carter's work was later generalized by Anderson (1970) to yield $K = 1 - 0.015 * I$, where K is the runoff coefficient and I is the impervious area in the watershed. Thus, over a span of 10 years the effects of urbanization evolved from a poorly understood problem without clear solutions to a linear equation. R.W. Carter supervised a study by S.W. Wiitala (1961) of the effects of urbanization and storm sewering in the Red Run and Plum Brook Basins of the Clinton River watershed in Michigan. Among Wiitala's findings were much shorter lag times and higher peak flows in the sewered Red Run as compared to the (then) relatively undeveloped Plum Brook.

Contributing substantially to that evolution were a series of relatively high profile studies of basins undergoing rapid development. These included Permanente Creek in Santa Clara, California (Harris and Rantz, 1964); Scott Run in Northern Virginia (Vice et al., 1969); and several streams in metropolitan Charlotte, North Carolina (Martens, 1968). These studies were all in response to the limitations cited in the previous Savini and Kammerer (1961) report. Each study was structured, to the greatest degree possible, to collect time-series data through the development cycle. The Permanente Creek example (Harris and Rantz, 1964) was nearly the perfect case – a small watershed, completely undeveloped at the beginning of the study, was instrumented and then became heavily developed within several years. This study clearly showed decreased lag times and increased runoff peak flows associated with increased impervious surface.

These results and the cumulative body of knowledge on urban hydrology generated in this period were summarized in a seminal Circular by Luna Leopold in 1968, Hydrology for Urban Land Planning – A Guidebook on the Hydrologic Effects of Urban Land Use. This report, Circular 554, drew extensively from examples on the Brandywine Creek in southeast Pennsylvania in documenting the various alterations to the hydrologic system resulting from urbanization, including predicted rates of increase for the average annual flood based on the extent of storm sewering and the extent of impervious surface. The two key hydrograph parameters evaluated were lag time and peak discharge. The unit hydrograph (Snyder, 1938) is a classical parametric measure of watershed response, developing a streamflow response curve to a given input of precipitation.

Leopold (1991) makes a compelling case that the unit hydrograph is not robust in dealing with inaccuracies in the two key quantities measured to create a unit hydrography - precipitation and streamflow. The most significant issues associated with precipitation data error are gage undercatch (usually due to wind) and reporting error derived from the minimum unit of measurement – as much as 0.1 inch in some older equipment. Stream discharge is continuously affected by changes in channel geometry through sediment movement and vegetation growth and decay. These changes, particularly the effects of vegetation, are typically addressed through 'shifts' in the stage-discharge relationship (Rantz, 1981). These shifts, while recorded, were not typically applied to unit data prior to 1992. Regardless, they are only updated approximately every 6 weeks. Thus identifying the lag between the two centers of mass relies only on the relative accuracy of the measurements and the accuracy of the timekeeper, not the absolute accuracy of the flow or precipitation measurement.

An alternative approach to characterizing a stream flow regime is the use of a flow duration curve, a plot of the empirical cumulative distribution function of streamflow, most often daily (Stedinger, Vogel, and Foufoula-Georgiou, 1993). Although flow duration curves (FDC) can be constructed for any time frame, most often they are annual or longer. The streamflow regime of rivers and streams can be directly compared by overlaying flow duration curves on the same plot (Mosley and McKercher, 1993). The flow duration curve provides a graphical and statistical summary of the streamflow variability at a location with the shape determined by the rainfall patterns and landscape characteristics of the basin (Best et al., 2003). Vogel and Fennessey (1994a) developed a statistical understanding and defense of multi-year FDCs as a tool to understand watershed characteristics. Although investigations into changes in FDCs as a result of landscape change are limited in North America, they have been widely used in the United Kingdom and Australia. Burt and Swank (1992) used FDCs in a paired catchment study in the UK. By developing a regression relating the FDC of a control catchment to a treatment catchment, they were able to evaluate the effect of vegetation change over a 7-year period. Lane et al. (2005) used FDCs to evaluate the effects of vegetation maturation and climate change on catchments in Australia. Serengil et al. (2006) used FDCs to investigate the effects of forest thinning in Turkey. Vogel and Fennessey (1994b) and Smakhtin (2001) each provide numerous additional examples of applications of FDCs.

Since the late-1960s, hundreds of studies have followed Leopold's circular, largely reconfirming, elaborating, or embellishing on Leopold's finding. The studies documented in the early publications were based primarily on temporal observations – that is, making measurements at the same site in a watershed over a period of many years as construction occurred. Many of the more recent studies, however, have been based on the more commonly applied gradient technique (McMahon and Cuffney, 2000; Cuffney et al., 2000), in which several similar watersheds with varying intensities of land use are measured over a relatively short period of time, perhaps a year or two. The results of these measurements are then related statistically to the degree of urbanization in the watershed. This method has several advantages, not the least of which is a short period of study and, consequently, much greater control of factors such as data collection techniques, climate inputs, and analytical procedures. The burdens of the former approach – maintaining long-term monitoring and consistent methods, are largely addressed by the latter approach, but at the expense of a degree of certainty (Cuffney et al., 2000) based on the assumption that relevant similarities and differences between catchments are being accurately described.

The U.S. Geological Survey has been involved in data collection in Southeast Michigan for over 70 years, and completed a robust study of urbanization and water resources in the late 1960s (Twenter and Knutilla, 1972). More recently, this study was updated and revised based on new data collection (Aichele, 2005a; Aichele, 2005b). Temporal analysis of these two datasets, as well as data collected in the intervening three decades, indicates little change in either water quantity or quality, despite significant increases in urbanization, population, and impervious surface. A gradient analysis carried out with just the data collected in the more recent study indicates the presence of all the predicted adverse effects – increased peak flows, increased run off, and various water quality impairments. This discrepancy has led me to postulate that later suburban and exurban development (such as was captured in the 2005 studies by Aichele) may behave differently than earlier, pre-1970 suburban development.

Subsequent to the surge in related research activity in the 1960s, considerable effort was exerted by many investigators in documenting the relationship Leopold and other authors described in different contexts around the world. Similarly, the relationship has been elaborated upon to present secondary effects of increased flows on stream morphology, ecology and habitat, water quality, and sediment yield. These effects have been summarized periodically in both hydrologic papers (Hirsh et al., 1990; Sauer et al., 1983) and in papers for various affected communities, such as urban planning (Arnold and Gibbons, 1996) and ecology (Paul and Meyer, 2001).

Sauer et al. (1983) conducted a rigorous literature review in support of understanding changes in flood frequency associated with urbanization. Synopses of these articles were published separately in Rawls et al. (1980). The literature review generally supported the assertion that urbanization caused runoff volume to increase and basin response time to decrease. Peak discharges also generally increase, particularly for low-order floods; more significant floods were less affected because a larger fraction of the precipitation would have been runoff anyway.

Hirsch et al. (1990) summarized the results of Sauer et al. (1983) but added some further supporting information based on other studies. Among other related research findings was the conclusion that although the mapped drainage network of an urban watershed is often less dense than a natural watershed, when the engineered drainage is included, the urban drainage network is frequently more dense (Dunne and Leopold, 1978).

A peer-reviewed journal dedicated to the subject of urban hydrology was initiated in 1999, *Urban Water Journal*, and restarted in 2004 under new publishers. An article by Schuster et al. (2005) presents a review of the current state of understanding of the effect of urbanization on watersheds. In the second paragraph, they summarize the current state of knowledge:

> Specifically, increases in impervious surface result in increased hydraulic efficiency in urban catchments, and can cause substantially decreased capacity for a given landscape or region to infiltrate precipitation, with a concomitant increase in the production of runoff (Booth, 1991; Hsu et al., 2000; Hey, 2001), shorter times of concentration or lag times (Sauer et al., 1983; Rhoades, 1995), and decreased recharge of water tables with a corresponding decline in base flows (Klein, 1979; Smakhtin, 2001)… The effects are especially apparent in newer ex-urban fringe development… (Marsh and Marsh, 1995; Kauffman and Marsh, 1997).

Most recently, McCray and Boving (2007) introduced a special issue of the Journal of the American Water Resources Association (JAWRA) on the subject of "Urban Watershed Hydrology," suggesting the need for more inclusive and system-oriented studies of watershed hydrology, rather than the more traditional flood, sediment, water-quality, and storm-flow assessments. Although the articles included in the section are not particularly germane to a temperate humid region such as southeast Michigan, each goes to some pains to illustrate the incompleteness of our understanding in this area. Most notably, Oelsner et al. (2007) identify agricultural lands near the Rio Grande as sinks of nitrogen, as opposed to sources.

Several articles have recently begun to question some of this conventional theory. McMahon et al. (2003) developed several stage-based metrics of flashiness, which remove some of the uncertainty associated with discharge-based metrics (specifically, the long-term stability of the stage-discharge relationship for a site). McMahon et al. (2003) also discovered some inconsistencies in hydrologic responses of similar urbanized basins, and postulated that these may be the result of differences in the landscape configuration of imperviousness within the basin. Several authors have begun to evaluate the patterns of urbanization as a predictor of the effects on hydrologic systems. Carle et al. (2005) evaluated six streams near Durham, North Carolina. Although the focus of this study was on water quality effects, their findings indicate that the density of impervious surface, contiguity of impervious surface, and proximity of impervious surface to other drainage all influence the delivery of NPS pollutants, by way of stormwater, to streams.

Hood et al. (2007) compared the effects of urbanization in three Connecticut watersheds, one a control, one with what was characterized as "traditional" development, and one implementing newer Low-impact development (LID) principles. Many LID practices have been adopted either intentionally or accidentally in newer development in Southeast Michigan – curbless roads, permeable driving surfaces, low fractions of impervious surface in the overall development, and significant on-site storage for runoff. In Hood et al. (2007), these and other practices within the context of a planned cluster development resulted in twice as high an initial abstraction, the amount of water absorbed by the watershed before runoff commences, and reduction of nearly 90% in peak discharge, as well as increased lag time as compared to traditional development. These common practices, whether implemented intentionally or not, may have similar effects in mitigating some of the effect of development and land-use change in suburban watersheds.

IMPERVIOUS SURFACE MAPPING

Within Circular 554, Leopold draws attention to several studies demonstrating the inverse relationship between lot size and impervious surface, expressed as a fraction of the lot size (Leopold, 1968). Impervious surface has emerged as one of the key indicators of watershed health and sustainability (Arnold and Gibbons, 1996). Impervious surface areas greater than 10 percent of the total watershed area have been shown to adversely affect stream flow, water quality, and associated aspects of habitat and biodiversity (Scheuller, 1994). However, considerable variation, and indeed uncertainty, exists regarding methods of measuring impervious surface. Generally the most accurate approach to measuring land-use is considered to be manual digitization of high-resolution orthophotography (Sloenecker and Tilley, 2006; Dougherty et al., 2004). Although accurate and effective for small areas, this approach is very labor intensive and subject to some quality concerns when large numbers of interpreters are involved in the processing. The data generated by SEMCOG and MIRIS are examples of this technique.

Several other methods have been attempted, with mixed levels of success. Among the most common is a 'coefficient' approach, where an impervious surface coefficient is associated with a particular land use, typically a vector polygon representation such as a tax parcel or zoning district (Capiella and Brown, 2001). A similar, alternative approach, based on synoptic remotely sensed land-cover data, has been implemented in the Chesapeake Watershed Program and the EPA's ATTilA application (Ebert and Wade, 2003; Jennings and Jarnagin, 2002).

Dougherty et al. (2004) present a similar comparison, where unconditioned satellite-derived impervious surface areas are underestimated by 50 percent or more compared to manually delineated approaches. However, Dougherty et al. (2004) actually identify over-classification in the manually delineated data set as the issue, not underestimation in the remotely sensed data. Likely some of the error was also the result of land cover classification error in the National Land Cover Dataset (NLCD) as described in McMahon (2003). He identified the relatively poor classification accuracies for developed (as compared to agricultural or undeveloped) land covers as a source of systematic bias in the dataset – i.e. developed areas are more likely to be underrepresented.

Yang et al. (2003) developed an approach to synergistically use high-resolution remotely sensed imagery (such as orthophotography or IKONOS imagery) and Landsat 7 ETM+ imagery to develop impervious surface estimates. Their assessment was similar to that of Sloenecker and Tilley (2006), i.e., good agreement but general underestimation. Overall, impervious surface estimates derived from the NLCD program are likely to be several percent short of the actual. In many respects, these results are all generally in agreement with the loss of detail and features, particularly linear features, in increasingly coarse raster representations of the landscape (Turner et al., 1989). In summary, no single good method exists to characterize impervious surface. Manual digitizing from aerial imagery brings the interpreter's skill to the product, but is time-consuming, and thus expensive, over large areas if mapping units are small enough to capture impervious surface. Applying impervious surface coefficients to existing land-use datasets (such as parcel maps) is more cost effective when parcel maps are available, but is limited in its accuracy by the need to characterize many parcels with a few coefficients. Remote-sensing techniques with moderate resolution sensors (10m-30m) can be both effective and efficient, but is inherently limited by the resolution of the data and a tendency to under-represent covers that are less than the ground sample distance in width. A higher resolution data source for the remote sensing approach might help address some of these representation issues.

WATERSHED MODELING

Digital watershed models have evolved rapidly since the Stanford Watershed Model (SWM) was first developed in 1966 (Crawford and Linsley, 1966). Some of this evolution has been driven by advances in computer technology, and some by a better understanding of the complexity of environmental problems (Singh, 1995). Much of the evolution has been driven by specific needs – a need to better estimate peak flows or low flows, a need to better understand erosion or pollutant discharges, or a need to better understand watershed processes.

Before delving too deeply into the abstract world of modeling, George E.P. Box's comment that "Essentially, all models are wrong, but some are useful," is worthy of consideration (Poeter, 2007). A model, not unlike a map, seeks to represent selected relevant elements of the world for the purpose of prediction or understanding (Silvert, 2001). But by nature, they limit the complexity present in the real world and are based on the assumptions of the modeler regarding how the system functions (Silvert, 2001).

One of the simplest forms of models is the unit hydrograph described previously, an analytical representation of streamflow resulting from precipitation for a specific basin (Snyder, 1938). In that case, an empirical relationship is developed between observed inputs and outputs for a specific basin, without much consideration of processes inside the basin. Although such a model provides predictive power, it provides relatively little understanding of processes or generalizability beyond the subject basin.

The number of digital watershed models available is considerable – as of 1991 the U.S. Bureau of Reclamation had identified 64 distinct watershed models, and the number has continued to grow (Singh and Frevert, 2006). Some are almost entirely empirical, such as TOPMODEL (Beven and Kirkby, 1979); some are rigorously physical, such as the Precipitation Runoff Modeling System (PRMS; Leavesley et al., 1983). Many fall somewhere in between – Soil Water Assessment Tool (SWAT; Arnold 2005) and its forerunner, the Simulator for Water Resources in Rural Basins (SWRRB; Williams et al., 1985), The Sacramento Soil Moisture Accounting Model (SAC-SMA; Burnash, 1995), the Hydrologic Engineering Center (HEC) family of models (Feldman, 2000), Hydrologic Simulation Program – FORTRAN (HSPF; Johanson el at. 1980), and dozens of others.

Similarly, many of the models listed above compromise some amount of spatial discretization (often referred to as parameter distribution) for computational and conceptual efficiency. Most create subwatersheds or Hydrologic Response Units (HRUs; Winter, 2001) that have similar soils, land cover, and landscape position. Computations can then be carried out for the HRU (rather than individual models cells) and resulting water budget components tabulated. Unfortunately, no model perfectly fits every location or situation. For instance, where HEC and HSPF are more oriented to predicting discharge within a channel, PRMS and SWAT are oriented toward replicating processes in the watershed.

A fundamental tension in watershed modeling is between the ability to represent different watershed characteristics versus the potential for overparameterization (Werkhoven et al., 2008). The issue of overparameterization has been well documented (van Genuchten, 1991; Hooper et al., 1988; Beven, 1989). A complex watershed model such as HSPF, SWAT, or PRMS might contain hundreds of parameters, used to predict stream discharge at a single point. A variety of attempts have been made to outline a process for addressing the issue of overparameterization (Jakeman and Hornberger, 1993; Wagener and Wheater, 2006) with limited success. Some (Wagener and Wheater, 2006; Vrugt et al. 2006, Hogue et al., 2006) have suggested stochastic parameter estimation techniques, while others have suggested limiting the number of parameters fitted (Beven, 1989; Jakeman and Hornberger, 1993; Werkhoven et al., 2008). The advantage of stochastic parameter estimation is a better fit model, and better prediction. The advantage of only fitting a limited number of parameters is that the modeler retains control and can relate physical reality to the parameter values.

Two somewhat dated but still excellent resources for comparing the various watershed models and families of models include DeVries and Hromadka (1993) and Singh (1995). Singh and Frevert (2006) provides an update to the previous work, and some additional models.

Research Questions

The body of prior work described in the previous section suggests several issues and approaches concerning the absence of the expected change in stream-flow characteristics over the past several decades in Oakland County, Michigan.

1) What is the extent of exurban land-use/land-cover change within the watersheds of interest during the recent decades?
2) What is (are) the optimum characterizations and quantifications of these changes? Does the choice of rendering affect either the interpretation of change or the interpretation of the hydrologic processes?
3) What changes have occurred in the stream-flow characteristics of these watersheds? To what degree can these changes be described or quantified with the data available?
4) What are the independent effects of climate change and land-cover change on streamflow? How do these factors interact?

Successfully addressing these questions will help resolve several issues. Identifying the reliability of various land-use datasets as representations of land cover, particularly impervious surface, as well as their effects on hydrologic modeling, will yield valuable insights into systematic inaccuracies in watershed models. Further analysis of stream flow characteristics may disprove the previous research (Aichele, 2005a) identifying little change in stream flow despite non-stationarity of both climate and land cover. Finally, using a physical, process-based model to artificially create a stationary system of first land-cover then climate will allow for better management of local change (i.e. land cover) as well as better preparation for regional or global change (i.e. climate).

Chapter 2

METHODS

Measuring land-use/land-cover change

To address the first research question, one must first identify a means of quantifying land-use/land-cover change. As discussed previously, a variety of techniques exist, and may yield differing results. By far the most common method of monitoring land-use is through visual inspection and digitizing of features from aerial orthophotography (Sloenecker and Tilley, 2006). This approach has been widely used for decades around the world, usually based on a variation of the Anderson et al. (1976) land-use/land cover classification.

The result of this method is a dataset comprised of irregular polygons describing roughly homogeneous land uses. Such a dataset exists for the study area, developed by the Southeast Michigan Council of Governments (SEMCOG, 2000). The data are based on manual interpretation and digitizing from aerial orthophotography supported by tax assessment records. The data are organized with a modified Anderson et al. (1976) classification (RSGIS, 2002), with particular emphasis on urban land uses, and a minimum mapping unit of one acre. Urban areas described by this dataset, shaded to correspond with Anderson Level 1 categories, are shown in Figure 7. Similar datasets were developed from imagery collected in 1978, 1985, 1990, and 1995. The dataset created from 1978 imagery was generated by the Michigan Department of Natural Resources (MDNR) Michigan Resource Information System (MIRIS) during the early 1980s (MDNR, 1981).

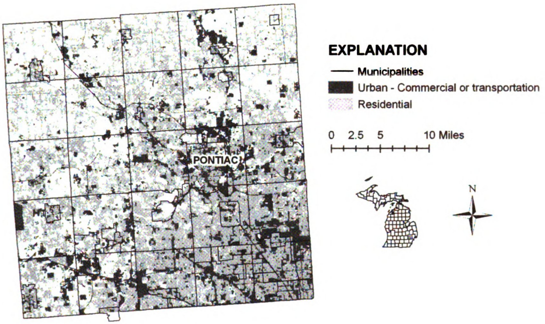

Figure 7: Selected urban land uses in Oakland County, Michigan, based on SEMCOG land-use data for the year 2000.

An alternative method of quantifying land-use is to use tax assessment information directly. This information has the advantage of being based on ground surveys of the site – and thus is more accurate in regard to land-use. As is the case with nearly all polygonal land-use datasets, these data are generally mapped to an entire parcel, meaning that an entire acre or more may be coded as "residential," without differentiation to the portion that is lawn and the portion devoted to structures and pavements. The land-use classifications from the parcel dataset are presented in Table 9. An example of this dataset, classified similarly to the previous figure, is shown in Figure 8.

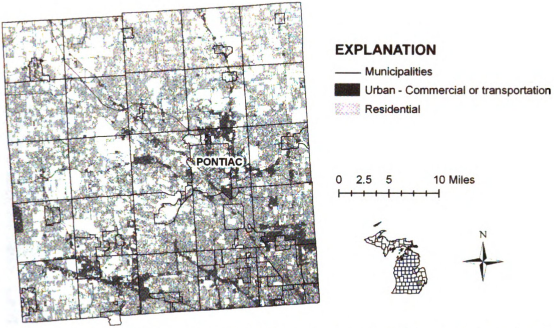

Figure 8: Land use in Oakland County, Michigan based on parcel based land-use for the year 2005.

A third alternative is a land-cover approach based on classification of digital remote sensing data. Although this approach is often problematic when coarse sensors (e.g. Landsat ETM) are used (McMahon, 2003; Yang et al., 2003), within the study area the opportunity existed to use high-resolution digital aerial imagery collected by the U.S. Department of Agriculture's National Agricultural Imagery Program (NAIP; http://165.221.201.14/NAIP.html). This imagery was collected in the summer of 2005 at a spatial resolution of one meter. Although four bands (blue, green, red, and near infrared) were collected, sensor and processing difficulties with the near-infrared band led to ghosting and other problems.

The NAIP imagery also has some limitations with regard to tonal balance. In particular, a band oriented north-south in the western half of the county is considerable darker than the rest of the imagery. An image of the county-wide NAIP image mosaic is shown in Figure 9. This tonal variation adversely affected some of the classifications, particularly the distinction between trees and grass.

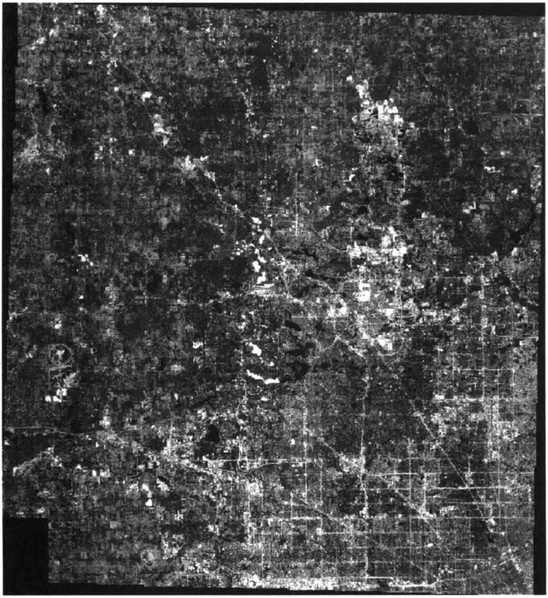

Figure 9: The U.S. Department of Agriculture's National Agricultural Inventory Program image of Oakland County, collected in 2005, showing some tonal variation in the western half of the image.

The three visible bands, however, are generally suitable for identifying the broad land cover classes present in the study area, and particularly distinguishing pervious and impervious surface. The imagery was classified into seven broad classes: open water, pavement, trees, grass, wetland, rooftop, and bare earth, using multiple training sites for each class. Coordinates of the training sites are presented in Table 3. A confusion matrix (also known as an error matrix or contingency table) identifies the classified value of a point along the column, and the known or independently verified value of the point in the rows (Lillesand and Kiefer, 2000, Van Genderen, 1977). A random sampling field of 1052 points was created filling the total extent of the county. The classification of each point was checked manually by visual inspection. The confusion matrix for the overall classification is shown in Table 4. Values along the diagonal of the matrix indicate correctly classified points. Values off the diagonal are incorrectly classified. The overall accuracy of a classification may be calculated by a Kappa statistic, in this case 0.61. Accuracies for individual classes are calculated below with both a "producer's accuracy" and "user's accuracy."

Table 3: Locations of training sites in Oakland County, Michigan used to classify land-cover types from 2005 National Agricultural Inventory Program imagery. Coordinate locations are centroids of features, expressed in meters, Universal Transverse Mercator projection (zone 16), 1983 North American Datum.

Cover type	Easting (m)	Northing (m)
Bare earth	315,069	4,732,215
Bare earth	315,051	4,733,628
Forest	313,986	4,731,422
Grass	315,210	4,732,337
Pavement	315,438	4,731,299
Pavement	315,242	4,732,134
Rooftop	314,535	4,732,957
Water	312,396	4,732,074
Water	315,861	4,731,592
Water	315,915	4,731,059
Wetland	314,520	4,732,739

Principal areas of confusion in the classification relate to the difference between tree canopy and grass, and to the water and wetland classification. Because the classification is strictly spectral, and does not benefit from pattern recognition or other enhancements, the difference between a tree canopy and a well-maintained grass, such as a suburban lawn or a golf course, is difficult to distinguish. Similarly, several cases were noted during inspection when the spectral difference between a body of water and an adjoining grass area was negligible; identification by visual inspection weighed on the shape of the feature or the presence of boat wakes. This issue also bears on the classification of wetlands, in this case emergent wetlands. Classification of wetlands was generally rather poor.

Table 5 shows a reduced confusion matrix, differentiating only pervious and impervious cover types. In this case, covers were identified correctly almost 88% or the time. Many of the cover issues discussed previously are not relevant in this classification. This classification breaks down to essentially features with chlorophyll compared to features without chlorophyll. The principle issue in this classification is the confusion between bare earth and either pavement or rooftop.

Table 4: Confusion matrix and accuracy statistics for the automated classification of 2005 National Agricultural Inventory Program imagery for Oakland County, Michigan into various land-cover classes.

		Actual						
		Water	Pavement	Trees	Grass	Wetland	Rooftop	Bare earth
Classed	Water	8	0	2	2	0	0	0
	Pavement	0	73	0	0	0	9	15
	Trees	16	0	495	115	16	0	0
	Grass	1	0	9	157	1	2	1
	Wetland	15	2	14	8	16	0	2
	Rooftop	0	18	0	0	0	32	4
	Bare earth	0	5	0	0	0	3	11

Producers Accuracy		Users Accuracy	
Water	0.20	Water	0.67
Pavement	0.74	Pavement	0.75
Trees	0.95	Trees	0.77
Grass	0.56	Grass	0.92
Wetland	0.48	Wetland	0.28
Rooftop	0.70	Rooftop	0.59
Bare earth	0.33	Bare earth	0.58

Kappa = 0.61

Table 5: Confusion matrix and accuracy statistics for the automated classification of 2005 National Agricultural Inventory Program imagery for Oakland County, Michigan into pervious and impervious land covers.

		Actual	
		Impervious	Pervious
Classed	Impervious	132	19
	Pervious	12	889

Kappa = 0.88

	Producers Accuracy	Users Accuracy
Impervious	0.92	0.87
Pervious	0.98	0.99

Figure 10 presents a subdivision as shown in the NAIP imagery and after classification. An additional concern in using NAIP imagery for this sort of analysis is the extent to which impervious surface is obscured by canopy. NAIP imagery is collected during the height of the growing season, so some structures and pavements will be obscured by canopy. However, all color digital imagery collected in Oakland County in the last decade has been at least partially leaf-on; NAIP was selected for this study because it is 1) available without restriction in the public domain, and 2) available across the continental United States with similar specifications, increasing the generalizability of the methods.

Figure 10: An example of NAIP imagery (left) and classified pervious-impervious surface (right) for a mixed land-cover area of Oakland County, Michigan. In the classified image, white areas are impervious, gray areas are pervious.

To address the concern of canopy obscuration, 500 parcels representing all use types, sizes, and development dates were selected at random to evaluate the extent to which canopy would obscure features on the ground. Although there is an apparent contradiction in estimating the extent of features that are obscured, operationally the shapes of man-made features tend to be predictable – observing a driveway on two sides of a tree canopy, one could safely assume the driveway continues under the canopy. Certainly the potential exists to miss a small out building or patio, but the major impervious features of residential parcels (dwelling structures and driveways) are almost always distinguishable. In commercial or transportation land-use settings, canopy obscuration is negligible.

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Results of the analysis are shown in Table 6. Although size of parcel had relatively little effect, the age of the parcel had a substantial effect on the degree to which impervious surface was obscured. Parcels developed since 1980 had, on average, about 7 percent of their impervious surface obscured, compared to approximately 30 percent for parcels developed before 1960. Similarly, where 60 percent of the parcels developed after 1980 were completely unobstructed, only 17 percent of the parcels developed before 1960 were unobstructed. This differentiation will be considered in the subsequent analysis of land cover.

Table 6: Impervious surface obstruction by leaf canopy in Oakland County for residential parcels less than one acre in size, estimated from 2005 National Agricultural Inventory Program imagery.

	Impervious surface obscured		Number of parcels	Parcels
Year built	Average	Maximum	unobstructed	inspected
Before 1940	30	80	6	31
1940 -1960	28	90	16	88
1960 -1980	15	100	38	83
1980 -2005	7	50	31	53

When comparing the various land-use and land-cover datasets, there is a tension between spatial precision and attribute precision. The NAIP-based data are high resolution spatially (1m pixel), but attribute-poor (in one form, binary – pervious or impervious). Attempts to increase the attribute value of the classification, to differentiate commercial from residential structures, for instance, will decrease the accuracy of the classification. In contrast, the parcel data is noticeably coarser spatially (typically 500 square meters or more), but contains information on the use, age, and size of the parcel. Full assessing records contain a wealth of additional information on improvements (sewer and water availability, for instance) that will never be available through automated remote sensing. This tension is mirrored in the amount of labor associated with generating the datasets – where the parcel-based assessing database involves years of effort but is detailed and accurate for its purpose of valuing property, the classification of remote sensing imagery involves days of effort, but is substantially less detailed.

Each dataset provides a different mechanism to quantify change through time. The first polygon land-use data for the study area was developed as part of the Michigan Department of Natural Resources Michigan Resource Information System (MIRIS). Standardization of both the spatial and attribute content of the datasets was a primary concern in ensuring that land-cover changes identified were indeed true changes, not the result of positional or classification differences between datasets. Classification errors result from differences in attribution standards, either among photo interpreters in a single time period or between different mapping efforts. The more specific the classification, the more subjective error will be introduced. For instance, a light-industrial parcel could easily be confused for a commercial parcel based on aerial photography, but both would unquestionably be classified as "urban." Although all data were developed by visual classification of aerial imagery, differences in standards, classification schemes, and even software result in small differences between data sets. The datasets used in this project were created at five different times over a period of approximately twenty years by countless individual photointerpreters. Consistency within one mapping effort might be possible, but complete consistency through a data series spanning twenty years is unlikely. Further, the classification system itself changed slightly through time, resulting in slight inconsistency (Aichele, 2005a).

The parcel-based land-use classification includes an attribute describing the year the primary structure was built for residential parcels, although frequently not for commercial and transportation rights-of-way. Thus for residential parcels it is possible to "roll back" the landscape based on the construction date. Commercial parcels were estimated based on the average construction date of the survey section they fall in. This approach is an approximation, but in the absence of better data implies development at roughly the same time as the surrounding area. Comparatively, the area occupied by residential land uses is approximately one order of magnitude greater than the area of other "developed" uses, so this approximation is relatively minor.

Little comparable digital aerial imagery exists prior to the 2005 NAIP flight, making a direct comparison difficult. However, using the information from the parcel construction dates, it is possible to assign a date to the creation of impervious pixels, and thus gradually accumulate impervious surface over time. It is also possible to identify how many impervious surface pixels are located in a specific parcel, a specific class of parcels (e.g., single family residential, less than 8000 square feet), and a specific age of parcel (e.g., single family residential, less than 8000 square feet, built in 1957). These data were used to estimate patterns and trends in impervious surface associated with residential development through time.

Stream Flow Analysis

Daily stream-flow records were obtained for six U.S. Geological Survey (USGS) gaging stations in the study area. Gaging sites and watersheds are shown in Figure 11. Information about the gages is shown in Table 7. All sites operated continuously throughout the period from October 1, 1969 to September 30, 2005 (Water-years 1970-2005). Data were retrieved from the USGS National Water Information System (NWIS) database (http://mi.water.usgs.gov/mi/nwis). Stream flows are estimated based on the relationship of stage (elevation of the water surface above a datum) to discharge (Kennedy, 1984). Stages are measured in a stilling well, a well with one or more direct pipe connections into the stream channel. Stages were measured hourly and recorded mechanically on paper punch tape until the early 1990's, when the advent of digital recorders allowed 15-minute measurements(LeuVoy, personal communication, 2007).

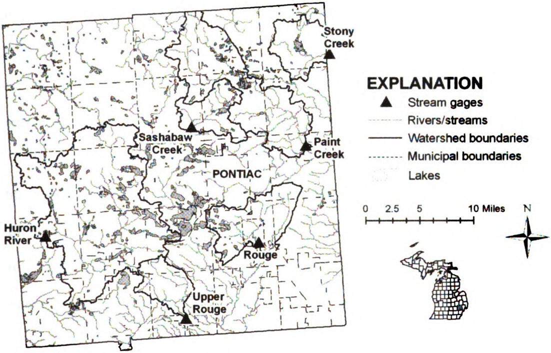


Figure 11: Locations of selected watersheds and gaging stations in Oakland County, Michigan.

Table 7: Characteristics of selected stream gages in Oakland County, Michigan.

USGS Station ID	Station Name	Year Started	Area (square miles)	Area (square km)
04160800	Sashabaw Creek nr Drayton Plains, Mich.	1959	20.9	54.1
04161540	Paint Creek at Rochester, Mich.	1959	68.2	176.6
04161580	Stony Creek nr Romeo, Mich	1964	25.6	66.3
04166000	River Rouge at Birmingham, Mich.	1950	33.3	86.2
06166300	Upper River Rouge at Farmington, Mich.	1958	17.5	45.3
04170000	Huron River at Milford, Mich.	1948	132	341.7

This stage-discharge relationship is updated periodically under varying flow conditions, typically at least every six weeks and in conjunction with exceptional events. Stream-flow measurements are made using a wading rod and either a mechanical flow meter or a hydro-acoustic flow meter. The relationship between stage and discharge may change through time, because of changes in stream morphology or because of seasonal growth of in-stream vegetation. These changes are incorporated as a 'shift' in the record, adding or subtracting from the stage value when calculating discharge. These shifts are applied to the daily data, not to unit data, making unit data somewhat less accurate. Prior to the early 1990s, unit data were not recorded digitally (LeuVoy, personal communication, 2007).

Precipitation data were also collected at various sites in the region through a partnership between the Michigan State Climatologist's Office and SEMCOG using continuous, analog, weighing-bucket recorders beginning in the late 1960s and continuing through the early 2000's. Digital scans of the original paper records are maintained at the Michigan State Climatologist's Office. In theory, it might be possible to construct unit hydrographs to quantify shifts in the stream response to precipitation. However, although precipitation was measured continuously, the hourly resolution of stream-flow data during the first 20 years of the study period did not provide sufficient temporal detail to distinguish a difference in response between precipitation events in the 1970s and events in the 2000s.

In lieu of unit hydrographs, a variety of tests were performed on the daily stream-flow characteristics, both individual statistics and characteristics of the flow duration curve (FDC). The daily data were tested for temporal trends in several characteristics.

The first characteristic is peak flow – the highest flow recorded annually. Kendall's Tau and Spearman's Rho statistics for each series of peak flows compared to the year were calculated using Systat 11 (Systat Software, 2004). The modified Mann-Kendall non-parametric trend statistic (Hirsch and Slack, 1984) and Sens slope (Sen, 1968) were also calculated, using an Excel-based technique developed by the Finnish Meteorological Institute (Salmi et al., 2002). Non-parametric statistics were used because the time variable does not meet the normality assumptions of a standard parametric correlation.

To evaluate the more subtle aspects of stream flow, the individual measurements of the FDC were employed (Smakhtin, 2001). For each site-year of stream-flow record, the 1st, 5th 10th, 25th, 50th (median), 75th, 90th, 95th, and 99th percentile flows were calculated. Each percentile flow was tested for trend using the four statistics described previously. A baseflow-dominated watershed would typically have a flatter CFD, whereas a flashier, run-off dominated watershed would have a steeper FDC (Smakhtin, 2001), as shown in Figure 12.

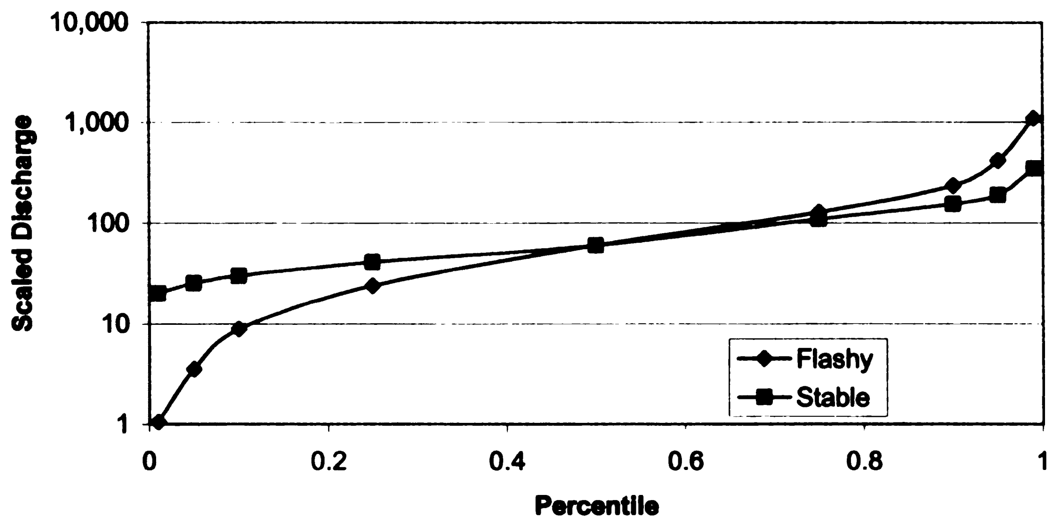


Figure 12: Generic flow duration curves for stable and flashy streams.

To quantify change (or non-change) in stream-flow characteristics, the slope of the CFD between the 10th and 90th percentiles, and between the 25th and 75th percentiles were calculated. This method is a simplification of the approach proposed by Best et al. (2003). Where Best et al. (2003) proposed a general approach comparing differing watersheds with potentially different areas, precipitation, and median flows, working with a single basin allows use of simply the slope of the curve through the median value. It is expected that the 10th and 90th percentile comparison will be more sensitive to changes in the peak- and low-flow characteristics. For each site, these slopes were then checked for trend using all four of the trend statistics described previously. Again, the time variable is not normally distributed, and the expectation is that there will be both a trend and a serial autocorrelation to the data, making a conventional parametric correlation inappropriate.

Finally, to evaluate the possibility of trends in variability (frequently referred to as flashiness), the standard deviation of daily flows, was calculated for each year. This annual standard deviation of daily flows was also tested for trend with both Kendall's Tau and Spearman's Rho.

Watershed Modeling

Testing the effects of climate and land cover change in real watersheds, other than Hubbard Brook, New Hampshire (Campbell et al., 2007) and a few other select sites, is not generally practical. To test hypotheses and understand relationships, one must turn to models. Every model has limitations, however a well constructed, process-based model can be instructive as an experimental tool to test watershed response to specific treatments. The Soil Water Assessment Tool (Arnold and Fohrer, 2005) has been used extensively around the world, and shown to provide good results in climates and land-use situations similar to those found in Oakland County, Michigan.

THE SWAT MODEL

The Soil Water Assessment Tool (SWAT) was developed by the Texas Agricultural Experiment Station and the USDA Agricultural Research Service (Arnold and Fohrer, 2005). Since its development, the SWAT model has become perhaps the most widely utilized surface water and watershed modeling application internationally. This model has been widely used around the world to describe and understand watershed processes over 250 applications of this model to diverse settings and problems problems within the peer-reviewed literature (Gasmann et al., 2007). At its most basic level, SWAT is a basin-scale, continuous-time model designed to estimate runoff, evapotranspiration, ground-water recharge, ground-water discharge, and various water-quality characteristics. This is accomplished by routing flow across Hydrologic Response Units (HRUs), watersheds or subwatersheds with similar characteristics. Over the last 10 years, the basic model has been continuously refined to address issues such as multiple HRUs in a basin (SWAT94.2), canopy storage and estimation of potential evapotranspiration with the Penman-Monteith methodology (SWAT96.2), snowmelt (SWAT98.1), bank storage of water (SWAT99.2), and Green-Ampt infiltration, as well as substantially improved and expanded climatic inputs (SWAT2000; Arnold and Fohrer, 2005). In 2002, the USEPA integrated SWAT into its BASINS application, distributing it to state, tribal, and local governments for estimating Total Maximum Daily Loads (DiLuzio et al., 2002).

A variety of modifications have been made to the original model to address specific application issues. Pachepsky et al. (2007) used SWAT to evaluate the effectiveness of filter strips in decreasing pathogen delivery. Various authors (e.g., Benavides-Solorio et al., 2007) have used SWAT to estimate delivery of suspended sediment. SWAT's effectiveness at predicting streamflow was found to be good, with Nash-Sutcliffe efficiencies of 0.90 (Ahl et al., 2007), although performance in winter months is generally not as good as in summer months (Levesque et al., 2008; Wang and Melésse, 2005; Fontaine et al., 2002). Numerous authors have used SWAT for runoff and water quality modeling, including Tong and Naramngam (2007).

Peschel et al. (2006) and Smith and Peschel (2006) used SWAT to separate the effects of land use change and climate change on recharge to the Edwards Aquifer in Texas. Jha et al. (2006) used SWAT to estimate the effects of a range of climate change scenarios on the Upper Mississippi River, with good quality results across a range of scenarios of varying precipitation and CO_2 concentrations. Menking and Minder (2004) used SWAT to evaluate the effects of urbanization in a heavily developed watershed near Poughkeepsie, New York.

Kalin and Hantush (2006) used SWAT, combined with inputs from the NEXRAD weather radar system, to predict streamflow in the Pocono Creek watershed of Pennsylvania. Model performance at the monthly time scale was slightly better with NEXRAD precipitation data, but performance at the daily time scale was superior using rain gage data. This likely indicates the trade off between the better spatial discretization of NEXRAD compared to the higher quality point measurement of a conventional gage. Spatial discretization is one of SWAT's greatest strengths. Arabi et al. (2006) identified through simulation an optimal HRU size less than or equal to approximately 4% of the overall watershed.

Chu and Shirmohammadi (2004) were unable to achieve an acceptable calibration of SWAT in a small (340 ha) watershed in Maryland due to deep ground-water discharge to the stream. Even after attempting to take the discharge into account, the predictions significantly underpredicted stream flow at the daily time step, although adequately representing monthly discharge. Spruill et al. (2000) were able to achieve good results even in the karst region of Kentucky, after incorporating appropriate calibration data to address solution channels transferring flows between topographic watersheds. Wu and Johnston (2007) used SWAT to evaluate the effects of climate change in the South Branch Ontonogan River of northern Michigan, again finding very high Nash-Sutcliffe efficiencies.

In applying a physically-based model, the quality of the input data sets becomes very relevant. Peschel et al. (2006) identified a systematic bias in the result of models developed with SSURGO soils data as compared to STATSGO data. Specifically, runoff and ET were reduced, while deep percolation was enhanced. Wang and Melesse (2006) also found a bias between SSURGO and STATSGO, although in that case SSURGO was found to somewhat over estimate low stream flows. However, DiLuzio et al. (2005) identified the elevation model and land use as much more sensitive input parameters than soils. Earls and Dixon (2005) used input data sets a resolutions ranging from 240m to 30m, and identified a systematic trend to underprediction with increasing cell size.

SWAT MODEL DEVELOPMENT

The models were calibrated to match the stream-flow characteristics described by the FDC, in terms of the flow frequency distribution and the magnitudes of both high and low flows, as well as annual flow volumes. Several other models (e.g., HSPF, HEC) exist that provide more robust routing capabilities, but at the expense of obscuring watershed processes.

Modeling activities focused on one example watershed within the study area, with the intent of understanding how a single change in the system (e.g., land use or climate) would affect streamflow. The Paint Creek watershed is a mixed rural-suburban-urban watershed in the northeast part of Oakland County, gaged near Rochester, Michigan. This watershed drains to Lake St. Clair through the Clinton River. The watershed is approximately 176 square kilometers (68 square miles) in area, and approximately 28 km (17.4 miles) long.

Standard input data, common to all variations of the model used in this study include elevation, stream channels, and soils. Elevation data were obtained from the U.S. Geological Survey National Elevation Dataset, at a resolution of 1/9 arc second (approximately 3m or 10ft). This dataset was collected jointly by Oakland County and the USGS in the spring of 2008, and is available in the public domain (http://ned.usgs.gov). The overall watershed and subwatershed boundaries were derived using this elevation dataset.

Stream channel data were obtained from the National Hydrography Dataset at a scale of 1:24,000. This dataset is maintained jointly by the USGS and the State of Michigan, and is available in the public domain (http://nhd.usgs.gov). These data were used to "burn in" the channel locations on the elevation model, and more importantly to control the locations of outlets and confluences within the model. A separate network is created during model set up to carry model-specific attributes. This network closely aligns with the original network, but is generally slightly less extensive. The watershed was divided into 41 subbasins, which are shown in Figure 13.

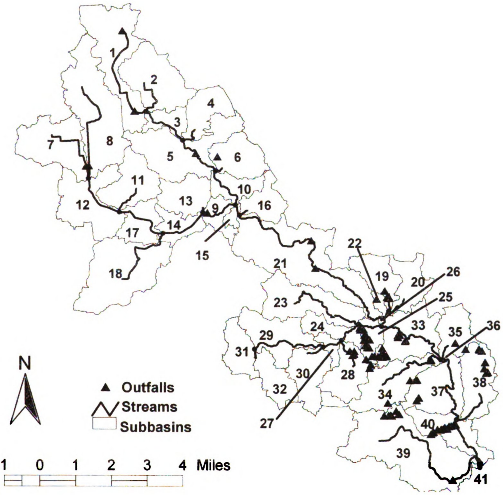


Figure 13. Map of the Paint Creek watershed, showing subbasins, outfall locations, and model generated stream channels.

Figure 13 also shows the consolidated outfalls mapped by the Oakland County Water Resources Commissioner's office (Ron Fadoir, written communication, 2005).

This dataset was developed by physically walking every section of channel, and collecting location and construction information on every outfall observed. Although the presence of these outfalls likely has some effect of accelerating runoff, they are concentrated in a few downstream watersheds, and likely have a limited effect on the response of the overall watershed.

Soils data for the model were downloaded from the SWAT reference site (http://www.brc.tamus.edu/swat/) and are derived from Natural Resources Conservation Service STATSGO source data (http://soils.usda.gov/survey/geography/statsgo). Although other soils datasets can be used, this dataset has been extensively attributed and documented by the model developers. The last major input components of the model are land-use or land-cover data, and climate data, which varied depending on the specific experiment. Observed climate data were obtained from NOAA Summary of the Day (NOAA/NCDC, 1976-2006) for the station at Milford, Michigan.

The general land-use and land-cover datasets were described previously. For both the SEMCOG land-use and the Oakland County parcel-based land-use, land-use categories were associated with standard SWAT land-cover types. These associations are shown in Tables 8 and 9.

Table 8: SEMCOG (2000) Land-use codes in the Paint Creek Watershed, and associated SWAT land-use codes.

SEMCOG Land-use Code	Short description	SWAT Land-use Code
1120	Urban, Resdential, Multi-family	URHD
1130	Urban, Resdential, Single-family	URMD
1150	Urban, Residential, Mobile Home park	URHD
1171	Urban, Residential, under development, 75% built	URLD
1172	Urban, Residential, under development, 50% built	URLD
1173	Urban, Residential, under development, 25% built	URLD
1174	Urban, Residential, under development, 0% built	URLD
1190	Urban, developing	URLD
1210	Urban, Commercial, CBD	UCOM
1220	Urban, Commercial, Malls/Retail	UCOM
1240	Urban, Mixed Business	UCOM
1260	Urban, Instutional	UCOM
1300	Urban, Industrial	UIDU
1380	Urban, Industrial Park	UIDU
1410	Urban, Transportation, Air	UTRN
1420	Urban, Transportation, Rail	UTRN
1441	Urban, Transportation, Limited-Access Road	UTRN
1460	Urban, Utilities	UTRN
1461	Urban, Utilities, Electric	RNGE
1464	Urban, Utilities, Solid Waste	UIDU
1710	Open pit/Extractive	UIDU
1930	Outdoor Recreation	PAST
1940	Cemetery	PAST
2100	Agriculture, Cropland	AGRL
2200	Agriculture, Orchard	ORCD
2300	Agriculture, Confined Feeding	PAST
2400	Agriculture, Permanent Pasture	PAST
2900	Agriculture, Other	PAST
2910	Agriculture, Other, Farmstead	URLD
3100	Grass and Shrub, Herbaceous	RNGE
3200	Grass and Shrub, Shrub	RNGB
4120	Forest, Broad leaf, Central Hardwood	FRSD
5200	Lake	WATR
6120	Wetland, Forested, Shrub	WETL
6210	Wetland, Non-forested, Non-emergent	WETL
6220	Wetland, Non-forested, Emergent	WETL

Table 9: Oakland County, Michigan, parcel land-use codes, 2005, and associated SWAT land-use codes.

Land Use Code	SWAT Land-use code	SWAT Description
Agricultural	AGRL	Agricultural
Commercial/Office	UCOM	Urban - Commercial
Extractive	UIDU	Urban - Industrial
Industrial	UIDU	Urban - Industrial
Mobile Home Park	URHD	Urban - Residential - High Density
Multiple Family	URHD	Urban - Residential - High Density
Public/Institutional	RYEG	Rye Grass
Railroad Right-of-Way	UTRN	Urban - Transportation
Recreation/Conservation	RNGB	Range and Brush
Road Right-of-Way	UTRN	Urban - Transportation
S.F. More than one unit per parcel	URHD	Urban - Residential - High Density
Single Family, 1 to 2.5 Acres	URML	Urban - Residential - Medium-low Density
Single Family, 14,000 to 43,599 sq. ft	URMD	Urban - Residential - Medium Density
Single Family, 2.5 to 5 acres	URLD	Urban - Residential - Low Density
Single Family, 5 to 10 acres	URLD	Urban - Residential - Low Density
Single Family, 8,000 to 13,999 sq. ft.	URMD	Urban - Residential - Medium Density
Single Family Greater than 10 acres	URLD	Urban - Residential - Low Density
Single Family Less than 8000 sq. ft.	URHD	Urban - Residential - High Density
Transportation/Utility/Communication	UTRN	Urban - Transportation
Vacant	RNGB	Range and Brush
Water	WATR	Water

Model calibration focused on two main objectives. First, the model was adjusted to match the overall volume of water discharged from the watershed with the observed discharge at the USGS stream gage – Paint Creek near Rochester, Michigan, gage number 04161540. The second objective was to match the annual flow frequency distribution for calendar year 2005 created by the model to the observed frequency distribution from the stream gage.

Calibration proceeded roughly as described in the manual (Neitsch et al., 2002, chapter 33). Overall volumes were generally increased using the GW_REVAP, REVAPMN, SHALLST, and GWQMN variables. Adjustment of the ESCO and EPCO variables away from the default settings (0.95 and 0.05, respectively) had relatively little effect. Overall stream discharge volumes for the SEMCOG-, parcel-, and NAIP-based land cover representations were 12.08 inches, 11.48 inches, and 10.97 inches respectively, compared to an observed value of 11.48. In each case, the ground-water component developed by the model was noticeably less than previous estimates of baseflow in the watershed. Baseflow estimates for the SEMCOG-, parcel-, and NAIP-based land-cover representations were 2.94 inches, 3.07, and 5.05 inches, respectively (Figure 14), compared to literature values of 6.6 inches (MDEQ, 2005) and 8.1 inches (Holtschlag, 1996). When the SWAT percolation term is added to each model run, the total ground-water components of the water budget become 3.78 inches, 4.25 inches, and 6.41 inches, for the SEMCOG, parcel, and NAIP based models respectively. Base-flow separation comes under routine criticism as a technique grounded in very little testing or empirical evidence, colorfully described as "one of the most desperate analysis techniques in use in hydrology" (Hewlett and Hibbert, 1967) and "that fascinating arena of fancy and speculation" (Applby, 1970). Although these authors perhaps take an extreme position, their views highlight the speculative nature of base-flow separation. In the absence of a direct physical or chemical measurement, judging between competing estimates is difficult.

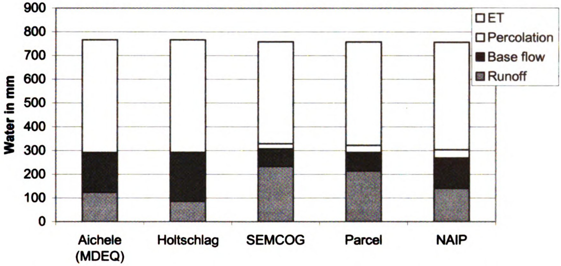


Figure 14: Model-estimated water-budget components for Paint Creek from different land cover classifications for the 2005 calendar year compared to previous estimates.

Matching the flow frequency distribution was accomplished largely by altering the recession constant (ALPHA_BF), and the surface water lag coefficient (SUR_LAG). These alterations largely addressed the lower flow portion of the distribution; however the model still tended to create higher peak flows than observed. Although the individual storm magnitudes varied, modeled peaks were often double the observed peaks. This overall flashiness was addressed by additively increasing the Manning's n coefficients in the upstream basins considerably (Table 10). The n coefficients were increased based on model-estimated channel width in each subbasin. These elevated n values compensate for various inline wetlands, low-head dams, and other obstructions present in the upstream watersheds that create in-channel storage. These values were carried through all versions of models. Finally, although hydraulic routing is not a strong point of the SWAT model, the Muskingum routing approach (Brakensiek, 1967) provided more comparable results in terms of flood peaks and low flow volumes than the default variable storage routing approach (Williams, 1969). A listing of the various fitted model parameters can be found in Table 11.

Table 10: Manning's n values for subbasins in the Paint Creek watershed SWAT model

Subbasin Number	Channel Width (m)	Manning's n
1	4.7	0.35
2	3.9	0.35
3	7.0	0.22
4	2.7	0.35
5	9.6	0.22
6	2.9	0.35
7	3.9	0.35
8	5.3	0.22
9	13.1	0.20
10	10.8	0.20
11	3.2	0.35
12	8.5	0.22
13	2.8	0.35
14	12.2	0.20
15	18.3	0.20
16	2.3	0.35
17	10.0	0.20
18	5.0	0.35
19	2.5	0.35
20	2.5	0.35
21	20.3	0.37
22	4.1	0.35
23	3.9	0.35
24	8.1	0.17
25	9.8	0.17
26	21.2	0.05
27	6.7	0.17
28	2.9	0.35
29	5.3	0.22
30	2.9	0.35
31	2.4	0.35
32	2.4	0.35
33	25.1	0.05
34	3.7	0.35
35	2.5	0.35
36	25.7	0.05
37	26.6	0.04
38	3.2	0.35
39	6.0	0.22
40	27.5	0.04
41	28.8	0.04

Table 11: Fitted parameters for the Paint Creek watershed SWAT model.

Parameter	Value	Units	Description
GW_DELAY	60	Days	Ground-water delay time (days)
REVAP_MN	10	mm	Minimum amount of water in shallow aquifer for capillary rise
SHALLST	500	mm	Initial storage in shallow aquifer (mm)
GWQMN	10	mm	Minimum amount of water in shallow aquifer base flow
ESCO	0.95	none	Soil evaporation constant
EPCO	0.05	none	Plant uptake compensation factor
SUR_LAG	1.5	Days	Surface runoff lag coefficient
ALPHA_BF	0.05	recession constant	Baseflow alpha factor

Additional information on variables is available in Nietsch and others, 2002.

Watershed model experimentation

UNDERSTANDING THE EFFECTS OF LAND COVER RENDERING

The first experiment conducted with SWAT was to evaluate the effect of differing representations of land-use/land-cover, holding all other inputs constant. Daily climatological data for the calendar year 2005 were obtained from the Michigan State Climatologist's Office (Andresen, written communication, 2008). Data series included daily maximum and minimum temperatures (°C), daily precipitation (mm), and daily solar radiation (MJ/m^2). A base model was developed using the SEMCOG land-use data and calibrated to match the range of flow values observed at the stream gage on the watershed, as described previously. The model was run for one year prior to the experiment year using synthetic data to allow the system to come to equilibrium. After calibration, each model was modified by substituting first the parcel-based land-use, then the NAIP-based land-cover, and rerunning the model. All other aspects of the model –

soils, climate, topography, channel geometry and condition – were held constant so that the only variable affecting the result was the rendering of land cover. This test provided three strings of daily stream-flow data, as well as water budget information, with which to compare the effects of different renderings of land use on estimated stream flow. The results were compared for both fit to observed stream-flow data and components of the water budget.

UNDERSTANDING THE EFFECTS OF LAND-COVER CHANGE

The second experiment conducted with SWAT was to evaluate the effects of land cover change, measured by each rendering, on predictions of stream flow. Each dataset, the SEMCOG Land-use/Land-cover (LU/LC), the Oakland County Parcel Land Use, and the NAIP-derived land cover, was modified to reflect as closely as possible the land cover conditions of 1975. The procedure varied slightly based on the dataset.

In the case of the SEMCOG dataset, a similar dataset developed by the Michigan Department of Natural Resources (MDNR) Michigan Resource Information System (MIRIS) exists. This dataset was developed with similar techniques and a nearly identical classification system based on 1978 aerial imagery (RSGIS, 2002). SEMCOG has also developed a companion dataset to their LU/LC indicating the date built for 10 acre grids (quarter-quarter-quarter sections in the Public Land Survey System) throughout their region, including the Paint Creek watershed (Cain, written communication, 2009). By overlaying the date-built grid with the LU/LC data, it is possible to identify areas developed since 1975.

The 1978 MIRIS land-use/land-cover dataset was used to better understand the antecedent land uses in areas developed since 1975. By overlaying parcels developed since 1975 with the MIRIS LU/LC data, it is possible to identify, within the accuracy of the MIRIS data, the prior land use. These results are shown in Table 12. The dominant source of new urban land was "open land" (Anderson class 3) followed closely by land classified as agriculture (Anderson class 2), representing 33 and 27 percent of land developed since 1975, respectively. Forest and wetlands each only make up 10 percent of the land developed since 1975. The remaining 21 percent of development occurred in areas already described as urban in the MIRIS dataset.

Table 12: Pre-development land use of parcels developed since 1975, based on 1978 MIRIS land-use/land-cover data.

	Area		
Class	Acres	Square miles	Percent of total
Total	13,575	21	100%
Urban	2,801	4	21%
Agriculture	3,614	6	27%
Open	4,451	7	33%
Forest	1,380	2	10%
Wetlands	1,297	2	10%

Based on these results, pre-developed land was assigned a value of "Range with Brush" as compromise class indicative of abandoned agriculture, and approximating pasture land and urban open land. Finally, in the NAIP-based dataset, the parcel dataset was again used to identify which impervious or road parcels were developed after 1975, and these cells in the raster were again recoded to "Range with Brush."

Synthetic weather data based on 1970-2000 normals were used, including synthetic solar radiation data. This dataset included daily precipitation, daily maximum temperature, daily minimum temperature, and daily solar radiation based on climatic normals from 1971-2000. Daily estimates of solar insolation for the entire study period were synthetically generated on the basis of the observed precipitation and temperature data with the Weather Generator (WGEN) methodology of Richardson and Wright (1984). No other model parameter was altered. This resulted in three plausible simulations of stream flow and water budgets that might have existed had development ceased in 1975, with the difference based entirely on land-cover, and the rendering of land-cover. The results from runs with 2005 land cover were compared to results for 1975 land cover to evaluate 1) changes in the shape of the FDC, 2) changes in annual water budgets, and 3) changes in monthly or seasonal elements of the water budget.

UNDERSTANDING THE EFFECTS OF CLIMATE

The third experiment directly addresses the effects of climate change. In this experiment, a synthetic, trendless daily climate series was substituted while the other components of the model were held constant. In the first set of simulations, observed daily weather data from the National Weather Service cooperative station at Milford, Michigan were used (NOAA/NCDC 1961-2006). This dataset, obtained from the Michigan State Climatologist's Office, included three strings of daily data from 1961 – 2005, describing the daily precipitation, daily maximum temperature, and daily minimum temperature. Because solar radiation data were not recorded, a synthetic dataset was generated within SWAT based on the WGEN algorithm (Richardson and Wright, 1984). Simulations using this synthetic climate data were run for each variant of land cover. Additionally, the 1978 MIRIS polygon-based land cover and the simulated 1975 NAIP land cover were also used. Differences among this set of model outputs will be entirely due to the different input land-cover datasets.

In the second set of simulations, synthetic weather data based on 1970-2000 normals, including synthetic solar radiation data, were used. This dataset included daily precipitation, daily maximum temperature, daily minimum temperature, and daily solar radiation based on climatic normals from 1971-2000. Daily estimates of solar insolation for the entire study period were synthetically generated on the basis of the observed precipitation and temperature data with the Weather Generator (WGEN) methodology of Richardson and Wright (1984). All together, two 30-year watershed data series were generated for each land cover; one reflecting the observed variations in temperature, precipitation amount, precipitation frequency, and so on, and one showing a base-line scenario with no change in the temperature or precipitation. Flow frequency characteristics and water budget components of each data series were compared to identify changes in flow patterns or water budgets attributable to climate change.

In addition, monthly and seasonal trends in water-budget components were explicitly tested for trend using the modified Mann-Kendall non-parametric trend statistic (Hirsch and Slack, 1984) and Sen's slope (Sen, 1968) using an Excel-based technique developed by the Finnish Meteorological Institute (Salmi et al., 2002).

Chapter 3

RESULTS

Land-use/land-cover change trends

As noted earlier, population growth in Oakland County has been both rapid and persistent, averaging roughly 100,000 new residents every decade since World War II, with the only break occurring in the early 1980s (Figure 2). This growth in population, and accompanying the expansion of residential land use, has resulted in vast areas of Oakland County being converted from agriculture, forest, or other open space into a variety of residential forms (see Table 12). Most watersheds that were relatively "undeveloped" (meaning less than 25% urban land uses) in 1980 experienced a doubling of their urban land in the period from 1980 to 2000 (Table 1).

However, not all of these urban uses are equal from the perspective of hydrologic effect, particularly related to impervious surface. Even within the relatively narrow classification of single family residential (an Anderson level three classification; Anderson et al., 1976) the relationship between land use and land cover, particularly impervious surface, varies widely. Over the decades, the preferred form of residential development has changed considerably. By using construction date information from Oakland County's tax parcel database, it is possible to identify the change in preferences through time. As is shown in Figures 15 and 16, during the post-war building boom, the preferred styles were smaller, with annual starts on lots less than 8000 square feet exceeding 5000 units in 1950, and exceeding 46,000 units between 1946 and 1960. This single class in a 15 year time period accounts for over 15 percent of all residential parcels in Oakland County.

Housing starts on lot sizes greater than one acre experienced a similar surge in the 1950s, but a larger and more sustained surge following the recession of the early 1980s (Figure 15). The difference is that where larger parcel development was relatively strong during the 1980s and 1990s, development on lots less than 8000 square feet was virtually non-existent. Where this development has occurred, it is in redevelopment of existing small-lot, primarily lakefront, parcels.

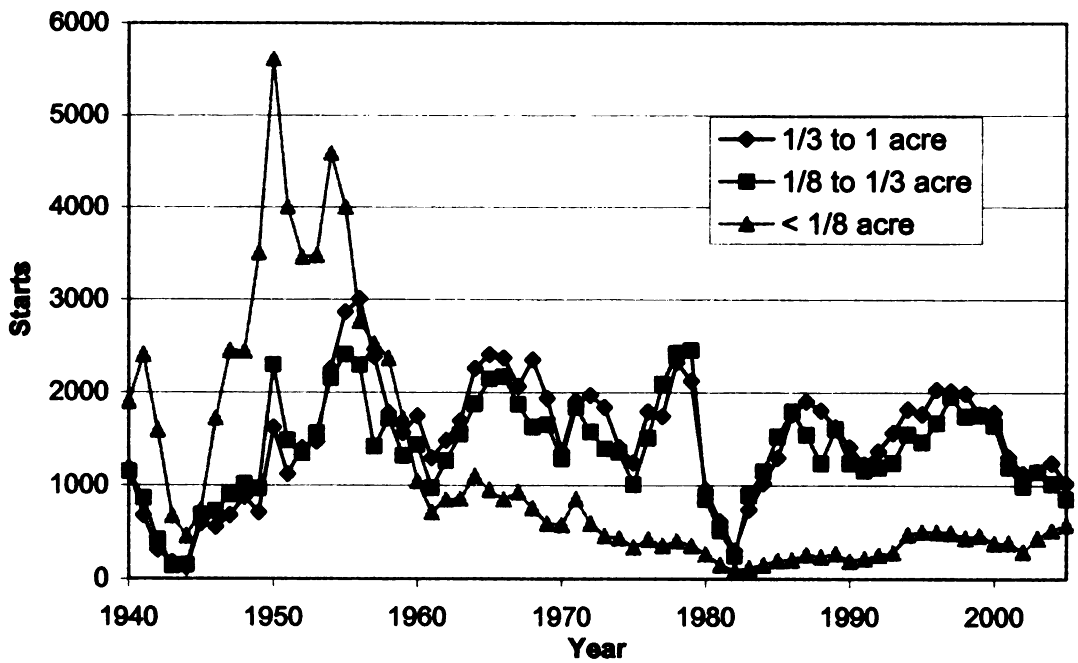


Figure 15: Number of housing starts by size of parcel, less than one acre, 1940 to 2005, in Oakland County, Michigan.

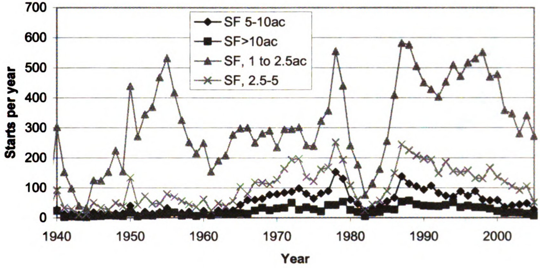


Figure 16: Number of single-family housing starts by size of parcel, greater than one acre, 1940 to 2005, in Oakland County, Michigan.

This shift in preference is evident at the parcel level, but is also written across the landscape of Oakland County. Figure 17 shows (on the left) the build date of residential parcels across Oakland County and (on the right) the parcels shaded by lot size. These maps are barely distinguishable from one another. Thus a temporal trend toward larger parcels, driven by social, economic, and technological changes, resulted in a distinct geographic pattern of development.

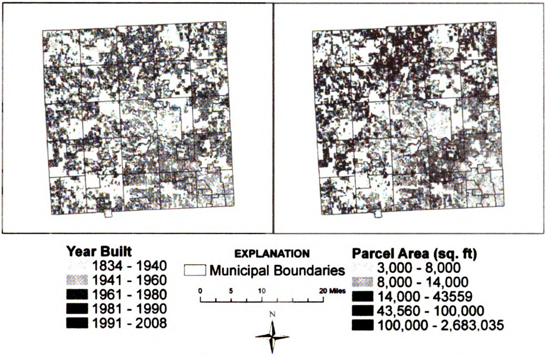


Figure 17: Comparison of parcel build date and parcel area. On the left, the build date of residential parcels in Oakland County, Michigan. On the right, the same residential parcels shaded by parcel size.

Even within an individual parcel size class (e.g., parcels less than 8000 square feet, for example), the allocation of space within that parcel, particularly impervious surface, has varied through time. Even more starkly, the impervious surface associated with larger parcel construction has ranged between 8 and almost 40 percent since 1940, although some of the data from 2000-2005 may be affected by the confusion between impervious surface and bare earth, noted in Table 4. Bare earth was approximately equally likely to be classified as pervious as it was to be classified as impervious. Visual inspection indicated that many parcels developed in the 2000-2005 timeframe included some bare earth or sparse vegetation, likely resulting in over-counting of impervious surface in these situations. These results are shown in Figure 18. Smaller parcels routinely devote a larger fraction of the total parcel area to impervious surface as compared to larger parcels. Some confusion may exist in the results for the last several years because of the previously described confusion between bare earth, typical of construction sites, and pavement. However, the overall trend in both datasets is toward increasing impervious surface, with both large and small lots containing almost twice as much impervious surface in 2000 as they did in 1940.

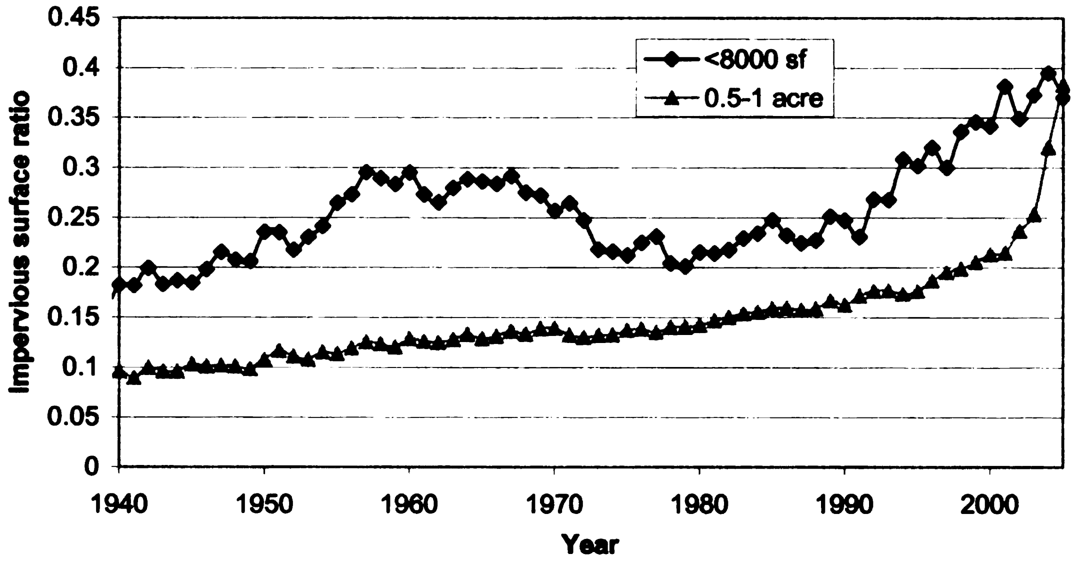


Figure 18: Impervious surface as a fraction of residential parcel area by year built, 1940 to 2005, of parcels less than 8000 square feet and parcels from 0.5 acre to 1 acre, Oakland County, Michigan.

The land area identified as urban is increasing at more than twice the rate of impervious surface (Figure 19). Both the digitized polygons and the parcel-based land-use present different impressions of watershed conditions. Appropriately, both the SEMCOG land-use and the parcel land-use describe much more of the watershed as urban than can be identified as impervious – a result that is reasonable based on less than 100 percent of the parcel being impervious. These results are shown in Table 13.

However, depending on the watershed and representation, the ratio of actual impervious surface to urban polygons varies from about 1:3 to as much as 1:14.

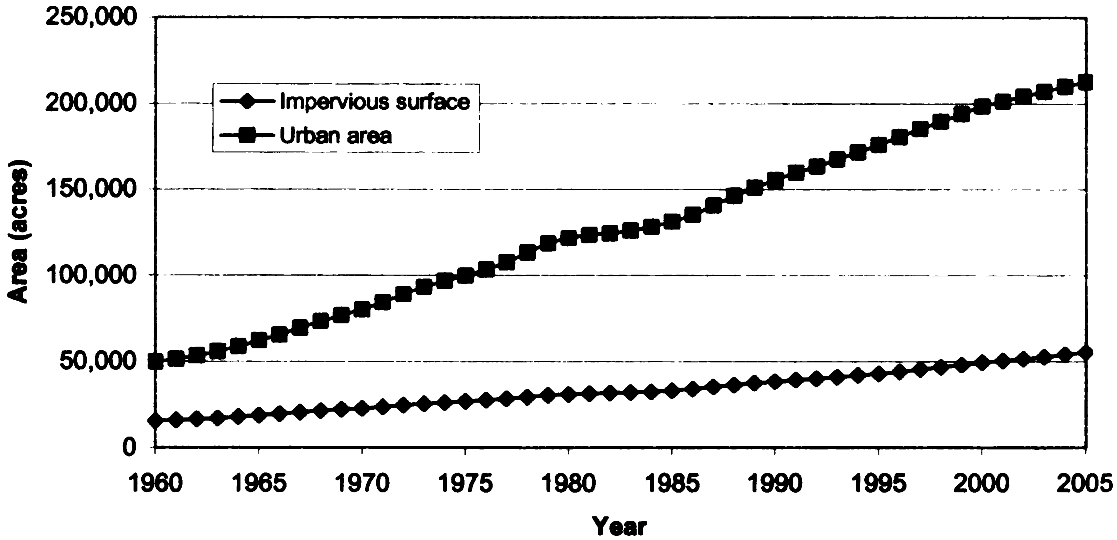


Figure 19: Accumulation of urban parcel area and impervious surface in Oakland County, Michigan, 1940 – 2000.

Table 13: Land classified as urban and impervious from different land use and land cover dataset for selected watersheds in Oakland County, Michigan, 2005.

	Total Area (square kilometers)	NAIP 2005 (impervious)	SEMCOG 2000 (urban)	Parcel 2005 (urban)
Sashabaw Creek	54.1	16%	50%	60%
Paint Creek	176.6	13%	52%	64%
Stony Creek	66.3	4%	30%	55%
River Rouge	86.2	21%	86%	84%
Upper River Rouge	45.3	22%	80%	76%
Huron River	341.7	13%	49%	52%

Although at a broad scale (county- or region-wide) the accumulation of impervious surface is occurring at a relatively constant rate, the actual installation of that impervious surface varies in density and location through time. Thus, using generic coefficients derived over a large area (a county, for example) to describe impervious surface (e.g. Capiella and Brown, 2001), may not provide a good approximation of impervious surface in small watersheds or HRUs, with the issue becoming more acute as spatial discretization of the model increases.

Results of Stream flow analysis

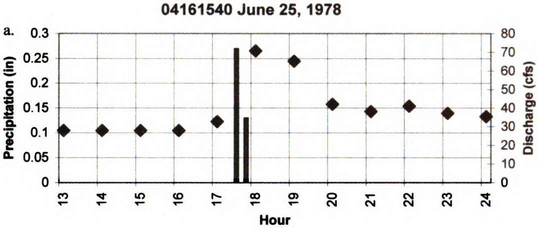
UNIT HYDROGRAPHS

As was noted in chapter 2, attempts to construct unit hydrographs for periods prior to 1992 were problematic because of a lack of temporal resolution in the streamflow data; attempts with later-period data were complicated by a sharp decline in the availability and consistency of precipitation records (Ordway, written communication, 2008). One event in two watersheds, on June 25, 1978, serves to illustrate the point.

The two watersheds in question are Sashabaw Creek, gaged near Drayton Plains, and Paint Creek gaged at Rochester. Prior to 1992, all unit stage data are stored are paper records on wide-format line printer paper. Streamflow data are estimated by measuring stage (the elevation of the water surface above some datum) and then computing a discharge through a regression or rating curve. For each event, unit stage data were obtained from the paper files and hand entered into a spreadsheet. To compute discharge accurately, a shift needs to be applied to the data to account for changes in the channel, primarily weed growth that alters the stage-discharge relationship. These shifts were applied in the spreadsheet. Finally, each value was manually related to a stream flow by means of a rating table. Thus, hourly discharge values were obtained for both sites.

Precipitation data were obtained from scans of original analog records in the Michigan State Climatologist's Office. In this case, the records for gage O-8 were used, based on its proximity to both watersheds and its generally high-quality data (Ordway, written communication, 2008).

The precipitation event itself involved approximately 0.4 inches of rainfall over a period of 30 minutes, 0.27 inches of which fell between 5:30pm and 5:45pm, and 0.13 inches between 5:45pm and 6pm. Sashabaw Creek reported 39.2 cubic feet per second (cfs) of discharge at 5pm, and peaked at 46.2 cfs at 6pm. Paint Creek reported 32.7 cfs of discharge at 5pm, and again had peaked at 6pm with a discharge of 70.8 cfs. These data are shown in Figures 20. Although it might be possible to further refine the time step on the precipitation data, the streamflow data were only measured on the hour, and thus the minimum unit of measurement. These events in the late 1970s were intended to be the 'before' events, and the expectation was that events in the 1990s and 2000s would respond more quickly. However, as far as we can determine, in 1978 the streams responded immediately, or at least within the next time step, and had started to recede within 2 hours. Referring back to the case of Paint Creek, the discharge at 5pm (30 minutes before precipitation) was 32.7cfs – the discharge at 4pm was 27.9 cfs, and had been steady (within 0.01 ft stage measurement error) the entire day.



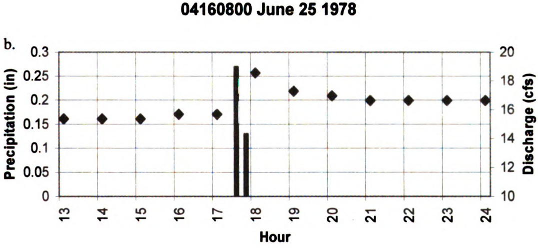


Figure 20: Stream discharge and precipitation for Paint Creek(a) and Sashabaw Creek(b), June 25, 1978.

Obviously one stream could not respond prior to rainfall commencing, and there are several reasons this might apparently occur. First, the rain gage is a single point; a convective event might have produced rainfall elsewhere in the watershed before reaching the raingage. Second, technology may have been a factor. Both gaging instruments relied on mechanical timekeepers (LeuVoy, personal communication, 2008;

Nurnberger, personal communication, 2008) that did drift somewhat over time. In short, both of these factors, combined with the designed 60 minute interval of the stream gage, conspire to cast doubt on the viability of reliably discerning fine shifts in unit hydrograph lag time in this area.

FLOW DURATION CURVES AND OTHER FLOW CHARACTERISTICS

The analysis of flow duration curves, percentiles of flow, peak flow characteristics and streamflow variability indicated that none of the watersheds in question became measurably flashier during the period 1975 through 2005. A series of flow frequency graphs are shown in Figure 21. Each of these graphs compares the flow frequency distribution for the subject watershed in the period 1975-1980 to the flow frequency distribution in the watershed for the period 2000-2005. Visually, these graphs are similar, and several appear to be flattening (i.e. becoming less flashy) through time.

Statistical analysis of the curves reveals a similar result. The Spearman's Rho and Kendall's Tau of the ratio of the 10th percentile flow to the 90th percentile flow and the ratio of the 25th to 75 percentile flows for each watershed over the period 1975 to 2005 are shown in Table 14. None of the sites showed significant increases in flashiness, peak flow, or slope of the flow duration curve. Several sites, notably those on the River Rouge, actually showed significant increases in low flows, or flattening of the flow duration curve.

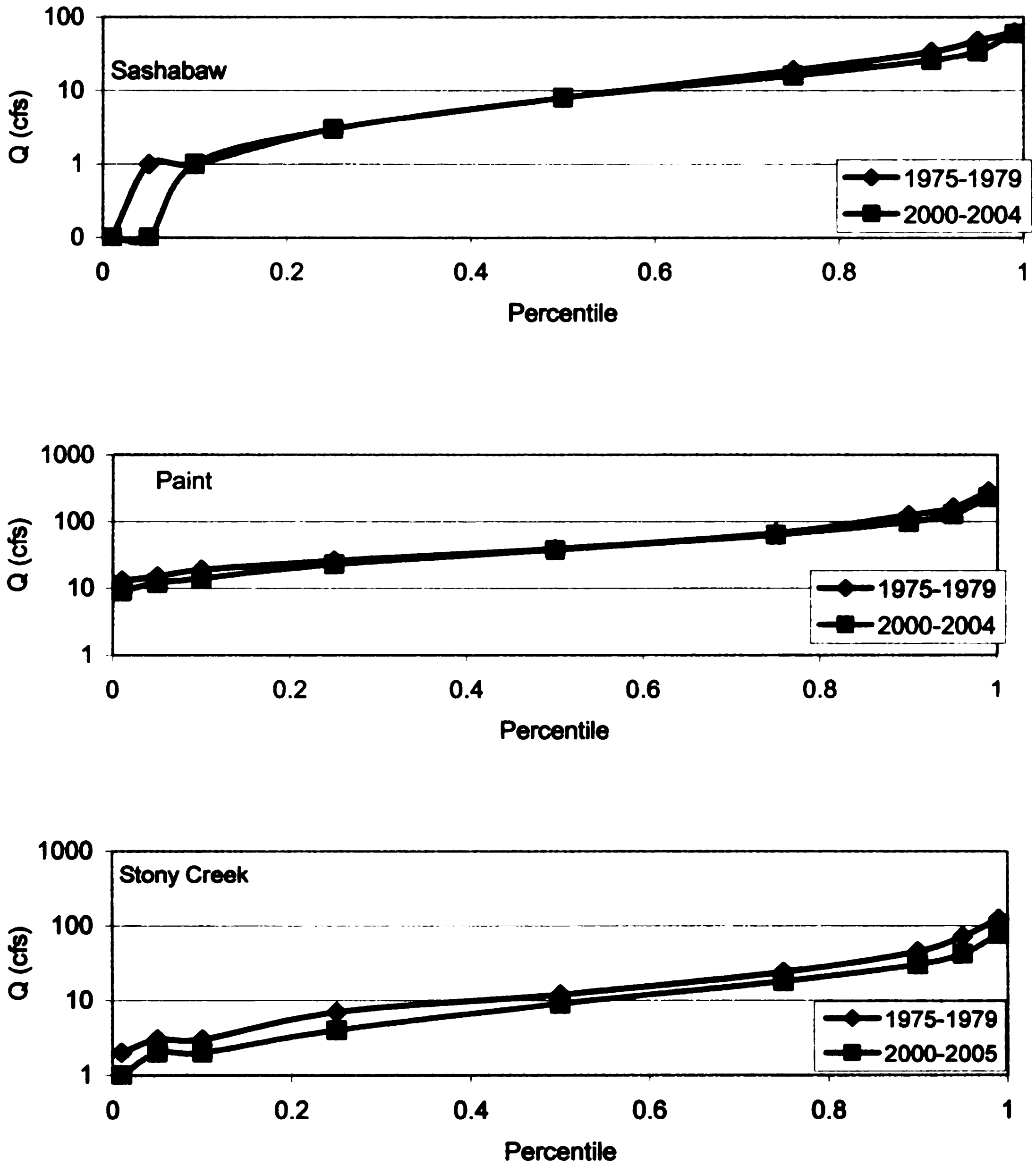


Figure 21: Flow duration curves for selected watersheds in Oakland County, Michigan, 1975-1979 and 2000-2004.

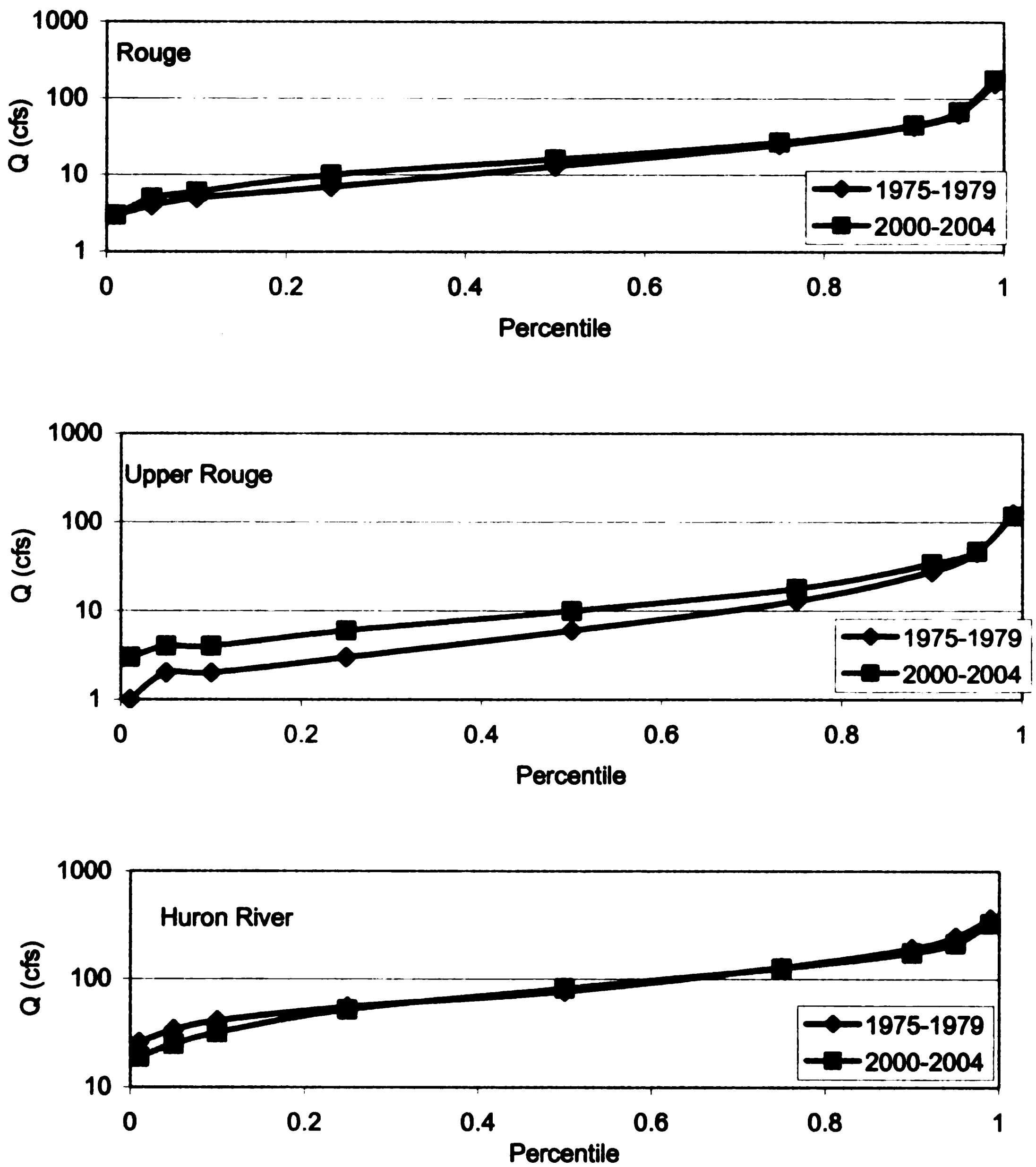


Figure 21 (cont'd): Flow duration curves for selected watersheds in Oakland County, Michigan, 1975-1979 and 2000-2004.

Table 14: Rho and Tau for annual stream flow characteristics for selected watersheds in Oakland County, 1975-2005. * indicates significance at the 0.95 confidence level; ** indicates significance at the 0.99 confidence level.

Watershed		Rho	Tau	Watershed		Rho	Tau
Paint Creek	0.01	-0.41	-0.30	Upper River Rouge	0.01	0.05	0.59
	0.05	-0.27	-0.17		0.05	0.01	0.51
	0.10	-0.26	-0.17		0.10	-0.01	0.47
	0.25	-0.12	-0.08		0.25	-0.13	0.52
	0.50	0.12	0.11		0.50	-0.04	0.48
	0.75	0.13	0.13		0.75	-0.08	0.40
	0.90	0.06	0.06		0.90	-0.16	0.32
	0.95	-0.10	-0.08		0.95	-0.15	0.11
	0.99	0.10	0.05		0.99	-0.06	0.00
	25/75 ratio	-0.36	-0.25		25/75 ratio	-0.10	0.36
	10/90 ratio	-0.12	-0.08		10/90 ratio	0.10	0.37
	Peak	0.16	0.12		Peak	0.03	-0.04
Stony Creek	0.01	-0.29	-0.22	River Rouge at Birmingham	0.01	0.31	0.21
	0.05	-0.45	-0.33		0.05	0.36	0.27
	0.10	-0.48	-0.35		0.10	0.38	0.29
	0.25	-0.28	-0.19		0.25	0.36	0.26
	0.50	-0.11	-0.04		0.50	0.34	0.27
	0.75	-0.11	-0.05		0.75	0.23	0.18
	0.90	-0.24	-0.17		0.90	0.12	0.07
	0.95	-0.29	-0.22		0.95	0.05	0.02
	0.99	-0.24	-0.16		0.99	0.19	0.13
	25/75 ratio	-0.20	-0.14		25/75 ratio	0.36	0.23
	10/90 ratio	-0.29	-0.21		10/90 ratio	0.55	0.41
	Peak	-0.06	-0.03		Peak	0.16	0.08
Sashabaw Creek	0.01	0.06	0.05	Huron River at Milford	0.01	-0.20	-0.12
	0.05	-0.02	0.01		0.05	-0.12	-0.07
	0.10	-0.02	-0.01		0.10	-0.09	-0.05
	0.25	-0.17	-0.13		0.25	0.03	0.02
	0.50	-0.10	-0.04		0.50	0.08	0.08
	0.75	-0.13	-0.08		0.75	0.12	0.13
	0.90	-0.20	-0.16		0.90	0.04	0.05
	0.95	-0.22	-0.15		0.95	0.00	0.00
	0.99	-0.06	-0.06		0.99	0.07	0.08
	25/75 ratio	-0.16	-0.10		25/75 ratio	-0.08	-0.07
	10/90 ratio	0.10	0.10		10/90 ratio	0.02	0.00
	Peak	0.06	0.03		Peak	0.14	0.11

The modified Mann-Kendall Z statistics for trend did identify several significant trends. These results are shown in Table 15. Most notable are the increases in low flows in the Upper Rouge River watershed, as well as in Stony Creek and the River Rouge. These trends all indicated a statistically significant flattening of the flow duration curve in these watersheds over time. A decrease in the lowest flow (1 percentile) discharge is noted in Paint Creek, although this was related to a significant change in the slope of the FDC or the peak flow. No other statistically significant trends were noted.

Table 15: Modified Mann-Kendall Z and Sen's Slope (Q) for annual streamflow statistics for selected sited in Oakland County, Michigan, 1975-2005. [α; probability the Z statistic is equal to zero]

Site	Statistic	Test Z	α	Q	Site	Statistic	Test Z	α	Q
Paint Creek	0.01	-2.66	0.010	-0.200	Upper River Rouge	0.01	4.42	0.001	0.091
	0.05	-1.75		-0.164		0.05	3.65	0.001	0.095
	0.10	-1.75		-0.200		0.10	3.46	0.001	0.100
	0.25	-1.01		-0.148		0.25	3.87	0.001	0.133
	0.50	0.32		0.087		0.50	3.61	0.001	0.214
	0.75	0.39		0.188		0.75	3.08	0.010	0.250
	0.90	-0.02		0.000		0.90	2.47	0.050	0.320
	0.95	-0.95		-0.960		0.95	0.83		0.203
	0.99	-0.10		-0.096		0.99	0.00		-0.023
	25/75 ratio	-1.50		-0.002		25/75 ratio	2.83	0.010	0.004
	10/90 ratio	-0.54		0.000		10/90 ratio	2.88	0.010	0.002
	Peak	0.46		2.043		Peak	-0.31		-1.188
Stony Creek	0.01	-0.39		0.000	River Rouge at Birmingham	0.01	1.54		0.040
	0.05	-1.13		0.000		0.05	2.06	0.050	0.077
	0.10	-1.13		-0.035		0.10	2.18	0.050	0.083
	0.25	-0.49		0.000		0.25	1.95		0.125
	0.50	0.00		0.000		0.50	2.05	0.050	0.190
	0.75	-0.11		0.000		0.75	1.38		0.143
	0.90	-0.66		-0.217		0.90	0.49		0.133
	0.95	-1.52		-0.680		0.95	0.14		0.023
	0.99	-1.41		-0.956		0.99	1.02		1.113
	25/75 ratio	-0.09		-0.001		25/75 ratio	1.79		0.002
	10/90 ratio	-0.09		0.000		10/90 ratio	3.18	0.010	0.002
	Peak	-0.57		-0.813		Peak	0.63		1.462
Sashabaw Creek	0.01	0.34		0.000	Huron River at Milford	0.01	-0.95		-0.107
	0.05	0.04		0.000		0.05	-0.54		-0.130
	0.10	-0.09		0.000		0.10	-0.41		-0.100
	0.25	-0.99		0.000		0.25	0.10		0.000
	0.50	-0.31		0.000		0.50	0.63		0.375
	0.75	-0.63		-0.063		0.75	1.02		0.769
	0.90	-1.22		-0.200		0.90	0.34		0.267
	0.95	-1.12		-0.250		0.95	0.00		-0.097
	0.99	-0.42		-0.098		0.99	0.65		1.580
	25/75 ratio	-0.78		-0.002		25/75 ratio	-0.54		-0.001
	10/90 ratio	0.78		0.001		10/90 ratio	0.00		0.000
	Peak	0.20		0.111		Peak	0.88		2.000

Seasonally, a number of statistically significant trends are noted below. In this case, seasons were defined both meteorologically (Table 16) and by the conventional astronomical divisions (Table 17). The differences in outcome between the seasonal groupings are generally minor. The Upper River Rouge indicated a strong positive trend in total flow. In conjunction with strong positive trends in summer, fall, and winter flows, and a decreasing trend in spring flows, these seem indicative of the increase in base flow (i.e., low flows) noted in the Table 15.

Table 16: Modified Mann-Kendall Z and Sen's Slope (Q) for meteorological seasonal streamflow statistics for selected sites in Oakland County, Michigan, 1975-2005. In this case, "Spring" includes March, April, and May. [α; probability the Z statistic is equal to zero]

			Total	Spring	Summer	Fall	Winter
Flow volume	Sash-abaw Creek	Z	-0.95	-2.14	0.51	-0.82	-0.17
		α		0.05			
		Q	-43.69	-27.55	3.47	-10.00	-1.79
	Paint Creek	Z	-0.51	-1.56	0.24	-0.51	0.71
		α					
		Q	-64.25	-65.96	7.15	-19.73	23.25
	Stony Creek	Z	-0.57	-1.85	0.35	-0.75	-0.04
		α		0.01			
		Q	-27.65	-46.00	7.00	-9.50	-1.38
	Upper Rouge River	Z	2.55	-1.53	3.40	2.21	2.69
		α	0.05		0.00	0.05	0.01
		Q	70.04	-15.87	36.57	25.06	27.21
	Rouge River	Z	1.26	-1.80	2.41	1.63	1.38
		α		0.10	0.05		
		Q	61.00	-28.50	36.32	19.00	24.17
	Huron River	Z	0.37	-1.73	1.12	0.03	1.39
		α		0.10			
		Q	115.00	-71.15	82.00	6.48	71.70

			Spring	Summer	Fall	Winter	Summer/ fall	Winter/ spring
Percent of Annual Flow	Sash-abaw Creek	Z	-1.05	1.80	-0.82	0.27	0.65	-0.65
		α		0.10				
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Paint Creek	Z	-1.67	1.29	-0.85	1.05	0.92	-0.92
		α	0.10					
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Stony Creek	Z	-2.07	1.45	-0.22	1.28	0.97	-0.97
		α	0.01					
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Upper Rouge River	Z	-2.96	3.03	2.04	1.60	3.23	-3.23
		α	0.01	0.01	0.05		0.01	0.01
		Q	-0.01	0.00	0.00	0.00	0.01	-0.01
	Rouge River	Z	-2.72	3.06	1.22	0.82	2.99	-2.99
		α	0.01	0.01			0.01	0.01
		Q	-0.01	0.00	0.00	0.00	0.00	0.00
	Huron River	Z	-2.24	1.87	0.03	1.46	1.36	-1.36
		α	0.05	0.10				
		Q	0.00	0.00	0.00	0.00	0.00	0.00

Table 17: Modified Mann-Kendall Z and Sen's Slope (Q) for astronomical seasonal streamflow statistics for selected sites in Oakland County, Michigan, 1975-2005. In this case, "Spring" includes April, May, and June. [α; probability the Z statistic is equal to zero]

			Total	Spring	Summer	Fall	Winter
Flow volume	Sashabaw Creek	Z	-0.82	-0.22	-1.63	-0.37	-0.54
		α					
		Q	-26.31	-1.60	-20.04	-1.92	-5.20
	Paint Creek	Z	0.00	0.10	-1.09	-0.58	0.20
		α					
		Q	-2.27	6.00	-47.38	-16.40	5.08
	Stony Creek	Z	-0.44	-1.19	-1.37	-0.31	-0.55
		α					
		Q	-27.55	-23.82	-31.00	-1.25	-7.75
	Upper Rouge River	Z	2.58	0.54	1.00	2.99	2.07
		α	0.01			0.01	0.05
		Q	63.86	8.55	7.28	29.36	22.27
	Rouge River	Z	1.43	0.22	0.00	1.70	1.29
		α				0.10	
		Q	54.52	7.67	-0.05	21.83	16.38
	Huron River	Z	0.48	0.85	-1.12	0.31	0.82
		α					
		Q	119.29	59.90	-82.25	14.60	54.95

			Spring	Summer	Fall	Winter	Summer/ fall	Winter/ spring
Percent of Annual Flow	Sashabaw Creek	Z	0.07	-1.12	0.10	-0.48	0.14	-0.14
		α						
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Paint Creek	Z	0.34	-0.82	0.00	-0.37	-0.10	0.10
		α						
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Stony Creek	Z	-0.31	0.00	0.62	-0.53	-0.13	0.13
		α						
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Upper Rouge River	Z	-1.50	-1.26	2.52	1.22	-2.79	2.79
		α			0.05		0.01	0.01
		Q	0.00	0.00	0.00	0.00	-0.01	0.01
	Rouge River	Z	-1.26	-0.85	1.73	0.65	-1.87	1.87
		α			0.10		0.10	0.10
		Q	0.00	0.00	0.00	0.00	0.00	0.00
	Huron River	Z	0.00	-1.70	0.14	0.44	-0.95	0.95
		α		0.10				
		Q	0.00	0.00	0.00	0.00	0.00	0.00

All watersheds except Sashabaw Creek exhibited decreases in the percentage of annual flow occurring during meteorological spring, although in Paint Creek that trend was only significant at the 90 percent confidence level. All watersheds except Paint Creek exhibited an increase in the percentage of annual flow occurring during meteorological summer, although in Sashabaw Creek and the Huron River these trends were only significant at the 90 percent confidence level.

Overall, neither Paint Creek nor Sashabaw Creek show any particularly strong trends indicative of urbanization, despite increases in urban land use of approximately 100 percent (now up to approximately 50 percent of watershed area) in both watersheds.

Results of watershed modeling

A process-based, digital model allows for watershed response to different scenarios of climate and land cover to be tested in a manner that simply is not feasible in the real world. Of the two watersheds that showed relatively little change (Paint Creek and Sashabaw Creek), Paint Creek was selected as a demonstration site to test several hypotheses about the effect of land-cover representation on model results, the effect of land cover change on watershed hydrology, and the effect of climate trends on watershed hydrology. Although Sashabaw Creek exhibited a similar absence of trends, Paint Creek was selected because 1) it is larger, resulting in more sustained flows, 2) it has a better measurement section at the gage site (LeuVoy, personal communication, 2008), and 3) Sashabaw Creek flows through a large wetland immediately upstream of the gage site, potentially complicating calibration and interpretation of results.

Specifically related to the subsequent sections isolating the effects of land-use can climate change, the availability of multiple land-cover datasets of two vintages (c1975 and c2005), and two climate series (one composed of observed weather data and one composed of synthetic weather data based on 30 year climate normals) with each type of land-cover input provided the opportunity to investigate the combined effects of land-cover and climate, the effect of climate alone (by comparing each model with simulated and actual climate series), or the effect of land cover alone (by comparing 1975 and 2005 land cover), and the effect of land-cover representation on the model results.

MODEL CALIBRATION AND LAND-COVER RENDERING RESULTS

As was mentioned in the section on model development, the model was calibrated to match as closely as possible the observed total outflow from the watershed and the flow frequency distribution. The watershed model generally did a good job of matching the middle 80 percent of flow characteristics (Figure 22). However, both peak flows (95th percentile and above) and low flows (5th percentile and below) were problematic. Specific event peak flows were generally within 20 percent of observed peaks, although some larger differences occur during periods of convective precipitation when events in the watershed may not match events at the Milford weather site. Although no objective measured data exist describing base flow (ground-water-derived streamflow) at the site, a number of analytical estimates have been made using hydrograph separation and regression techniques (MDEQ, 2005; Holtschlag, 1996). The modeled base flows for the NAIP-derived land cover came considerably closer to matching analytically estimated base flows than did the land-use derived land-cover representations (Figure 23).

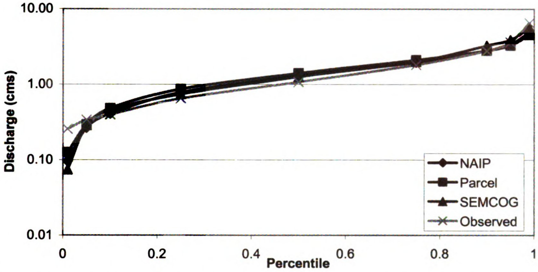


Figure 22: Flow duration curves for calendar 2005 for fitted SWAT models for Paint Creek watershed, by land-cover source.

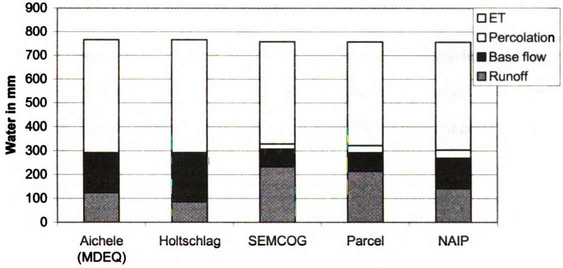


Figure 23: Model-estimated water-budget components Paint Creek for different land–covers for the 2005 calendar year compared to previous estimates.

All land covers tended to overestimate runoff, and while the NAIP-based model tended to underestimate total streamflow slightly, the fraction of streamflow derived from ground water is within the range of what has been estimated previously, albeit at the low end. It is also worth considering that both of the analytical estimates of base flow were made based on over 30 years of record, so a single year may not match the mean exactly.

Table 18: Difference in model-estimated annual water budget components for Paint Creek based on change in land cover, based on observed climate data, 1975-2005.

	NAIP (mm)	Parcel (mm)	SEMCOG (mm)
SURQ	17.54	16.67	40.55
LATQ	-3.93	-3.20	-10.48
GWQ	-4.69	-2.15	-7.50
PERCO	-4.71	-2.31	-7.57
SW	-18.22	-7.55	-30.75
ET	-8.37	-0.70	-23.16
PET	0.21	9.06	-1.14
WYIELD	8.31	10.24	23.21

SURQ, overland flow; LATQ, Lateral soil flow; GWQ, Ground-water flow; PERCO, percolation to deep ground water; SW, soil water storage; ET, Evapotranspiration; PET, Potential evapotranspiration; WYIELD, total water yield to channel (streamflow)

One spatial resolution experiment was attempted as well, resampling the NAIP land-cover data from 1m spatial resolution (used in calibration and generally hereafter) to 10m, which might be more reflective of the magnitude of an impervious patch necessary to have a substantive difference hydrologically (Alley and Veenhius, 1983). In essence, the additional runoff generated by small impervious surfaces might be absorbed by adjacent pervious surfaces, resulting in a reduced effective impervious surface. However, the only difference between the two model outputs is that the 10m resolution land cover results in slightly more ground-water recharge, without any difference in any other water budget component. A larger patch size threshold should theoretically result in more recharge, because small impervious patches (driveways, sidewalks, patios, etc) would no longer be represented. But the water balance should still balance, and it is not theoretically plausible that changing the input land-cover resolution would create water, albeit a small amount. On average, the change in spatial resolution from 1m to 10m resulted in 3.5mm more recharge annually, with a monthly median of 0.1mm.

EFFECTS OF LAND-COVER CHANGE ON WATERSHED HYDROLOGY

The modeled effects of land cover change are approximately as predicted in the literature (e.g., increased runoff, decreased recharge), although the extent of the effect varies considerably based on the land cover data used. All land cover datasets tested resulted in increased overland flow, decreased recharge, and decreased base flow. Summary characteristics for several output variables based on model runs with synthetic climate data are included in Table 19.

Table 19. Model estimated effects of land-cover change in Paint Creek watershed c.1975 to c.2005 based on synthetic climate data. [all quantities expressed in mm]

Period	Source	Statistic	SURQ	LATQ	GWQ	PERCO	SW	ET	PET	YIELD
Monthly	Parcels	Max	27.13	0.33	0.34	0.36	7.43	4.04	1.12	23.78
		Average	1.39	-0.27	-0.18	-0.19	-6.43	-0.06	0.75	0.85
		Median	1.10	-0.18	-0.08	0.00	-6.89	0.21	0.77	0.66
		Min	-11.93	-2.99	-1.85	-4.27	-17.25	-9.61	0.41	-15.55
	SEMCOG	Max	46.40	0.00	0.00	0.29	-11.94	0.00	-0.05	38.67
		Average	3.38	-0.87	-0.62	-0.63	-30.01	-1.93	-0.09	1.93
		Median	2.94	-0.66	-0.31	-0.01	-30.22	-1.59	-0.10	1.56
		Min	-19.78	-7.03	-4.71	-10.78	-40.83	-10.12	-0.14	-27.39
	NAIP	Max	17.94	0.08	1.38	0.24	-8.29	8.84	0.03	8.01
		Average	1.46	-0.33	-0.39	-0.39	-18.46	-0.70	0.02	0.69
		Median	1.27	-0.23	-0.05	0.00	-17.71	-0.79	0.02	0.71
		Min	-3.71	-2.85	-8.15	-7.45	-27.95	-4.83	0.01	-10.19
Annual	Parcels	Max	30.16	-1.41	0.02	0.11	1.93	4.61	10.48	18.25
		Average	16.67	-3.20	-2.15	-2.31	-7.55	-0.70	9.06	10.24
		Median	15.30	-2.82	-1.57	-1.91	-8.16	-1.02	9.03	10.18
		Min	9.48	-7.73	-12.95	-10.61	-14.19	-7.08	8.37	3.24
	SEMCOG	Max	68.46	-5.02	-0.26	-0.32	-20.85	-12.81	-1.05	32.99
		Average	40.55	-10.48	-7.50	-7.57	-30.75	-23.16	-1.14	23.21
		Median	38.37	-9.58	-5.79	-6.1	-31.36	-23.26	-1.14	23.3
		Min	21.49	-21.49	-30.08	-24.99	-39.17	-31.06	-1.31	5.38
	NAIP	Max	31.18	-2.02	0.19	-0.04	-13.16	1.05	0.24	12.67
		Average	17.54	-3.93	-4.69	-4.71	-18.22	-8.37	0.21	8.31
		Median	16.98	-3.56	-3.15	-4.05	-17.43	-9.09	0.21	9.32
		Min	10.70	-8.61	-16.71	-19.12	-23.72	-13.94	0.19	1.18

SURQ, overland flow; LATQ, Lateral soil flow; GWQ, Ground-water flow; PERCO, percolation to deep ground water; SW, soil water storage; ET, Evapotranspiration; PET, Potential evapotranspiration; WYIELD, total water yield to channel (streamflow)

Flow durations curves of daily model output were created for the 2005 calendar year climate for each land-cover representation, both for the earlier period (c.1975) and the later period (c.2005). Figure 24 shows the comparison for the NAIP-based land cover, the parcel-based land cover, and the SEMCOG based land cover. This comparison essentially asks the question "what would conditions have been like had no development occurred since 1975?" Figure 24 includes both the 1978 MIRIS land-cover data, the directly measured dataset, and the reconstructed 1975 dataset based on development date data provided by SEMCOG. Qualitatively, the flow duration curves exhibit more change in the SEMCOG-based datasets, and less change in the NAIP based dataset. The parcel based model output exhibits less change than the SEMCOG data, but more than the NAIP. These flow duration curves themselves are indicative of a general pattern or tendency associated with the change in land cover. The most notable effects are in the parcel-based scenario, where flows increase by almost 1 cubic meter per second (cms). However, none of the curves seem to indicate a dramatic change in flow characteristics.

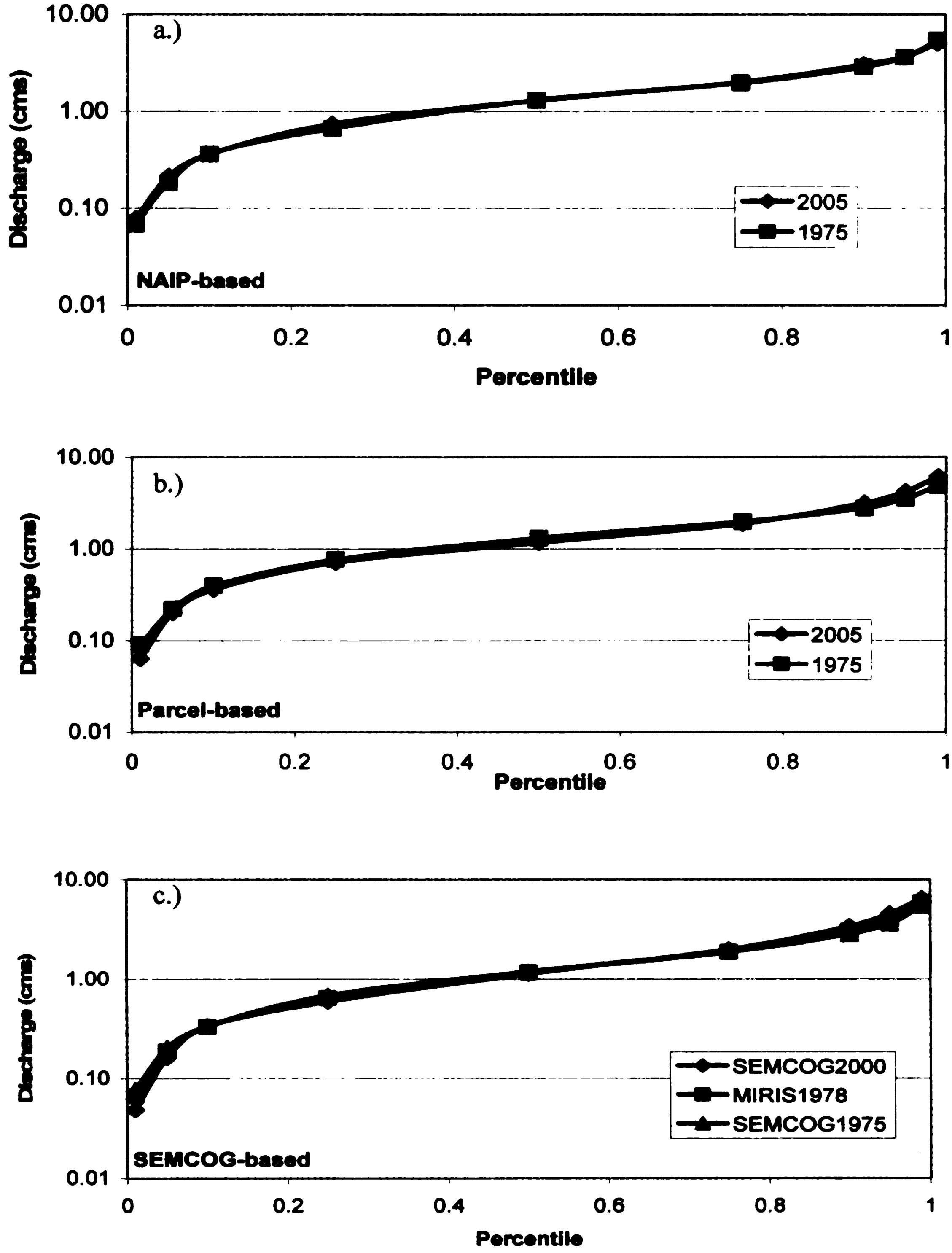


Figure 24: Modeled effects of land-cover change on Paint Creek, c1975-c2005, based on NAIP(a), parcel (b), and SEMCOG (c) land-use and land-cover datasets. [cms; cubic meters per second]

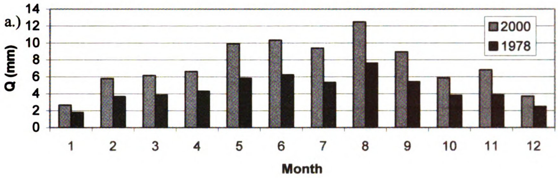
On both an annual and monthly basis, the SEMCOG, parcel, and NAIP land-covers all estimate an increase in surface water flow, averaging 38.19mm, 14.23mm, and 14.95mm, respectively. For the ground-water components (LATQ, GWQ, and PERCO) the NAIP, and parcel, based estimates are almost indistinguishable, while the SEMCOG-based estimates are substantially greater. The key difference comes in the ET and PET terms. The SEMCOG-based data actually lead to a slight decrease in ET, likely a shortage of available moisture as a result of increased runoff, while the parcel- and NAIP-based data each estimate an increase, although the NAIP increase averages only 0.19mm, while the parcel-based averages 8.17mm. A summary of the differences for each water budget component is included in Table 20.

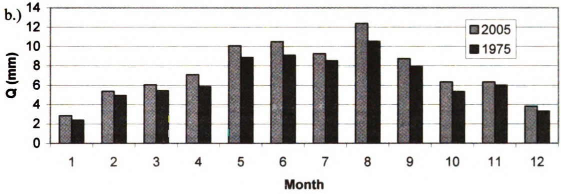
Table 20: Difference in model estimated annual water budget components based on land cover change in the Paint Creek watershed, c.1975 to c.2005, based on observed climate data. [all quantities expressed in mm]

			SURQ	LATQ	GWQ	PERCO	SW	ET	PET	WYIELD
Monthly	Parcels	Max	7.66	0.00	0.11	0.46	4.69	2.98	1.18	3.65
		Average	1.19	-0.30	-0.30	-0.30	-8.54	0.02	0.68	0.49
		Median	0.91	-0.23	-0.17	-0.01	-9.95	0.25	0.69	0.35
		Min	-0.80	-2.72	-1.75	-5.58	-13.29	-6.60	0.22	-1.47
	SEMCOG	Max	16.06	0.00	-0.01	0.02	-7.51	0.85	-0.03	8.70
		Average	3.18	-0.89	-0.97	-0.97	-20.92	-1.39	-0.09	1.37
		Median	2.49	-0.72	-0.69	-0.20	-21.57	-1.14	-0.09	0.96
		Min	-0.65	-6.51	-4.02	-13.04	-32.73	-5.39	-0.15	-3.32
	NAIP	Max	7.48	0.13	1.80	0.38	-7.56	5.79	0.03	3.92
		Average	1.25	-0.27	-0.32	-0.33	-14.83	-0.62	0.02	0.60
		Median	1.05	-0.20	-0.02	-0.02	-14.44	-0.61	0.02	0.68
		Min	0.01	-2.25	-6.01	-5.82	-24.27	-5.06	0.00	-3.52
Annual	Parcels	Max	23.15	-1.81	-0.29	-0.05	-1.73	4.35	8.56	10.14
		Average	14.23	-3.58	-3.61	-3.60	-9.88	0.28	8.17	5.90
		Median	13.96	-3.42	-2.89	-2.45	-11.43	-0.57	8.20	5.93
		Min	8.98	-6.84	-11.35	-12.04	-12.89	-2.93	7.32	0.38
	SEMCOG	Max	59.53	-5.15	-1.53	-1.05	-10.17	-9.91	-0.92	25.12
		Average	38.19	-10.72	-11.60	-11.58	-20.84	-16.65	-1.03	16.47
		Median	37.89	-10.29	-9.98	-8.92	-21.25	-17.05	-1.03	17.24
		Min	23.86	-19.4	-29.95	-30.67	-30.13	-21.48	-1.08	5.43
	NAIP	Max	22.07	-1.32	2.37	0.16	-11.58	-2.79	0.20	12.33
		Average	14.95	-3.24	-3.90	-3.97	-13.71	-7.41	0.19	7.23
		Median	14.67	-2.95	-3.43	-2.90	-13.55	-8.34	0.19	7.60
		Min	9.16	-6.62	-12.51	-13.90	-16.51	-10.85	0.17	2.45

SURQ, overland flow; LATQ, Lateral soil flow; GWQ, Ground-water flow; PERCO, percolation to deep ground water; SW, soil water storage; ET, Evapotranspiration; PET, Potential evapotranspiration; WYIELD, total water yield to channel (streamflow)

The differences both between stages of development and between land-cover renderings are somewhat easier to evaluate graphically. Figures 25a-c depict the average monthly overland flow characteristics for the SEMCOG-, parcel-, and NAIP-based land covers using the synthetic climate data series. Each shows an increase in overland flow, but the SEMCOG land-cover data shows substantially more change. The overall magnitude is worthy of note as well – where the 2005 SEMCOG and parcel-based results are almost identical, the NAIP-based results are approximately half as great in magnitude.





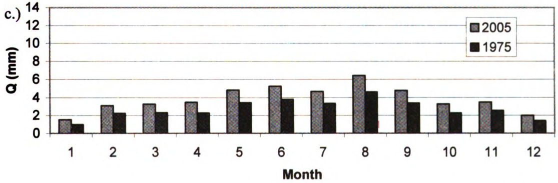


Figure 25: Model-estimated overland flow for Paint Creek watershed, by month for c.1975 and c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic climate data.

In terms of total stream flow, the results are much more comparable, with all the datasets showing a general increase in stream flows, although the SEMCOG dataset tends to estimate more difference than either the parcel- or NAIP-based datasets. These results are shown in Figures 26 a-c.

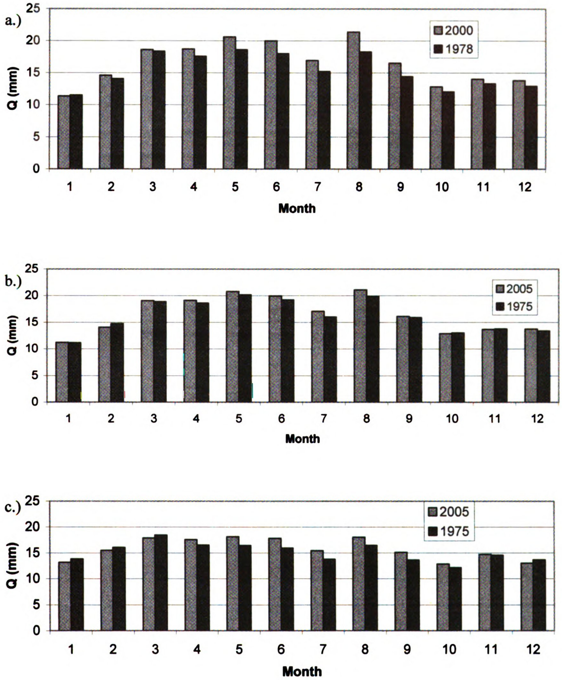


Figure 26: Model estimated total stream flow for Paint Creek watershed, by month for c.1975 and c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic climate data.

The ground water components of the water budget (GW_Q, LAT_Q, and PERC) show a similar trend, with decreases estimated for all land covers. The NAIP-based land covers are associated with the least change, while the SEMCOG-based land cover exhibits the most. These results are shown in Figure 27a-c.

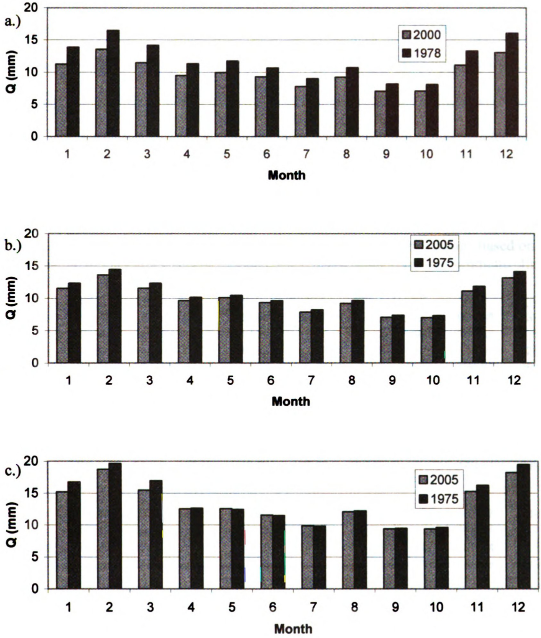


Figure 27: Model estimated ground water components of the water budget for Paint Creek watershed, by month for c.1975 and c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic climate data.

Finally, in terms of ET, the parcel- and NAIP-based models both suggest a slight increase in ET, while the SEMCOG-based model predicts a decrease. In all cases, ET is constrained by the availability of water in the soil, and the much larger portion of precipitation diverted to overland flow in the SEMCOG model likely explains the decrease in overall ET over the course of the year. Within the NAIP-based model, a slight increase in ET is estimated in March and April, compensated by a slight decrease from May through September. The parcel-based model estimates a slight decrease in ET in April, and very little difference throughout the rest of the year. These results are shown in Figure 28 a-c. These results are summarized annually in Table 21.

Table 21: Difference in model estimated annual water budget components based on land cover change in the Paint Creek watershed, c.1975 to c 2005, based on synthetic climate data. [all quantities expressed in mm]

		PREC	SURQ	LATQ	GWQ	PERCO	SW	ET	PET	WYIELD
SEMCOG	Max.	510.20	182.33	51.31	36.90	29.44	43.18	249.13	699.58	239.33
	Ave.	31.47	22.25	-10.55	-18.24	-18.04	-55.32	46.86	345.55	-6.45
	Med.	62.30	14.03	-10.00	-15.22	-7.93	-62.42	51.85	337.91	-25.27
	Min.	-450.10	-93.52	-76.22	-90.88	-93.83	-170.98	-108.04	190.92	-260.34
Parcel	Max.	510.20	172.71	52.46	64.78	44.27	49.53	231.20	693.79	248.04
	Ave.	31.47	23.59	-9.70	-16.81	-16.73	-42.23	49.15	347.97	-2.76
	Med.	62.30	28.90	-4.46	-14.01	-14.13	-42.13	49.21	338.96	-3.16
	Min.	-450.10	-88.95	-75.11	-106.28	-107.83	-136.31	-140.73	143.71	-269.73
NAIP	Max	510.20	130.45	74.31	89.21	70.31	59.23	227.07	687.47	239.50
	Ave.	31.47	19.52	-11.23	-22.95	-22.67	-42.64	46.40	344.01	-14.69
	Med.	62.30	17.70	-0.82	-20.80	-21.39	-34.18	48.29	335.04	-19.98
	Min	-450.10	-50.41	-99.34	-138.98	-140.45	-147.43	-178.67	143.88	-287.77

PREC, precipitation; SURQ, overland flow; LATQ, Lateral soil flow; GWQ, Ground-water flow; PERCO, percolation to deep ground water; SW, soil water storage; ET, Evapotranspiration; PET, Potential evapotranspiration; WYIELD, total water yield to channel (streamflow)

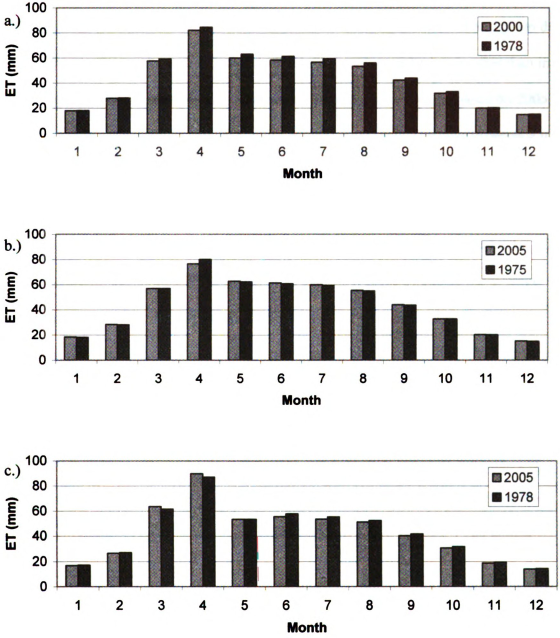


Figure 28: Model estimated evapotranspiration for Paint Creek watershed, by month for c.1975 and c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic climate data.

EFFECTS OF CLIMATE ON WATERSHED HYDROLOGY

The effects of climate on the hydrology of the watershed are somewhat more difficult to discern, because the synthetic climate data series is constructed to incorporate daily, monthly, and annual variability within the constraints of observed climate normals. Therefore, although the dataset represents a trendless "normal" climate, at any given day, month, or year, the synthetic data have no correlation with the actual data other than in overall summary characteristics. All analyses shown in this section are based on 2005 land-cover data applied throughout the entire 30 year sequence. The only difference in inputs is the climate data series.

Within the actual input climate data series, there appears to be a shift in the timing of precipitation, in addition to a generally increasing trend noted in the annual data. This is consistent with the finding in Hodgkins et al. (2007). Figure 29 shows the average monthly precipitation for both the actual and synthetic data series. In general, the patterns are similar, with the actual data series dipping below the synthetic in February and March, then generally exceeding the synthetic for the rest of the year including a resurgence in precipitation in November. The peak in the synthetic data series in August, and indeed both series through July and August, are heavily affected by outliers. For instance, the August precipitation for both data series ranges from less than 20mm to more than 200mm, a considerably larger range than the rest of the year. The annual results are shown in table 22.

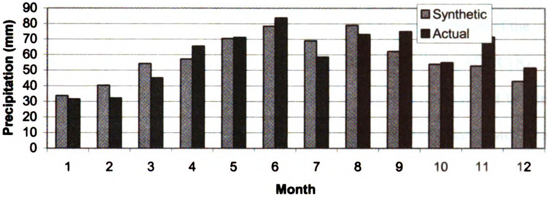


Figure 29: Observed (1975-2005) and synthetic average monthly precipitation for Milford, Michigan.

Table 22: Difference in model estimated annual water budget components based on observed and synthetic climate data in the Paint Creek watershed, c.2005 land cover data. [all quantities expressed in mm]

		PREC	SURQ	LATQ	GWQ	PERCO	SW	ET	PET	WYIELD
SEMCOG	Max	510.20	182.33	51.31	36.90	29.44	43.18	249.13	699.58	239.33
	Average	31.47	22.25	-10.55	-18.24	-18.04	-55.32	46.86	345.55	-6.45
	Median	62.30	14.03	-10.00	-15.22	-7.93	-62.42	51.85	337.91	-25.27
	Min	-450.10	-93.52	-76.22	-90.88	-93.83	-170.98	-108.04	190.92	-260.34
Parcel	Max	510.20	172.71	52.46	64.78	44.27	49.53	231.20	693.79	248.04
	Average	31.47	23.59	-9.70	-16.81	-16.73	-42.23	49.15	347.97	-2.76
	Median	62.30	28.90	-4.46	-14.01	-14.13	-42.13	49.21	338.96	-3.16
	Min	-450.10	-88.95	-75.11	-106.28	-107.83	-136.31	-140.73	143.71	-269.73
NAIP	Max	510.20	130.45	74.31	89.21	70.31	59.23	227.07	687.47	239.50
	Average	31.47	19.52	-11.23	-22.95	-22.67	-42.64	46.40	344.01	-14.69
	Median	62.30	17.70	-0.82	-20.80	-21.39	-34.18	48.29	335.04	-19.98
	Min	-450.10	-50.41	-99.34	-138.98	-140.45	-147.43	-178.67	143.88	-287.77

PREC, precipitation; SURQ, overland flow; LATQ, Lateral soil flow; GWQ, Ground-water flow; PERCO, percolation to deep ground water; SW, soil water storage; ET, Evapotranspiration; PET, Potential evapotranspiration; WYIELD, total water yield to channel (streamflow)

In general, the models respond to the different climate series in a much more uniform manner than they responded to the change in land cover with development.

Observed precipitation during the period 1975-2005 averaged 31.47mm (1.23 inches) more than would be expected based on the 1971-2000 normals. Each version of the model accordingly distributed more water to surface water flow, with the SEMCOG, parcel-based, and NAIP-based land covers estimating 22.25mm, 23.59mm, and 19.52mm more surface water flow on average, respectively. Interestingly, while the SEMCOG and NAIP-based model runoff output had a negative skew (a median less than the average), the parcel data runoff had a positive skew. These and other annual results are shown in Table 22.

Also, despite having more water available as precipitation in the observed climate data as compared to the synthetic, each model estimates an overall decrease in water yield from the watershed: 6.45mm, 2.76mm, and 14.69mm for the SEMCOG, parcel-based, and NAIP-based models, respectively. Each model estimates an increase in actual ET of approximately 50mm (2 inches) on an annual basis in the actual data, with compensating decreases in ground-water discharge to streams, recharge, and soil moisture. As was noted earlier, the exact distribution among these ground-water terms within the model is somewhat dubious, but as an ensemble they actually paint a very similar picture – the observed climate generates an increase in ET of approximately twice the magnitude of the increase in precipitation compared to the synthetic climate, with the remaining additional ET compensated by a reduction in ground-water recharge, at least on an annual basis.

Figure 30a-c shows the overall monthly stream flow for each land cover. The overall magnitudes of all three models are roughly comparable. Both the SEMCOG and parcel-based models are noticeably more variable than the NAIP-based model. The

NAIP-based model also generates more stream flow early in the year compared to the other two models. All three models show generally lower total streamflow under observed climate conditions compared to the synthetic conditions.

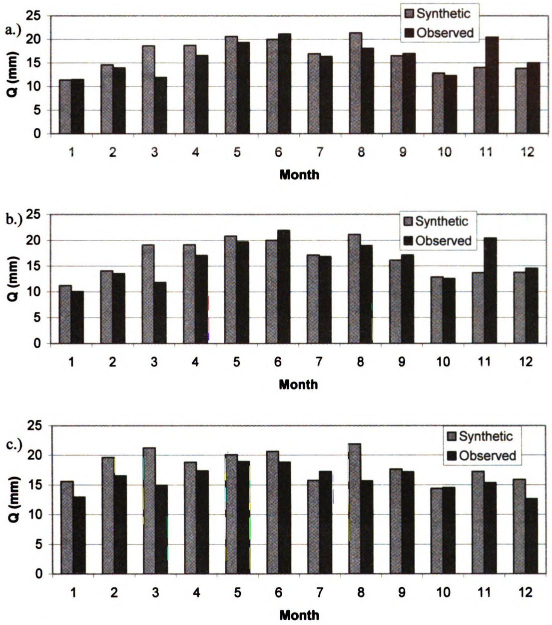


Figure 30: Model estimated total stream flow for Paint Creek watershed, by month, for c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic and observed climate data.

In strict overland flow, the NAIP model generates substantially less and also somewhat more variable overland flow than the other two models. The SEMCOG and parcel-based models tend to produce more overland flow under actual climate conditions than under simulated climate conditions, whereas the NAIP model actually seems to alter the seasonality of the overland flow a bit, with higher overland flows under actual climate conditions in the winter, and higher flows under simulated climate conditions in the winter. These results are shown in Figure 31a-c.

All three models show a marked decrease in ground water components of the water budget, most notably in the spring. The SEMCOG and parcel models generally predict larger differences in the winter, but lower overall ground water volumes than the NAIP-based model. These results are shown in Figure 32a-c.

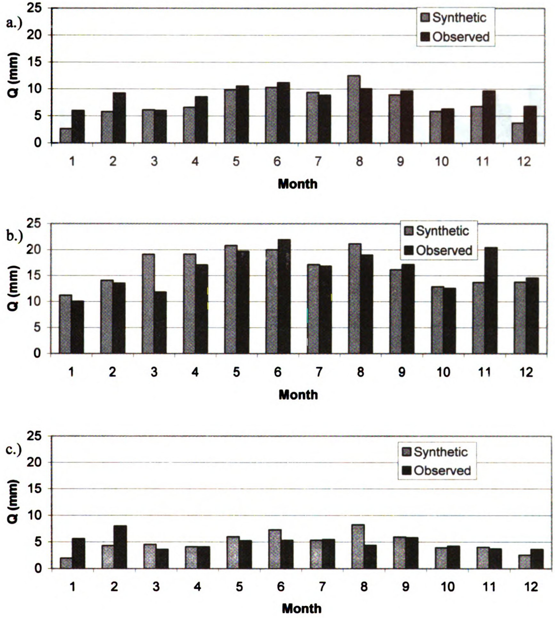


Figure 31: Model estimated overland flow for Paint Creek watershed, by month, for c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic and observed climate data.

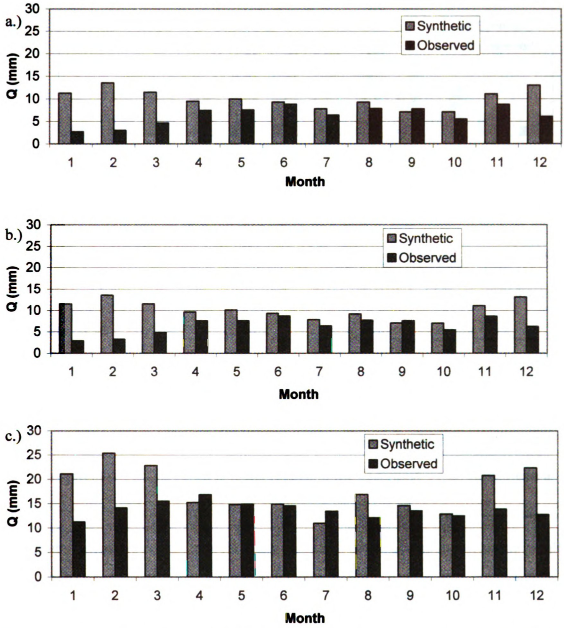


Figure 32: Model estimated ground-water components of the annual water budget for Paint Creek watershed, by month, for c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic and observed climate data.

Finally, all three models show a similar shift in the timing of peak ET from April to May, in response to a substantial increase in PET (shown in Figure 33).

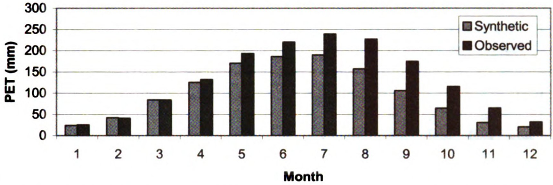


Figure 33: Model estimated potential evapotranspiration (PET) for Paint Creek watershed, by month (for all land covers), based on synthetic and observed climate data.

Actual ET is limited by both water availability and the estimated phenology of the land cover, and is thus subject to constraints based on cumulative temperature and water availability, as well as surface energy-balance constraints. In this case, we see a difference of approximately 10mm per month between the simulated and observed AET values, but also a difference in the timing of the peak ET in the spring. This matches well with the observed difference in precipitation during February and March, which would tend to constrain AET. This shift is likely related to the decreased water available as a result of diminished precipitation in February and March under actual conditions as compared to synthetic conditions. All the models also estimate a modest increase in fall ET. The NAIP model predicts somewhat more ET at the peak in May than the SEMCOG or parcel-based models. These results are shown in Figure 34a-c.

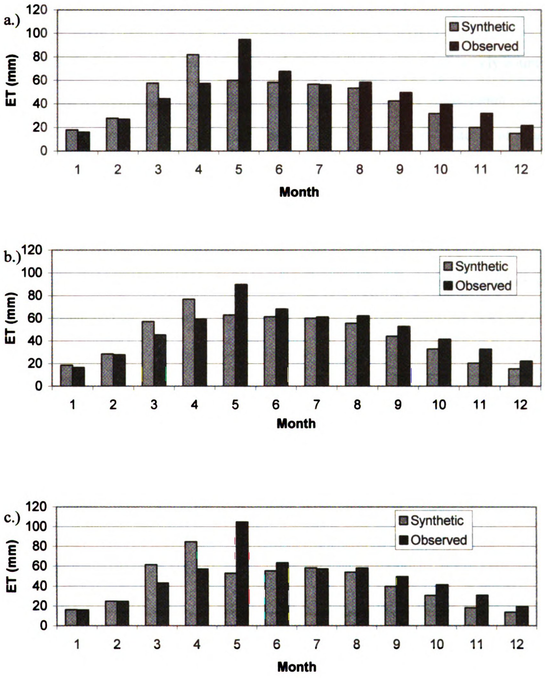


Figure 34: Model estimated actual evapotranspiration for Paint Creek watershed, by month, for c.2005 using SEMCOG (a), parcel (b), and NAIP (c) land cover, based on synthetic and observed climate data.

Chapter 4

DISCUSSION AND CONCLUSIONS

The background and results presented thus far depict a situation largely counter to conventional hydrologic theory: a watershed undergoes substantial urbanization over a relatively short period of time, yet there is no statistically significant evidence of changes in the stream-flow response. Complicating the interpretation is the non-stationarity of the system – interannual variability in climate, combined with several overarching trends in climate, as well as continuous change in land cover, regulations, and societal preference.

To a degree, it is possible to question the basic supposition – is suburbanization and coincident land use change a fair indicator of the more hydrologically relevant land-cover change? Analysis of parcel-based land-use and high-resolution remotely sensed land-cover data has demonstrated that although land-use change is clearly related to land-cover change, the relationship is constant through neither time nor space. Neither digitized land-use derived from aerial imagery nor parcel-based land use derived from tax assessment data maintained a fixed relationship with the land-cover through time.

The costs and availability of the competing datasets are also worthy of consideration. Land-use/land-cover datasets digitized from either analog or digital imagery have been a standard of land-use-change analyses for almost 30 years, certainly since the advent of the U.S. Environmental Protection Agency/USGS GIRAS LU/LC dataset at the national level (USGS, 1986) and the MIRIS dataset for Michigan. However, like any map or model, these datasets are selective abstractions of reality, created for a specific purpose (sometimes more than one).

An interpreter must identify and delineate tens or even hundreds of thousands of map units, consistently. Very often, several interpreters are set to the task. Although the level of consistency that can be achieved is impressive, there will always be differences of opinion. And seldom is such a dataset developed with the explicit purpose of modeling a physical process. The costs associated with developing such a dataset are generally large, measured in thousands of person-hours per county.

Tax parcel data is again a selective abstraction of reality, this time focused on the divisions between ownership boundaries, the use of the land, and the taxable value. The result is often higher resolution (certainly in urban areas) than data digitized from aerial imagery (and in practice aerial imagery often supports parcel maintenance), but again the salient aspects relate to the improvements and use of the land, not the physical properties of the land. Although maintaining a parcel and land-use base is a fundamental role of government, the costs associated are great. This cost leads the maintainers of these data to restrict its availability, making it the most common and yet least available form of land-use data.

A remotely-sensed land-cover dataset relies entirely on the availability of recent, high-resolution, preferably digital, aerial imagery. As a result of the U.S. Department of Agriculture's NAIP program (NAIP; http://165.221.201.14/NAIP.html), data with a pixel resolution of at least one meter will be available every three to five years in the public domain, nationwide. Areas with urban centers or large suburban populations, such as Oakland County, will be available every two to three years with a resolution of 0.3m. Classification of such three- or four-band imagery into rudimentary land-cover classes (such as were used in this study) is a relatively simple affair with appropriate desktop computer software. The labor associated with the automated classification used in the project amounted to approximately 50 hours, with the majority of that time invested making fine adjustments to marginally improve the accuracy of the classification.

The advantage to a hydrologic modeling application is apparent – the remotely sensed land cover dataset provides highly discretized information identifying areas of impervious surface, tree canopy, grass land, and so forth. Such an approach obviously does not provide much information on the ownership of a parcel, the extent of the parcel, or whether the parcel contains a residence or a business.

All of the approaches described involve varying levels of investment, specialized software, and skills. Perhaps the most expeditious approach would be to develop a time- and parcel-size and use-dependent model (such as is suggested in figure 18) of impervious surface and forest cover based on the parcel data already being maintained by local governments across the country.

With this background, the likelihood is that most use-based, and certainly both the SEMCOG aerial-imagery derived and county parcel-based, renderings of landcover overstate the extent of change, at least as it relates to impervious surface. Where the results previously cited from Aichele (2005a) indicated a doubling of urban land-use to the total of approximately 50 percent of the Paint Creek watershed, and parcel based estimates identified nearly 65 percent of the watershed to be in urban use (with over 60 percent of that change occurring in the past 30 years), remote sensing estimates indicated only 13 percent impervious cover.

Moreover, the conversion of land from certain undeveloped uses, particularly seasonal agriculture, to developed uses such as fixed residential, has been shown to have unexpected effects on water budgets. For instance, a tilled field with no cover in the spring will produce more runoff, a higher sediment load, and far less evapotranspiration than a lawn or wooded area. Similarly, a paved or otherwise impervious surface produces localized runoff, but virtually no evapotranspiration, as a result of precipitation.

In addition to the demonstrated issues associated with the relationship between land use and land cover in the SEMCOG and parcel datasets, both datasets seemed to bias the partition of precipitation into runoff rather than recharge, with the both polygon land-use sets estimating approximately 75 percent as much recharge as the NAIP-based land cover, which was itself lower than previously published analytical estimates. Although direct measurements of recharge are extremely rare, and the analytical technique of hydrograph separation leaves considerable room for improvement, a variety of authors and techniques have gradually coalesced toward agreement. Neff et al. (2005) tested six different hydrograph separation techniques for the Paint Creek gage, as well as over 3900 other gages, and found that the techniques produced estimates ranging from 81 percent to 61 percent of annual stream flow, with an average of 76 percent. The average of the ground-water components of the water budget using observed climate inputs for the NAIP-based model was 75 percent for the period from 1975-2005, while the parcel-based and SEMCOG-based models estimated 50 and 48 percent, respectively, for the same period.

Analysis of daily stream flow characteristics for the period from 1975 through 2005 for six basins in Oakland County produced more evidence of change than the previous work (Aichele, 2005a), but generally supported the same conclusions. Where the previous analysis had focused on annual stream-flow characteristics, and yielded little evidence of change, analysis of seasonal stream-flow components produced more evidence of change, although not necessarily as anticipated. The most common trend among all watersheds was an increase in the magnitude of low flows (flows in the 10^{th} and 25^{th} percentile annually), combined with decreasing stream flow in the spring season (March-May). No compensating increasing trends in other seasons (particularly adjacent winter or summer) were evident. The trends were also more evident during spring defined as March through May, rather than April through June.

Analysis of regional precipitation records for the period show no appreciable change in seasonality of precipitation (Figure 35), nor does a Mann-Kendall test for trend indicate a statistically significant change in precipitation through the period. However, the incremental 5-year flow duration curves for Paint Creek indicate that although there was no statistically significant change in the shape of the flow duration curve during the period from 1975-2005, the discharge values for each percentile during the period 2000-2005 are either the lowest or near the low-end of the range for the six five-year periods, suggesting that systematically less water is making it into the stream versus the past.

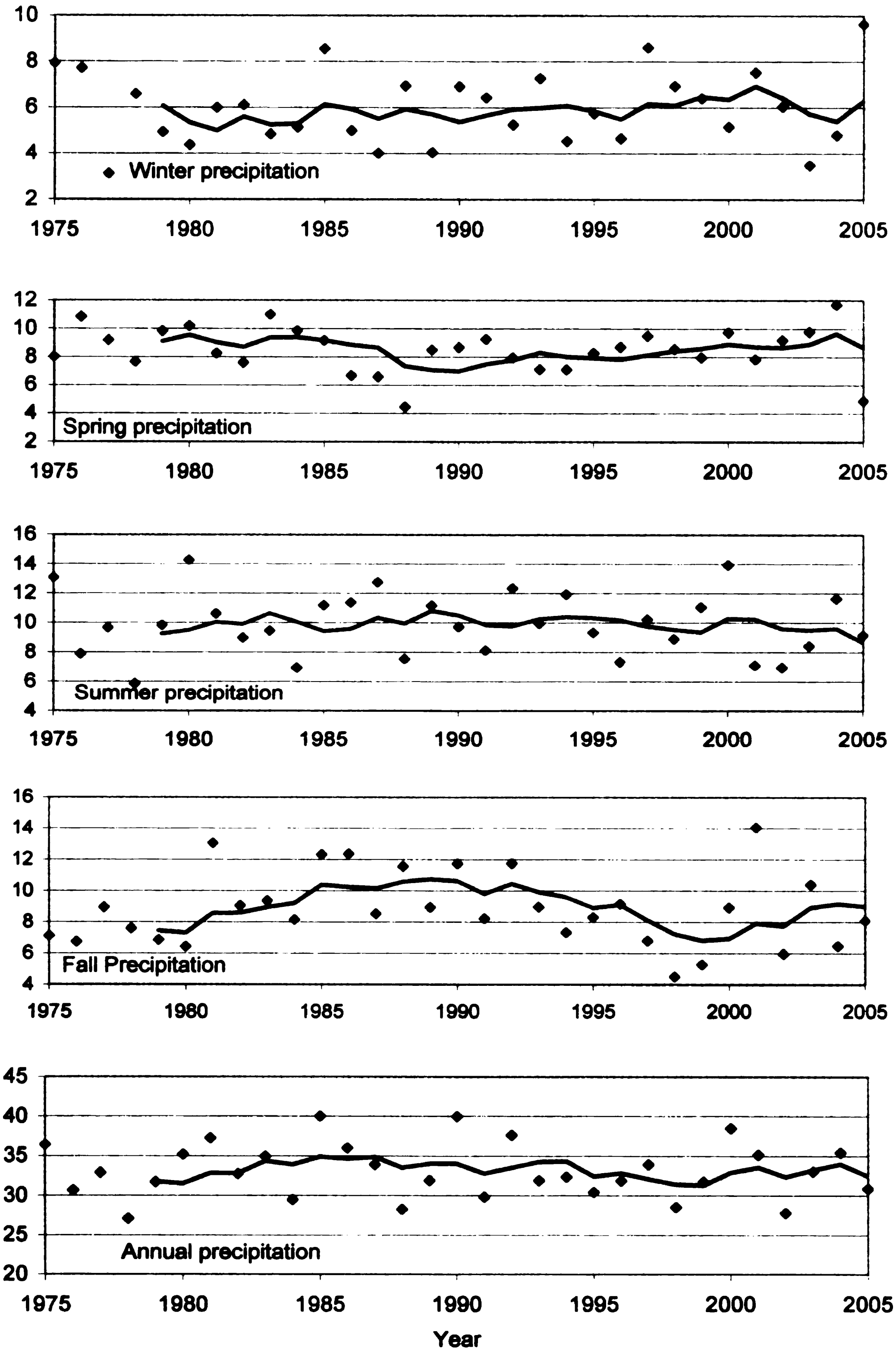


Figure 35: Annual and seasonal precipitation, in inches, 1975-2005, southeast Michigan (NWS Michigan Climate Division 10)

Considering the basic water budget equation:

$$P = Q + R + ET + \Delta S$$

where P is precipitation, Q is overland runoff, R is recharge, ET is evapotranspiration, and ΔS is change in storage, two likely sinks are implied. The first, R, is ground-water recharge. As was previously discussed, there is some reason to be skeptical of the ground-water processes described in the model, because of the relatively low base-flow estimates produced during the calibration period relative to more conventional analytical approaches. Further, the critical period based on observed changes in streamflow appears to be the spring, when snowmelt is an important contribution to stream flow in the region (Hodgkins, et al., 2007). Fontaine et al. (2002) observed that the SWAT model's snowmelt simulation processes are rather limited. Wang and Melesse (2006) attempted a formal parameter estimation process in order to improve snowmelt performance of the SWAT model, but with limited success. Levesque et al. (2008) have recently suggested 1) calibrating the model to the season (essentially fitting one model specifically to summer observations, then a second model to winter observations), or 2) a two-step composite calibration in which the model is fitted to summer data then a parameter estimation process applied to optimize a winter fit. Wu and Johnston (2007) actually observed that model performance was improved by reducing the spatial resolution of temperature and precipitation data, a finding somewhat counter to conventional wisdom. In none of these cases were year-long models as robust at winter season prediction as summer.

Further complicating matters is the relative lack of information regarding soil conditions during the period of snowmelt. A snowpack melting onto frozen soils is likely to produce far more surface runoff than snowpack melting into unfrozen soils, but the availability of soil temperature data, particularly outside of the growing season, is extremely limited. Many of the results associated with winter and spring season runoff and recharge are thus relatively difficult to estimate with certainty.

Setting these limitations aside for the moment, one finds that although ground-water recharge estimated by the model was lower under actual climate conditions than it was under the simulated normal condition, model-estimated recharge increased substantially in the spring months during the period from 2000-2005 (Figure 36). Possibly contributing to that increase is an increase in the above freezing temperatures during the early spring observed in Aichele (2005b; Figure 37) and the general warming in winter minimum temperatures noted in Andresen and Winkler (2009), both of which may be conducive to earlier soil thawing.

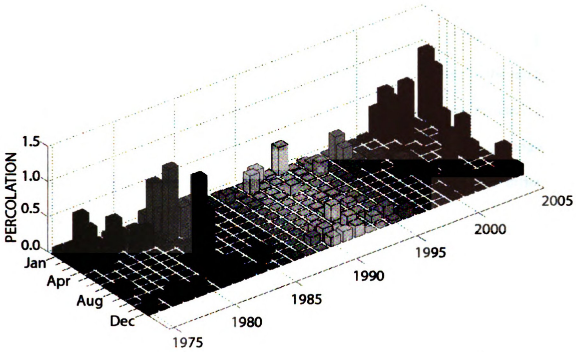


Figure 36: Average daily percolation (in mm) by month for the Paint Creek watershed estimated by the SWAT model using NAIP-based cover and observed climate data, 1975-2005.

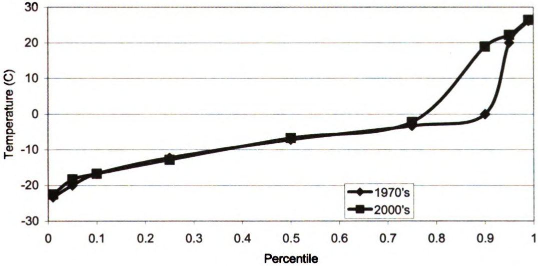


Figure 37: Cumulative frequency distribution for minimum daily temperatures (ºC) at Milford, Michigan, 1971-1980 and 2000-2005.

The increase in model-estimated recharge between 2000 and 2005 based on observed climate does not really speak to the overall tendency toward lower recharge when comparing output of the model based on 30-year observed climate to the model based on synthetic climate data. Even with increases in model-estimated recharge, overall the ground-water components of the water budget are declining, suggesting some of this modeled recharge may be a product of how SWAT apportions water to different subsurface pathways.

This also does not address the general decline in flow volumes across the frequency range. Increased spring recharge might divert more water to ground water, but most of that water should reappear in the stream later in the year as base flow. However, the earlier warming may also be associated with acceleration of the second major sink, ET. Fernandez et al. (2007) found a strong increasing trend in annual ET in the Canadian Great Lakes during the second half of the 20th century, with a magnitude similar to what might be fitted through the modeled SWAT data.

SWAT estimates ET based on available soil moisture and cover type, and because the synthetic climate series was created to replicate interannual variability within the 30 year study period, direct year-to-year comparisons are somewhat problematic. Model results generally support the assertion that ET has been greater under observed climate conditions than would have been expected based on the 1971-2000 normal climate, with a dramatic increase visible in the difference between annual and simulated PET totals in the watershed. However, analysis of the 30 year actual climate series indicates a significant (α=0.01) increase in February PET through the period, and graphically suggests an apparent increase in February ET, although this trend is not statistically significant. On an annual basis, observed net watershed ET (P-Q) appears to be increasing in recent years (Figure 38), particularly the period from 2000 – 2005, for all six basins studied in Oakland County, although the trends are not statistically significant based on the 1975-2005 period.

Finally, the effects of land-cover change must be considered. Increases in impervious surface generally do result in increased runoff and decreased ground water recharge, although based on the data analyzed in this research, the extent of the impervious surface can be dramatically less than the extent of developed area. An additional temporal bias may be present, as 1) seasonal agriculture is replaced by continuous land-covers, and 2) continuous land-covers matures. Much of the research in this area has been conducted in semi-arid environments (e.g. McVicar et al., 2007; Moore and Rebel, 2008), particularly in China (e.g. Wang et al., 2008; McVicar et al., 2007, Bi et al., 2008) and thus may not be fully applicable. However, Wattenbach et al. (2006), working in northern Germany, studied a formal policy-driven shift from agriculture to forest and identified dramatic increases in ET with the most pronounced increases occurring in the spring. Salm et al. (2005) working in the Netherlands went somewhat further, identifying both an increase in ET as a result of afforestation, and an continued increases in ET as forests mature. Matheussen et al. (2000) as well as Vanshaar et al. (2002), both working in the Columbia River Basin, have observed that as forest maturity and leaf area index increase, so do ET, and as a result stream flows decrease.

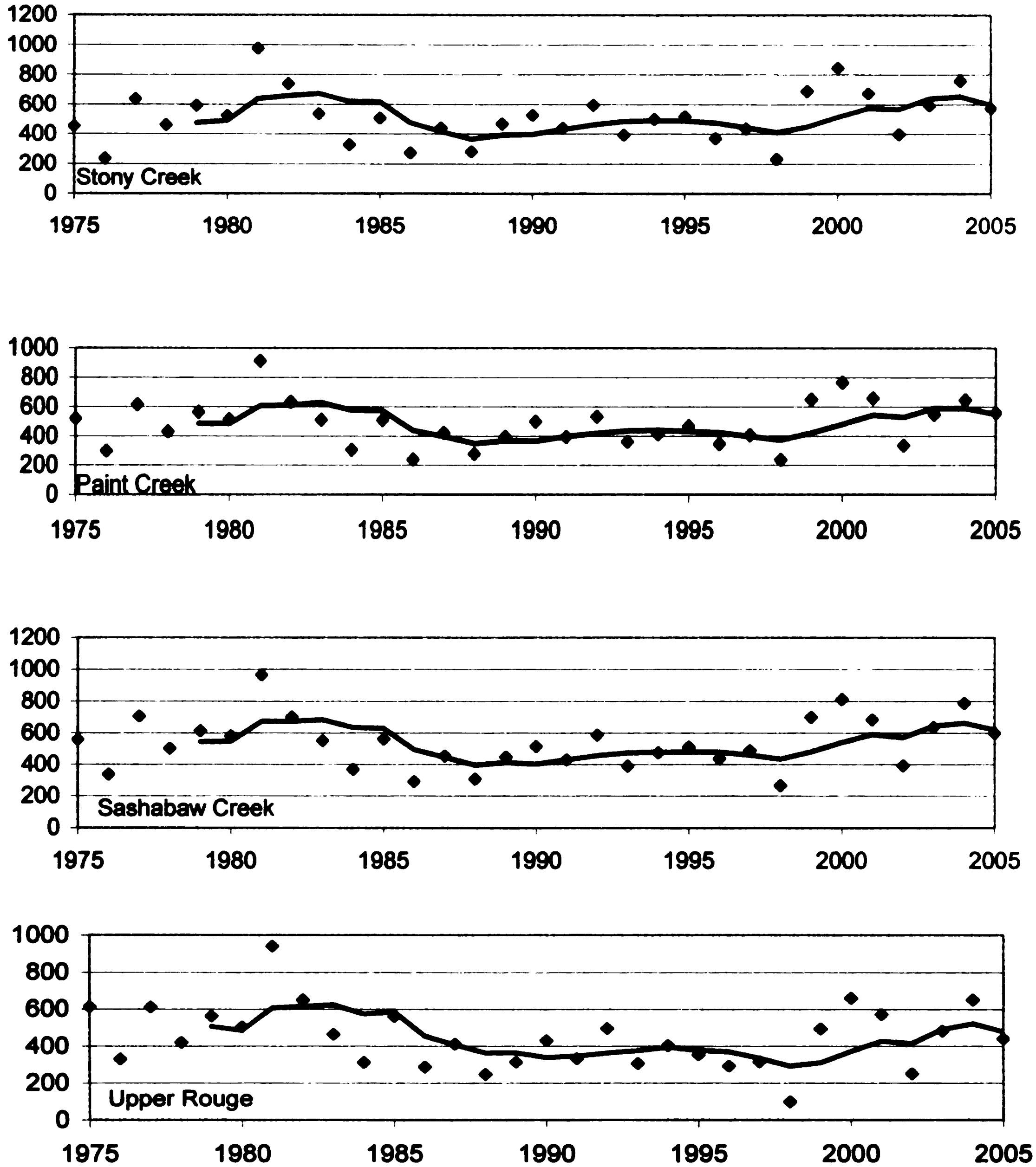


Figure 38: Observed evapotranspiration (precipitation – stream flow) for selected watersheds in Oakland County, Michigan, 1975-2005.

By separating the effects of land cover change and climate, it is possible to estimate the effect of each forcing on the watershed system. Drawing just the NAIP-based comparison tables from Tables 21 and 22, it is possible to relatively quantify the effects of land-cover change and climate on the Paint Creek watershed (Table 23).

Table 23: Comparison of modeled effects of climate and land-cover change on annual water budget components for the Paint Creek watershed, 1975 to 2005, in mm.

			PREC	SURQ	LATQ	GWQ	PERCO	SW	ET	PET	YIELD
Climate effects	NAIP	Max.	510.20	130.45	74.31	89.21	70.31	59.23	227.07	687.47	239.50
		Ave.	31.47	19.52	-11.23	-22.95	-22.67	-42.64	46.40	344.01	-14.69
		Med.	62.30	17.70	-0.82	-20.80	-21.39	-34.18	48.29	335.04	-19.98
		Min.	-450.10	-50.41	-99.34	-138.98	-140.45	-147.43	-178.67	143.88	-287.77
Land cover change effects	NAIP	Max.		22.07	-1.32	2.37	0.16	-11.58	-2.79	0.20	12.33
		Ave.		14.95	-3.24	-3.90	-3.97	-13.71	-7.41	0.19	7.23
		Med.		14.67	-2.95	-3.43	-2.90	-13.55	-8.34	0.19	7.60
		Min.		9.16	-6.62	-12.51	-13.90	-16.51	-10.85	0.17	2.45

PREC, precipitation; SURQ, overland flow; LATQ, Lateral soil flow; GWQ, Ground-water flow; PERCO, percolation to deep ground water; SW, soil water storage; ET, Evapotranspiration; PET, Potential evapotranspiration; YIELD, total water yield to channel (streamflow)

Overall, land-cover change during the period from 1975 to 2005 is estimated to have resulted in a net increase of slightly more than 7mm of stream flow on an annual basis. In contrast, observed climate during the period 1975-2005 resulted in a decrease in stream flow of more than 14 mm annually compared to the simulated climate. Thus these effects are largely counteracting.

Within the water budget, both climate and land cover change tend to increase surface runoff (by 19.5mm and 14.95mm per year on average, respectively) and decrease both ground water recharge (by 22.7mm and 4.0mm per year on average, respectively) and base flow (by 34.2mm and 7.1mm per year on average, respectively). The effect of climate is twice as great as land cover change in affecting runoff (decrease of 14mm annually compared to 7mm), and five times greater in affecting the ground-water components of the water budget (a decrease of 56.9mm for climate compared to a decrease of 11.1mm for land cover). Much of that is driven by a substantial increase in ET (46.5mm) based on climate, offset by a small decrease (7.4mm) in ET based on land cover change.

Thus the effects of climate and land cover change on the primary measured characteristic of watershed hydrology, stream flow, offset each other and generally tend toward decreasing stream flow. Recharge and base flow are not directly measured, however ground-water levels are. A long-term record of water levels in the area would serve as partial substantiation of many of the relationships outlined here.

Seven glacial wells in Oakland County have been monitored in association with specific projects data collection activities over the period from 1965 to 2005. Periods of record and frequency of measurement vary, and the records have substantial discontinuities. Two of the wells were abandoned in the 1990s, and one is heavily affected by pumping. However, all of the remaining wells recorded new maximum depths to water during 2003 (Table 24). Although this is somewhat indicative, because of the long discontinuities and infrequent measurements, separating a seasonal pattern from a long-term trend is difficult. Unfortunately, no long-term observation wells have continuous records in the immediate area of the study watershed.

Table 24: Locations of current USGS monitoring wells in Oakland County, Michigan, not significantly affects by pumping, with period of record and maximum depth to water for the 2003 water year.

Site ID	Site Name	Previous period of record	Previous maximum depth to water (ft)	New (2003) maximum depth to water (ft)
423423083324001	Proud Lake	1969-1992	6.40	6.81
424133083293101	Teggerdine Rd.	1972-1981	30.80	30.93
424133083293201	White Lake Rd.	1972-1981	11.16	12.36
425116083321501	Holly Rec. Area	1965-1995	26.50	28.23

A long-term monitoring well does exist in Lucas County, Ohio, approximately 75 miles to the south, an area of suburban Toledo subject to the same climate, if not necessarily exactly the same land-use forcings. This well is deeper than the wells in Oakland County, and likely a better indicator of long-term trends than some of the shallower wells (Howard Reeves, written communication, 2009). The Lucas County well has shown decline in water levels of approximately 12 feet between the spring of 1987 an the spring of 2005 (figure 39) , with most of that decline occurring during the period from 1997-2005. Similarly, the net basin ET estimates cited previously are strongly indicative of an increase in annual ET with five year mean estimates of ET increasing by between100 and 200mm between 1995 and 2005.

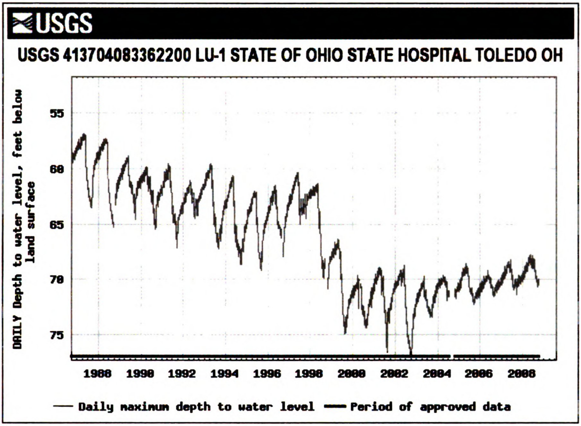


Figure 39: Depth to ground water for U.S. Geological Survey monitoring well LU-1 in Lucas County, Ohio, 1985-2009 (obtained from USGS website http://waterdata.usgs.gov/oh/nwis).

Chapter 5

SUMMARY

A multi-phased study of hydrologic processes was conducted in Oakland County, Michigan, a rapidly developing suburb of Detroit to better understand the effects of land-use change and climate on watershed hydrology. Population in Oakland County increased by 200,000 during the period 1980 to 2000, and by almost 800,000 since 1950. Considerable land-use and land-cover change has accompanied that population increase. Various measures of land use were compared to remotely-sensed land-cover data to evaluate the effect of different land cover data collection methods. Polygon-based land-use descriptions generally included more area classified as developed than would be identified by evaluating impervious surface. Although this result is not particularly surprising, given the different purpose of the land-use data, the polygon-based data also failed to capture the temporal variations occurring within land use. Impervious surface proportion associated with general land-uses (e.g., residential, single family) and even relatively specific land-uses (e.g., single family, 1.0-2.5 acres) were found to vary in a time-dependent, and thus spatially correlated manner by up to 100 percent. This variation is likely the result of a combination of social and economic factors such as transportation and utility infrastructure, fuel costs, local taxes, and social preferences. This finding casts doubt on the common practice of applying a constant impervious surface proportion to polygon based land use datasets as a means of estimating impervious surface cover.

Stream-flow records for six watersheds in Oakland County were analyzed for annual and seasonal trends using the modified Mann-Kendall trend test, and Sen's slope estimator. Despite the population increase and associated land-use change, the study watersheds exhibited either 1) no change in streamflow characteristics, or 2) a flattening of the flow duration curve, contrary to the conventional expectation of increased peak flows, decreased low flows, and a steepening flow duration curve. The one relatively common trend was decreased flows during the spring months (March – May). Concurrent with this land-use change, climate variability, most notably warming during the winter months, was also occurring.

A series of SWAT model simulations for the Paint Creek watershed were developed using common parameters to evaluate the effects of specific components on the system. The three versions of land-cover evaluated indicated a bias toward increased runoff and decreased recharge in the land-covers derived from polygon land use. All performed equally well at predicting flows across the flow duration curve and matching annual observed water budgets.

Land-use change scenarios were constructed for the period 1975 through 2005. The only direct observations available in both periods were polygon land-use derived from aerial imagery. However, parcels with development dates were used to artificially reconstruct pre-development land cover for both parcel-based land use and the remotely sensed land-cover data. Results from this process again predicted substantially more change in stream flow using the polygon and parcel-based land-use data than the land-cover data, although all land-cover renderings predicted increased stream flow.

Climate change scenarios were constructed for the period 1975 through 2005 using synthetic daily weather data fit to the 1971-2000 climate normals. These data were utilized to recreate a trendless series of temperature, precipitation, and solar radiation, including normal interannual variability and serial autocorrelation. Each of the land-cover renderings predicted increased stream flow as a result of development, but the model using simulated climate data generally predicted more overland flow, less recharge, and more actual ET than the model using observed climate data.

Overall, the effects of suburban land-use change on watershed hydrology in Oakland County appear to be offset by the effects of climate trends. For the most plausible land-cover rendering – land-cover derived by automated classification of aerial imagery - comparing the effects of land-cover change to the effects of climate change, climate change resulted in approximately twice as much alteration to annual stream flow as land-cover change, and in an offsetting direction. Both land-cover change (increased impervious surface) and climate (increasing temperatures and ET) tended to decrease ground-water components of the water budget, which may be supported by long-term ground-water monitoring data.

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