Effects of Land Use Change on Streamflow: An Evaluation of the Salt River Basin, Kentucky

By
Alvin Rentsch

A thesis submitted in partial
fulfillment of the requirements for
the degree of

Master of Science

(Geography)

at the

UNIVERSITY OF WISCONSIN-MADISON
2011

Table of Contents

List of Figures

LIST OF TABLES

Acknowledgements

This research would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First and foremost, my utmost gratitude to my wife Dr. Amy Cavanaugh, whose sincerity and encouragement I will never forget. She has been my inspiration as I hurdle all the obstacles in the completion of this research work.

Dr. Clara Leuthart, at the University of Louisville, who always had kind concern and consideration regarding my academic requirements and growth as a researcher.

Dr. Yongjia Song for his tireless efforts and endless patience in helping me to understand the intricacies of computer modeling.

Tory Shelly and Becky Zug for keeping me grounded in reality during my time here at Madison

Many thanks to my advising committee members, their time and commitment to this thesis has been invaluable, Dr. Jack Williams, Dr. James Knox and my advisor, Dr. Multu Ozdogan. His guidance through this research endeavor has been greatly appreciated.

A special thank you to the staff at the Geography Department for their time assisting me to navigate the ins and outs of the administrative maze on campus. Thanks to Jamie Stoltenberg for her time and knowledge of the GIS data used in my research. I would also like to thank Dr. Ken Potter, for his experience and advice on water budgets. I am grateful to my colleagues Danielle Lamberson Phillip and Alison Coulson in the Nelson Institute for the consultations and moral support.

Last but not least, my omnipresent puppy Ranger, for giving me the strength to plod on despite my desire to give up and throw in the towel; thank you so much Ranger.

Abstract

The Salt River basin has experienced extensive land use change during the second half of the twentieth century as a result of expansion of urbanized areas. Due to expected climate change, the hydrological regime of the basin is expected to experience more extreme flood peaks and low flows. Land use changes may reinforce the effects of this shift through urbanization. In this study, we investigate the effect of projected land use change scenarios on river discharge using the variable infiltration capacity (VIC) (version 4.0.6) model, forced by a high-resolution atmospheric data set.VIC is a hydrology model that explicitly accounts for the role of land cover. All projected land use change scenarios lead to an increase in streamflow. The magnitude of the increase, however, varies among subbasins. The model suggests that land use change could have large effects on streamflow, faster runoff response to precipitation was observed toward the end of the period, which does appear to be attributable to land cover change. Projected land use changes (urbanization and conversion of cropland into forest) have inverse effects.

1.0 Introduction

1.1 Background

The combination of climate and land use change over the last 100 years has modified water fluxes in many areas (DeFries et al., 2006; Bonan, 1996). As human pressures increase, it is critically important to assess future consequences of land use change on water resources. The Natural Resources Conservation Service (NRCS) estimates that there were about 13.75 million hectares of land converted to developed acres from 1982 to 2001 in the United States. In this context, developed land refers to land that has been altered from its natural state by construction or installation of impervious surface. Forestland accounts for 46% of the change while 20% can be attributed to cropland. In the period between 1992 and 2001, about 28% of developed land was converted from prime farmland.

The hydrologic cycle defines the continual flow and transfer of water between the atmosphere, land surface, oceans, and underground aquifers. When humans develop the environment, however, the balance of water is interrupted. Particularly in urban areas, the components of the hydrologic cycle are changed by the development of buildings, roof tops, roads, industrial facilities, and residential areas. An increase of such urban development means a decrease in the amount of forested land, wetlands, and other forms of open space in the natural system (Brabec et al., 2002). Precipitation that falls on developed areas quickly flows into streams without infiltration, which causes a significant increase in stormwater runoff quantity and degradation in the water quality.

To fully understand the implications of land use change on water resources in the future, the interplay between these two systems must be examined. Assessing land cover change with hydrology models provides one method to evaluate future interactions as well as answer policy questions related to our ability to fulfill current demands on resources. The dynamics and vulnerabilities of water resources are, most often, insufficiently appreciated and evaluated at the spatial and temporal scales where policy is formed and applied (Pielke et al., 2002; Bowling et al., 2004). For example, field watershed scale studies typically include analysis of paired watersheds over one time period (Grace, 2004; Bowling et al., 2000) or of one watershed that has undergone some type of change (a “before and after” analysis) (Zhao et al 2004; Yang and Liu, 2005; Dow 2007). The spatial and temporal scope of research addressing land use/cover change and its impacts on hydrology must be increased to support policy making at larger spatial scales that have longer temporal relevance. In field studies, the analysis of results is complicated by the many factors external to land use/cover change that may impact hydrology such as climate and human intervention through flow control structures. As a part of the set of tools available to researchers, numerical model simulations allow researchers to control for these factors by removing any human influences outside of land cover change and by controlling climate variation in a set of comparative model runs. This type of analysis serves as a “virtual” paired watershed study in the absence of adequate resources to conduct such field-based analysis.

Macroscale hydrological models are abundant and most have the ability to reasonably represent water resources and runoff from large river basins (Gerten et al., 2004; Arnell, 1999; Vörösmarty et al., 2000; Liang et al., 1994; Vörösmarty et al., 1989; Todini, 1996). However, the parameterization of the land cover is often insufficient in large-scale hydrologic models to adequately capture important regional land-hydrosphere interactions, particularly as related to the temporal dynamics of hydrologic response to changes in land cover (Gerten et al., 2004). Through more adequate representation of the land surface, by way of effective parameterization of vegetation and urban land uses, the spatial and temporal variability of the water budget in large basins will be more realistically assessed.

The purpose of my research was to understand the role of changing landscape –both in terms of human expansion and land use-on the hydrologic system. In this research, we take advantage of a highly detailed land cover dataset to assess the effects of increasing impervious surface on stream flow response. We calibrate and validate the Variable Infiltration Capacity (VIC) model over three 10-year periods for a representative basin, and use the calibrated model to explore the sensitivity of streamflow response to simulated increases in urban expansion using 30 years of atmospheric forcing data.

1.2 Study area

The Salt River watershed is a mixed rural-suburban-urban watershed in the north central part of Kentucky (Figure 1.). This watershed flows from south to north and joins the Ohio River near West Point, KY. The Salt River is a 225 km long river in Kentucky that drains 756,200 ha and is home to over 100 fish species and about 40 mussels. The watershed is dominated by intensive row crop agriculture. According to the U.S. Census Bureau, there has been a 55% population increase over the last 40 years. Agriculture covers 74% of the total land use followed by forest with 22%. The terrain around the river is deeply ridged until it nears its outlet. The shallow river valley is 149-161 meters above sea level. There has been a dramatic change in the land use for the Salt Watershed over the past few years.

Traditionally, areas within the Salt River Basin were rural agricultural farms involving horse, cattle and livestock production, and farms raising tobacco, corn, soybeans, sorghum, hay and alfalfa. Data from the U. S. Census Bureau indicate that four counties in the Basin had the largest percent of population increase during 1990-1999 (Figure 2).The movement of families from over-populated metropolitan areas toward Oldham, Shelby, Spencer and Bullitt counties has occurred during the past ten years, and the trend is likely to continue. Development of new communities has caused changes in land-use patterns. Development of new transportation corridors for roads and light railways creates the potential for increase in runoff across the basin. The watershed includes parts of ten counties. The Louisville metropolitan area is the largest urban area in the Salt River Watershed.

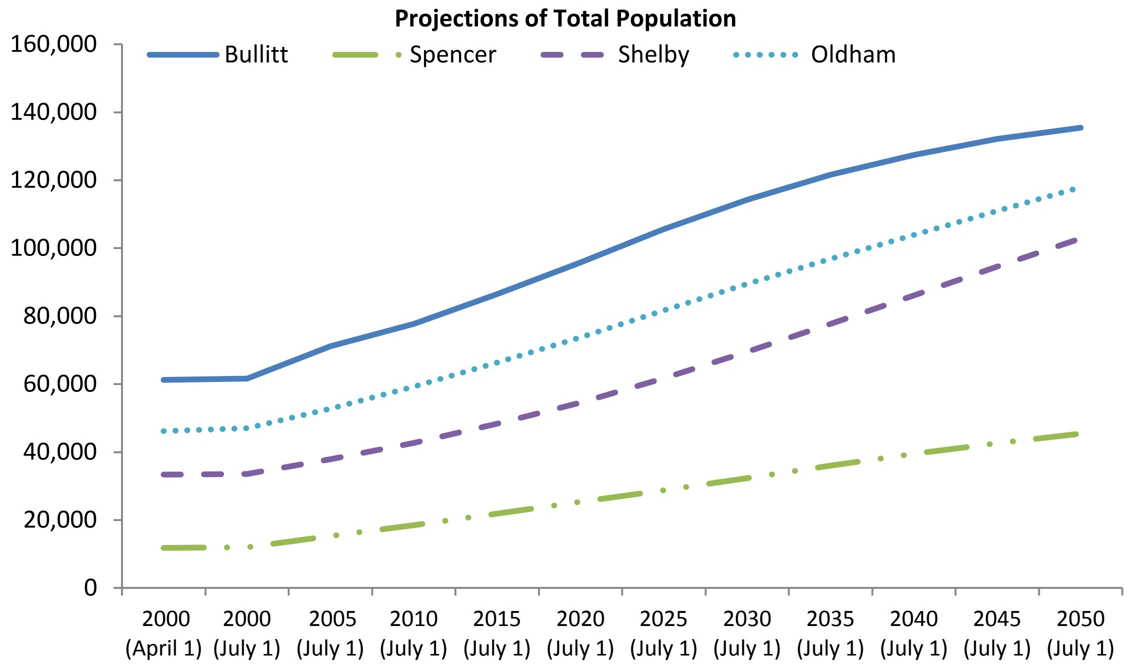


Figure 1. Population projections for Bullitt,Spencer, Shelby, and Oldham counties.

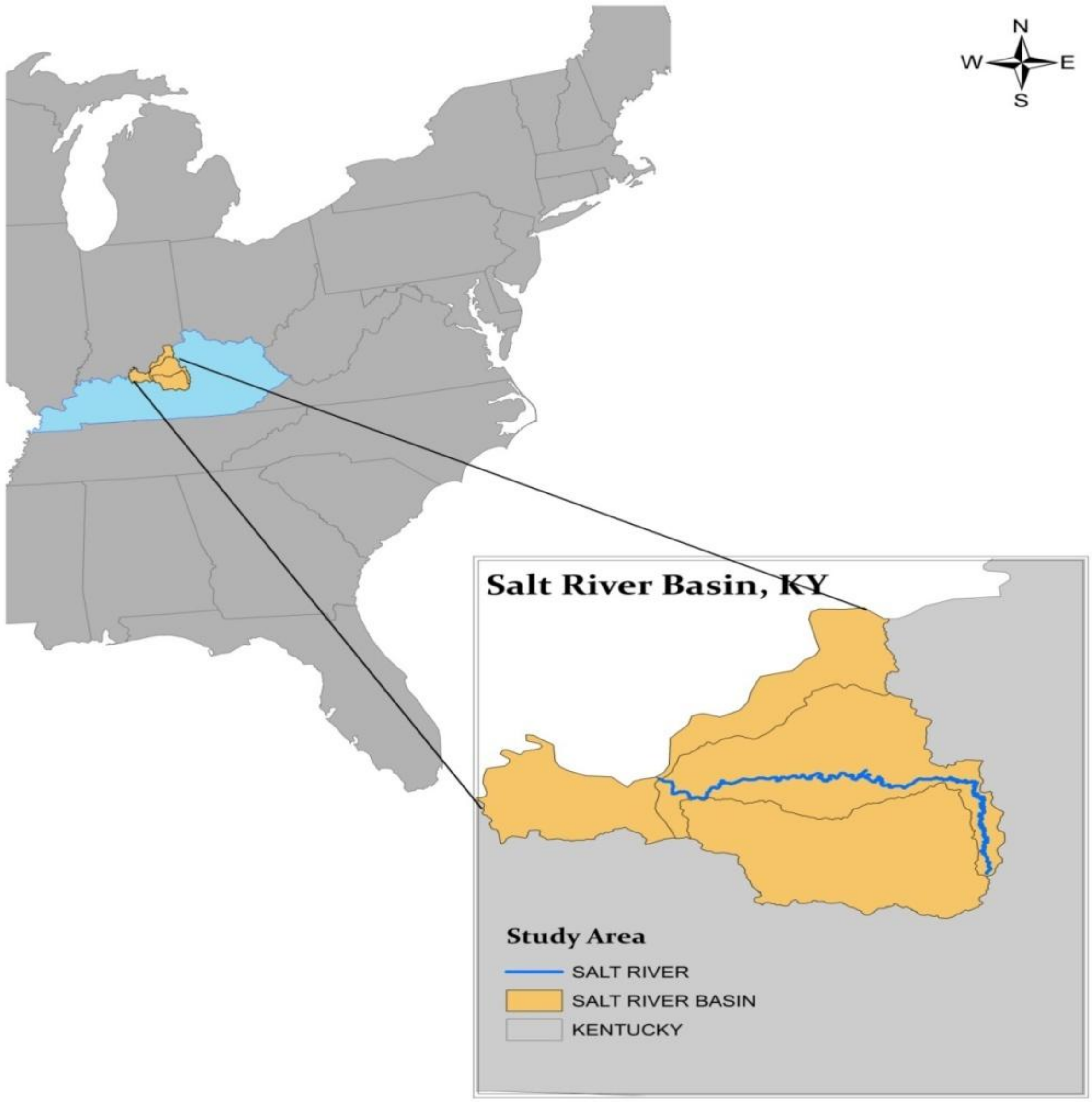


Figure 2. Salt River Basin located in North Central Kentucky.

1.3 Objectives

Current research suggests that climate change is altering regional rainfall patterns. The IPCC projects that temperatures will increase by 1.0 -2.4°C over the Southeastern U.S. by 2050, as a result of which the hydrologic cycle is expected to intensify. Together these factors suggest that Kentucky and the southeastern U.S. as a whole face significant water-related challenges in the future. Therefore, floods and droughts occurring in the basin can have vast consequences. For example, the floods in 1997 caused severe damage (in Louisville alone about 200 billion USD). Conversely, the drought period of 2008 was one of the most serious that Kentucky has experienced in recent history, affecting a wide range of sectors, from agricultural to hydropower generation.

It is worthwhile to investigate the potential for land use and management changes to decrease the flood peaks and alleviate extensive drought periods within the region. The primary goal of this research was to understand the role of changing landscape –both in terms of human expansion and land use-on the hydrologic system. More specifically, I had the following objectives:

1. *Determine the appropriateness of an existing hydrologic model to simulate rates and patterns of hydrologic change due to changes in the landscape, specifically in the form of urbanization.*
2. *Modify an existing model to better simulate the hydrologic processes that result from different urbanization scenarios.*
3. *Use these modeling results to predict possible trajectories of hydrologic regime under various landscape change scenarios.*

2.0 Previous research on the hydrologic impacts of urbanization

Changes in land cover alter the magnitude and variability of stream discharge, creating not only uncertainties in the discharge but a void in our knowledge of the consequences in the altered hydrologic regimes. For example, forest disturbance in a watershed has been shown to be associated with an increase in peak streamflow (Bates and Henry 1928; Verry 1986; Hornbeck et al. 1997). An increase in impervious areas through urbanization decreases infiltration rates thereby increasing overland runoff (Dunne and Leopold, 1978). Deforestation decreases evapotranspiration and increases land-surface temperatures (Claussen, et al 2001; Laurance, 2007). It is only through developing an understanding of the temporal and spatial scale of how water fluxes respond to land use/cover change that mitigation strategies can be created to lessen any negative impacts.

The expectations for environmental, and particularly hydrologic, changes associated with urbanization are well documented. 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 Soil Conservation Curve Number (SCS). 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.

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 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 amount storm sewers and the extent of impervious surface. The two key hydrograph parameters evaluated were; lag time and peak discharge.

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 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: 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.

An article by Schuster et al. (2005) presents a review of the current state of understanding of the effect of urbanization on watersheds. They summarize the current state of knowledge; specifically, increases in impervious surface result in increased hydraulic efficiency, ability of structures to conduct water, and urban catchments, and can cause substantially decreased capacity for a given landscape or region to infiltrate precipitation, with a related increase in the production of runoff (Booth, 1991; Hsu et al., 2000), 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.

Each of these studies illustrates the incompleteness of our understanding in hydrology. Most notably, 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 central Kentucky - 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.

3.0 Literature review on 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 to 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 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 1993) 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 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) provide an update to the previous work, and some additional models.

4.0 Methodology

4.1 Variable Infiltration Capacity (VIC) model description

VIC is a macroscale energy and water balance model in constant development. (Liang et al., 1994: Liang et al., 1996; Cherkauer et al., 2003; Bowling et al., 2004). In comparison to other Soil Vegetation-Atmosphere Transfer Schemes (SVATS), VIC is able to model subgrid variability in soil moisture capacity as a probability distribution and parameterize baseflow as a nonlinear regression so that it is separated from quick storm response (Zhao et al., 1980; Dumenil and Todini, 1992). Land cover classes are represented by vegetation parameters such as leaf area index (LAI), albedo, canopy resistance, and relative fraction of roots in each of the soil layers (Liang et al., 1994). Other output parameters including evapotranspiration, surface runoff, and baseflow are computed for each cover type and summed over all cover types within a grid cell. The outputs of the model are energy and water balance flux information. Flow out of each grid cell can be routed to produce outflow hydrographs (Lohmann et al., 1996).

Like most physically based hydrologic models, the VIC model has many parameters that must be specified (about 20, depending on how the term “parameter” is defined). However, most of the parameters can be derived from in situ measurement and remote sensing observation. The VIC model has been tested and applied at a large range of scales from large river basins to continental and global scales (for example, Wood et al., 1992; Stamm et al., 1994; Abdulla and Lettenmaier, 1996; Nijssen et al., 1997; Maurer et al., 2004). In a comparison with 16 land-surface schemes (LSSs) that participated in the Project for the Intercomparison of Land-surface Parameterizations (PILPS) phase 2(c) experiment, the VIC model was among 5 LSSs which performed well, within 25% of the total volume of naturalized observed streamflow for Arkansas River basin (drainage area of 409,273 sq km) and Red River basin (drainage area of 156,978 sq km) while it was among 4 LSSs representing better sub-grid runoff production (Lohmann et al., 1998).

4.1.1 Overview of VIC Model Processes

The overall VIC model framework has been described in detail in the literature (Liang et al. 1994; Liang et al., 1996; Nijssen et al., 1997). The key characteristics of the grid-based VIC are the representation of vegetation heterogeneity, multiple soil layers with variable infiltration, and non-linear base flow.

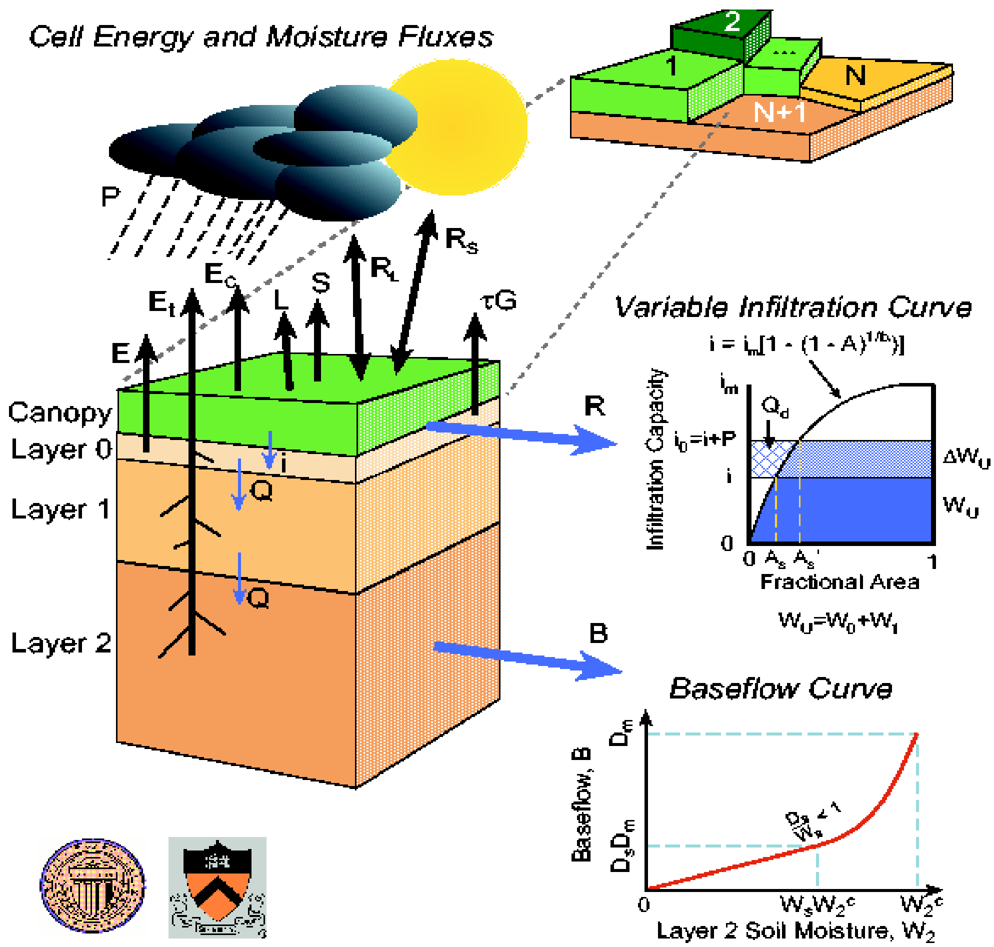


Figure 3. Schematic of the VIC model with mosaic representation of vegetation coverage http://www.hydro.washington.edu/Lettenmaier/Models/VIC/index.shtml.

Figure 3 (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/index.shtml) shows the schematic of the VIC model with a mosaic representation of vegetation coverage and three soil layers. The surface of each grid cell is described by N+1 land cover tiles, where n = 1, 2, … , N represents N different tiles of vegetation, and n = N+1 represents bare soil. For each vegetation tile, the vegetation characteristics, such as LAI, albedo, minimum stomatal resistance, architectural resistance, roughness length, relative fraction of roots in each soil layer, and displacement length (in the case of LAI) are assigned. Evapotranspiration is calculated according to the Penman-Monteith equation, in which the evapotranspiration is a function of net radiation and vapor pressure deficit. Total actual evapotranspiration is the sum of canopy evaporation and transpiration from each vegetation tile and bare soil evaporation from the bare soil tile, weighted by the coverage fraction for each surface cover class. Associated with each land cover type are a single canopy layer, and multiple soil layers. The canopy layer intercepts rainfall according to a Biosphere-atmosphere transfer scheme (BATS) parameterization (Dickinson et al., 1986) as a function of LAI. The top two soil layers are designed to represent the dynamic response of soil to the infiltrated rainfall, with diffusion allowed from the middle layer to the upper layer when the middle layer is wetter. The bottom soil layer receives moisture from the middle layer through gravity drainage, which is regulated by a Brooks-Corey relationship (Brooks and Corey, 1988) for the unsaturated hydraulic conductivity. The bottom soil layer characterizes seasonal soil moisture behavior and it only responds to short-term rainfall when the top soil layers are saturated. The runoff from the bottom soil layer is according to the drainage described by the Arno model (Franchini and Pacciani, 1991). Moisture can also be transported upward from the roots through evapotranspiration. Although vegetation subgrid-scale variability is a critical feature for the VIC model, the soil characteristics (such as soil texture, hydraulic conductivity, etc.) are held constant for each grid cell. In the model, soil moisture distribution, infiltration, drainage between soil layers, surface runoff, and subsurface runoff are all calculated for each land cover tile at each time step. Then for each grid cell, the total heat fluxes (latent heat, sensible heat, and ground heat), effective surface temperature, and the total surface and subsurface runoff are obtained by summing over all the land cover tiles weighted by fractional coverage.

The VIC model can be run in either a water balance mode or a water-and-energy balance mode. The water balance mode, used in this study, does not solve the surface energy balance. Instead, it assumes that the soil surface temperature is equal to the air temperature for the current time step. By eliminating the ground heat flux solution and the iterative processes required to close the surface energy balance, the water balance mode requires significantly less computational time than other model modes. These simplifications, combined with the daily time step that is typical of water balance mode simulations, yields a substantial savings in computational time.

In the VIC model, each grid cell is modeled independently without horizontal water flow. The grid-based VIC model simulates the time series of runoff only for each grid cell, which is non-uniformly distributed within the cell. Therefore, a stand-alone routing model (Lohmann., et al., 1996, 1998) is employed to transport grid cell surface runoff and base flow to the outlet of that grid cell then into the river system. In the routing model, water is never allowed to flow from the channel back into the grid cell. Once it reaches the channel, it is no longer part of the water budget. Figure 4 shows the schematic of the routing model. A linear transfer function model characterized by its internal impulse response function is used to calculate the within-cell routing. Then by assuming all runoff exits a cell in a single flow direction, a channel routing based on the linearized Saint-Venant equation is used to simulate the discharge at the basin outlet.

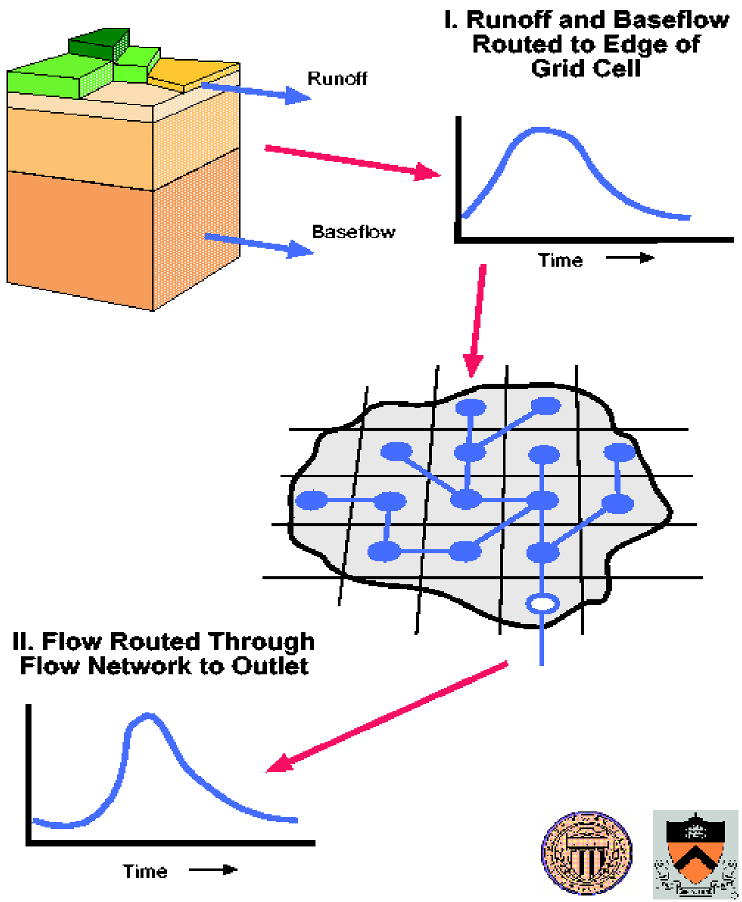


Figure 4. Schematic of VIC network routing models
http://www.hydro.washington.edu/Lettenmaier/Models/VIC/index.shtml

4.1.2 Water balance

The water balance in the VIC model follows the continuous equation for each time-step:

$$\frac{\partial S}{\partial t} = P - E - R$$

where dS/dt, P, E, and R are the change of water storage, precipitation, evapotranspiration, and runoff, respectively. Within the time step, all units of above variables are mm. Over vegetated areas, the water balance equation in the canopy layer (interception) is:

$$\frac{\partial W_i}{\partial t} = P - E_c - P_t$$

where W_i is canopy intercepted water (mm), E_c is evaporation from canopy layer (mm), and P_t is througfall (mm).

4.1.3 Evapotranspiration

The VIC model considers three types of evaporation: evaporation from the canopy layer (E_c, mm) of each vegetation tile, transpiration (E_t, mm) from each of the vegetation tiles, and evaporation from the bare soil (E_1, mm) (Liang et al. 1994). Total evapotranspiration over a grid cell is computed as the sum of the above components, weighted by the respective surface cover area fractions. The formulation of the total evapotranspiration is:

$$E = \sum_{n=1}^{N} C_n \cdot (E_{c,n} + E_{t,n}) + C_{N+1} \cdot E_1$$

Where C_n is the vegetation fractional coverage for the nth vegetation tile, C_N+1 is the bare soil fraction, and

$$\sum_{n=1}^{N+1} C_n = 1 .$$

4.1.4 Canopy evaporation

When there is intercepted water on the canopy, the canopy evaporates at the maximum value. The maximum canopy evaporation (E_c^* , mm) from each vegetation tile is calculated using the following formulation:

$$E_c^* = (\frac{W_i}{W_{im}})^{2/3} E_p \frac{r_w}{r_w + r_o}$$

Where W_{im} is the maximum amount of water the canopy can intercept (mm), which is 0.2 times LAI (Dickinson, 1984); the power of *2/3* is as described by Deardorff (1978). The architectural resistance, r_0, is caused by the variation of the humidity gradient between the canopy and the overlying air (s m-1). In the model, r_0 is assigned for each land cover type according to the vegetation library. The aerodynamic resistance, r_w, represents the transfer of heat and water vapor from the evaporating surface into the air above the canopy (s m-1). E_p is the potential evapotranspiration (mm) that is calculated from the Penman-Monteith equation (Shuttleworth, 1993) with the canopy resistance set to zero, which is:

$$\lambda_v E_p = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\Delta + \gamma}$$

where λ_v is the latent heat of vaporization (J kg-1), Rn is the net radiation (W m-2), G is the soil heat flux (W m-2), (e_s - e_a) represents the vapor pressure deficit of the air (Pa), ρ_a is the density of air at constant pressure (kg m-3), c_p is the specific heat of the air (J kg-1 K-1), Δ represents the slope of the saturation vapor pressure temperature relationship (P_a K-1), and γ is the psychrometric constant (66 Pa K-1). The Penman-Monteith equation as formulated above includes all parameters that govern the energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation.

The aerodynamic resistance (r_w, s m-1) is described as follows after Monteith and Unsworth (1990):

$$r_w = \frac{1}{C_w u_z}$$

where u_z is the wind speed (m s-1) at level z, and C_w is the transfer coefficient for water which is estimated taking into account the atmospheric stability. The algorithm for calculating C_w is based on Louis (1979).

When the continuous rainfall rate is lower than the canopy evaporation, the intercepted water is not sufficient for meeting the atmospheric demand within one time step. In such a case, the canopy evaporation (E_c, mm) is

$$E_c = f \cdot E_c^*$$

where f is the fraction of the time step for canopy evaporation to exhaust the intercepted water, and is given by:

$$f = \min\left(1, \frac{W_i + P \cdot \Delta t}{E_c^* \cdot \Delta t}\right)$$

4.1.5 Vegetation transpiration

The vegetation transpiration (E_t, mm) is estimated using Blondin (1991) and Ducoudre et al.(1993):

$$E_t = (1 - (\frac{W_i}{W_{im}})^{2/3}) E_p \frac{r_w}{r_w + r_o + r_c}$$

Where r_c is the canopy resistance (s m-1) given by:

$$r_c = \frac{r_{0c} g_T g_{vpd} g_{PAR} g_{sm}}{LAI}$$

where r_{0c} is the minimum canopy resistance (s m-1) according to the vegetation library, and g_T, g_{vpd}, g_{PAR}, and g_{sm} are the temperature factor, vapor pressure deficit factor, photosynthetically active radiation flux (PAR) factor, and soil moisture factor, respectively. Details about the four limiting factors are available through Wigmosta et al. (1994).

When canopy evaporation happens only for a fraction of the time step (f), the transpiration during that time step then has two parts as described by

$$E_t = (1 - f) E_p \frac{r_w}{r_w + r_o + r_c} + f \cdot (1 - (\frac{W_i}{W_{im}})^{2/3}) E_p \frac{r_w}{r_w + r_o + r_c}$$

where the first term represents the part of the time step when there is transpiration but no canopy evaporation, and the second term represents the part of the time step when there is both evaporation from the canopy and transpiration.

The vegetation transpiration from a certain vegetation tile is the total contribution from all three soil layers, weighted by the fractions of roots in each layer.

4.1.6 Bare soil evaporation

The bare soil evaporation only occurs on the top thin layer. When the surface soil is saturated, it evaporates at the potential evaporation rate. When the top soil layer is not saturated, its evaporation rate (E1) is calculated using the Arno formulation by Franchini and Pacciani (1991). The infiltration capacity (i) uses the spatially heterogeneous structure described by the Xianjiang Model (Zhao et al., 1980), which is expressed as

$$i = i_m (1-(1-A)^{1/b_i}) \quad \text{with} \quad i_m = (1+b_i)\cdot\theta_S \cdot |z|$$

where i_m is the maximum infiltration capacity (mm), A is the fraction of area for which the infiltration capacity is less than i, bi is the infiltration shape parameter, θ_s is the soil porosity, and z is the soil depth (m). All these variables are for the top thin soil layer.

The bare soil evaporation is described as

$$E_1 = E_p\left(\int_0^{A_S} dA + \int_{A_S}^{1} \frac{i_0}{i_m(1-(1-A)^{1/b_i})}\,dA\right)$$

with As denoting the fraction of the bare soil that is saturated, and i_0 representing the corresponding point infiltration capacity.

4.2 Soil moisture and runoff

The VIC model uses the variable infiltration curve (Zhao et al., 1980) to account for the spatial heterogeneity of runoff generation. It assumes that surface runoff from the upper two soil layers is generated by those areas for which precipitation, when added to soil moisture storage at the end of the previous time step, exceeds the storage capacity of the soil. The formulation of subsurface runoff follows the Arno model conceptualization (Franchini and Pacciani, 1991; Todini, 1996). The soil moisture and runoff algorithms for the VIC are explained with detail in Liang et al. (1996).

Similar to the total evapotranspiration, the total runoff Q is expressed as:

$$Q = \sum_{n=1}^{N+1} C_n \cdot (Q_{d,n} + Q_{b,n})$$

where $Q_{d,n}$ (mm) and $Q_{b,n}$ (mm) are the direct runoff (surface runoff) and base flow (subsurface runoff) for the n^{th} land cover tile, respectively.

The VIC model assumes there is no lateral flow in the top two soil layers; therefore the movement of moisture can be characterized by the one-dimensional Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(D(\theta)\frac{\partial \theta}{\partial z}) + \frac{\partial K(\theta)}{\partial z}$$

where θ is the volumetric soil moisture content, D(θ) is the soil water diffusivity (mm2 d-1), K(θ) is the hydraulic conductivity (mm d-1), and z is soil depth (m). By including the atmospheric forcing, the integrated soil moisture for the top two soil layers can be described as (Mahrt and Pan, 1984):

$$\frac{\partial \theta_i}{\partial t} \cdot z_i = I - E - K(\theta)\Big|_{-Z_I} + D(\theta)\frac{\partial \theta}{\partial z}\Big|_{-Z_I} \qquad \text{(i=1,2)}$$

where I is the infiltration rate (mm d-1), z_1 and z_2 are soil depth for layer 1 and layer 2, respectively. The infiltration rate I is the difference between the precipitation and the direct runoff Q_d,

For the lower soil layer, an empirical formulation derived from large scale catchment hydrology is used in which the drainage and subsurface drainage are lumped together as base flow (Q_b). The soil moisture for the soil layer is described by the water balance equation including diffusion between soil layers as:

$$\frac{\partial \theta_3}{\partial t} \cdot (z_3 - z_2) = K(\theta)\Big|_{-Z_2} + D(\theta)\frac{\partial \theta}{\partial z}\Big|_{-Z_2} - E - Q_b$$

If it is bare soil, the evapotranspiration term E is zero because there is no evaporation from the lower soil layer. Otherwise, if the vegetation roots go through into the lower soil layer, the evapotranspiration term E needs to be considered.

Since the top thin soil layer has a very small water holding capacity, the direct runoff (surface runoff, Q_d) within each time step is calculated for the entire upper layer (layer 1 and layer 2) as (Liang et al., 1996):

$$Q_d = \begin{cases} P - z_2 \cdot (\theta_S - \theta_2) + z_2 \cdot \theta_S \cdot (1 - \frac{i_0 + P}{i_m})^{1+b_i}, & P + i_0 \le i_m \\ P - z_2 \cdot (\theta_S - \theta_2), & P + i_0 \ge i_m \end{cases}$$

where the infiltration capacity associated terms (i_0, i_m, θ_s, and b_i) are explained in Section 4.1.3.

The formulation of base flow (sub surface runoff, Q_b), which used the Arno model formulation, (Franchini and Pacciani, 1991), is expressed as:

$$Q_b = \begin{cases} \frac{D_S D_m}{W_S \theta_S} \cdot \theta_3, & 0 \le \theta_3 \le W_S \theta_S \\ \frac{D_S D_m}{W_S \theta_S} \cdot \theta_3 + (D_m - \frac{D_S D_m}{W_S})(\frac{\theta_3 - W_S \theta_S}{\theta_S - W_S \theta_S})^2, & \theta_3 \ge W_S \theta_S \end{cases}$$

where D_m is the maximum subsurface flow (mm d-1), D_S is a fraction of D_m,, and W_S is the fraction of maximum soil moisture (soil porosity) θ_s. The base flow recession curve is linear below a threshold (W_S θ_s) and nonlinear above the threshold. The first derivative at the transition from the linear to nonlinear drainage is continuous.

4.3 Routing Model

The routing model is described in detail by Lohmann et al. (1996, 1998). It essentially calculates the concentration time for runoff reaching the outlet of a grid cell as well as the channel flow in the river network. It is assumed that most horizontal flow within the grid cell reaches the channel network within the grid cell before it crosses the border into a neighboring grid cell. Flow can leave each grid cell in eight possible directions but all flow must exit in the same direction. The flow from each grid cell is weighted by the fraction of the grid cell that lies within the basin. Once water flows into the channel, it does not flow back out of the channel and therefore it is removed from the hydrological cycle of the grid cells. The daily surface runoff and baseflow produced by the VIC model from each grid cell is first transported to the outlet of the cell using a triangular unit hydrograph, and then routed to in the river network to the basin outlet. The model assumes that the runoff transport is linear, causal, stable, and time invariant. It also assumes the impulse response function is never negative.

5.0 Model input data

5.1 Basin delineation

The major input data for basin delineation include elevation and stream channels. Elevation data were obtained from the U.S. Geological Survey National Elevation Dataset, at a resolution of 1/9 arc second (approximately 3m). The overall watershed and subwatershed boundaries were extracted using the USGS watershed dataset (Figure 5).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 Kentucky, 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. The watershed was divided into 215 subbasins, which are shown in Figure 6.

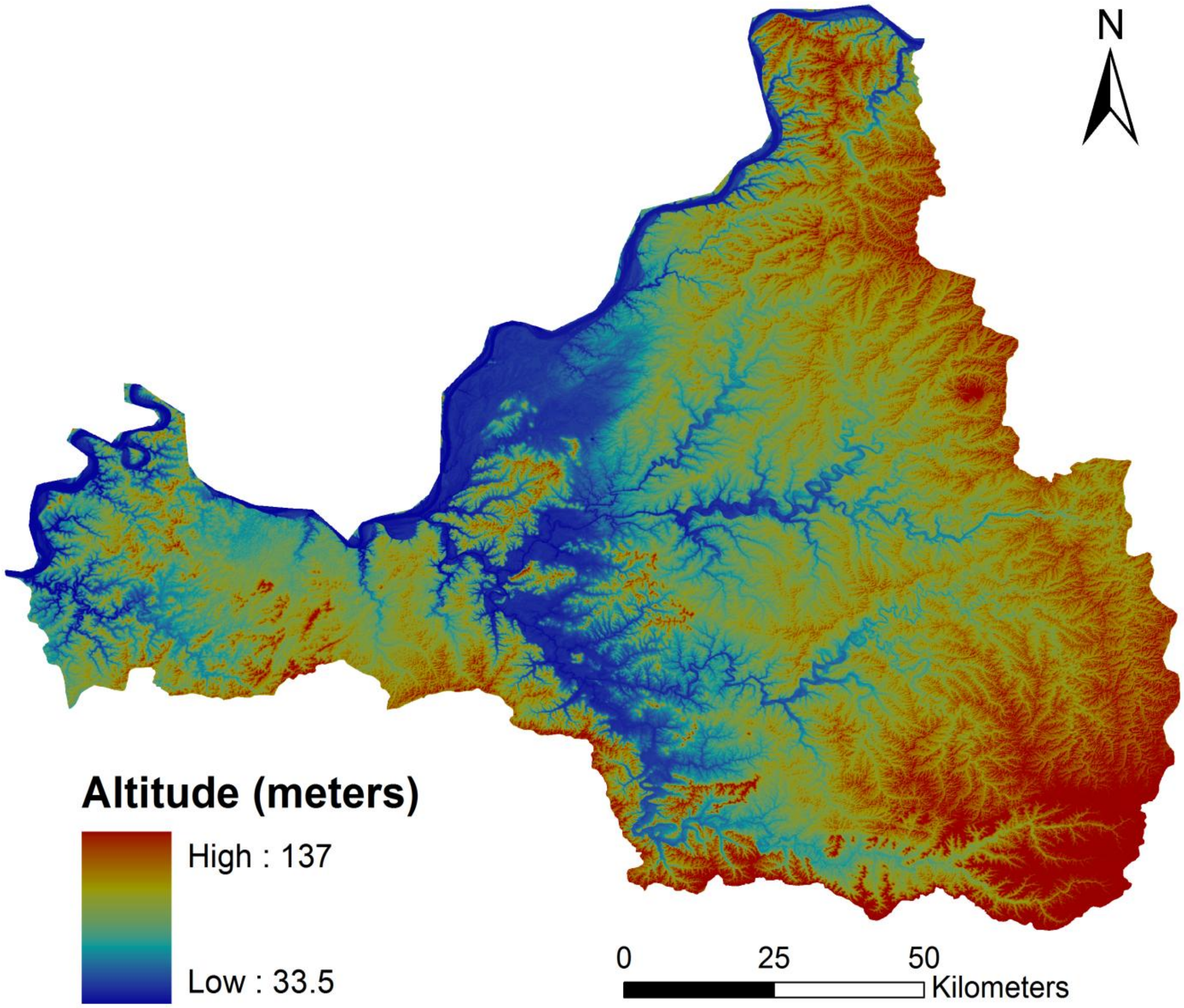


Figure 5.Elevation of the Salt River Basin.

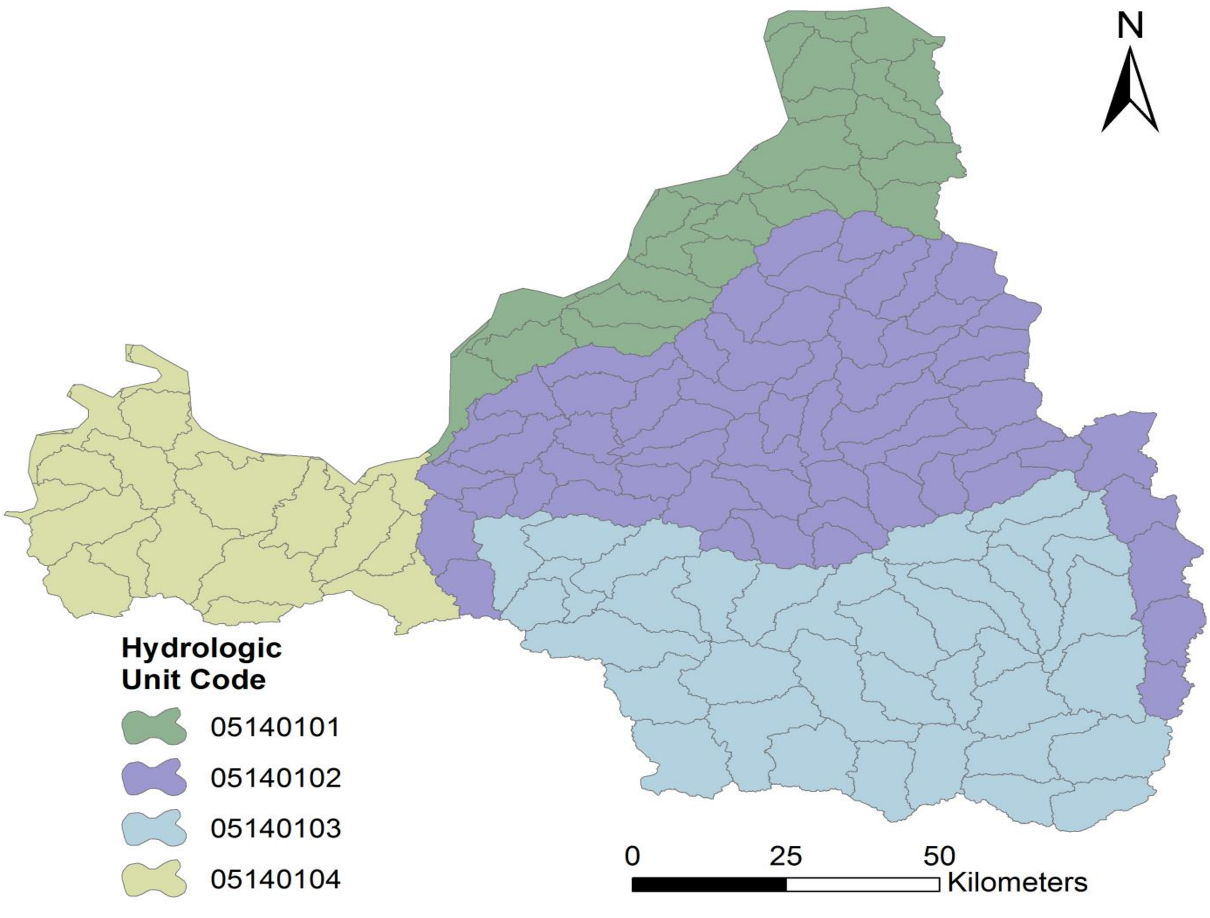


Figure 6. Salt River sub-basins.

5.2 Land cover data

The VIC model requires land cover inputs to extract vegetation parameters such as LAI, albedo, canopy resistance, and relative fraction of roots in each of the soil layers using a look up table approach. The National Land-Cover Dataset (NLCD) (Vogelmann et al.,2001) was used as the land cover dataset for this investigation. The NLCD is based on Landsat satellite data at 30-m resolution and covers the entire United States. According to Vogelmann et al. 2001 the NLCD dataset was created by using terrain-corrected and georegistered Landsat imagery resulting in a root mean square registration error of less than one pixel (30-m). A recent analysis (Wardlow and Egbert, 2003, Wickham et.al 2010) of the NLCD dataset indicated an overall accuracy of 80.5% and 85.3% respectively, with grasslands the most accurately classified landcover type and wetlands being the least accurate. There are enough differences in each of the classifications to confound any direct comparison of the two datasets. To overcome this limitation each of the data sets were converted to VIC-style land cover classes to facilitate their inclusion. Table 1 shows the transformations used for this study.

Table 1. Description of the NLCD 1992 and 2001 schema along with VIC schema.

1992 Scheme	VIC Scheme	2001 Scheme	VIC Scheme
11 - Open water	0 - water	11 - Open water	0 - water
12 - Perennial Ice/Snow	0 - water	12 - Perennial Ice/Snow	0 - water
21 - Low Intensity Residential	13-urban	21 - Developed, Open Space	13-urban
22 - High Intensity Residential	13-urban	22 - Developed, Low Intensity	13-urban
23 - Commercial/Industrial/Transportation	13-urban	23 - Developed, Medium Intensity	13-urban
31 - Bare Rock/Sand/Clay	12- bare ground	24 - Developed, High Intensity	13-urban
32 - Quarries/Strip Mines/Gravel Pits	12- bare ground	31 - Barren Land	12- bare ground
33 - Transitional	12- bare ground	32 - Unconsolidated Shore 1	12- bare ground
41 - Deciduous Forest	4-Decidious Broadleaf forest	41 - Deciduous Forest	4-Decidious Broadleaf forest
42 - Evergreen Forest	1-evergreen needle leaf forest	42 - Evergreen Forest	1-evergreen needle leaf forest
43 - Mixed Forest	5- mixed forest	43 - Mixed Forest	5- mixed forest
51 - Shrubland	9- open shrub land	51 - Dwarf Scrub 2	9-open shrub land
61 - Orchards/Vineyards/Other	9- open shrub land	52 - Scrub/Shrub	9-open shrub land
71 - Grassland/Herbaceous	9- open shrub land	71 - Grassland/Herbaceous	9-open shrub land
81 - Pasture/Hay	11- crops	72 - Sedge Herbaceous 2	9-open shrub land
82 - Row Crops	11- crops	73 - Lichens 2	9-open shrub land
91 - Woody Wetlands	9-open shrub land	74 - Moss 2	9-open shrub land
92 - Emergent Herbaceous Wetlands	9-open shrub land	81 - Pasture/Hay	11- crops
		83 - Small Grains	11- crops
		84 - Fallow	11- crops
		85 - Urban/Recreational Grasses	11- crops
		82 - Cultivated Crops	11- crops
		90 - Woody Wetlands	9-open shrub land
		91 - Palustrine Forested Wetland 1	9-open shrub land
		92 - Palustrine Scrub/Shrub	9-open shrub land

5.2.1 Identifying impervious surfaces

The primary purpose of this research is to investigate the effects of impervious area on hydrologic fluxes in the Salt basin. Therefore, identifying and mapping of impervious surfaces is an important part of database development. 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. Remote sensing techniques with moderate resolution sensors (10m-100m) can be both effective and efficient, but this approach is inherently limited by the resolution of the data and a tendency to under-represent land cover types that are less than the ground sampling distance or resolution. Dougherty et al. (2004) present a 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.

Impervious surface for this study was extracted by overlaying the 2001 impervious surface values onto the 1992 data. This allowed for the change in vegetation due to increasing urbanization to be accurately assessed between these datasets. The generation of projected (2040) impervious surface followed a linear increase that mimicked the observed growth rate between the 1992 and 2001 NLCD.

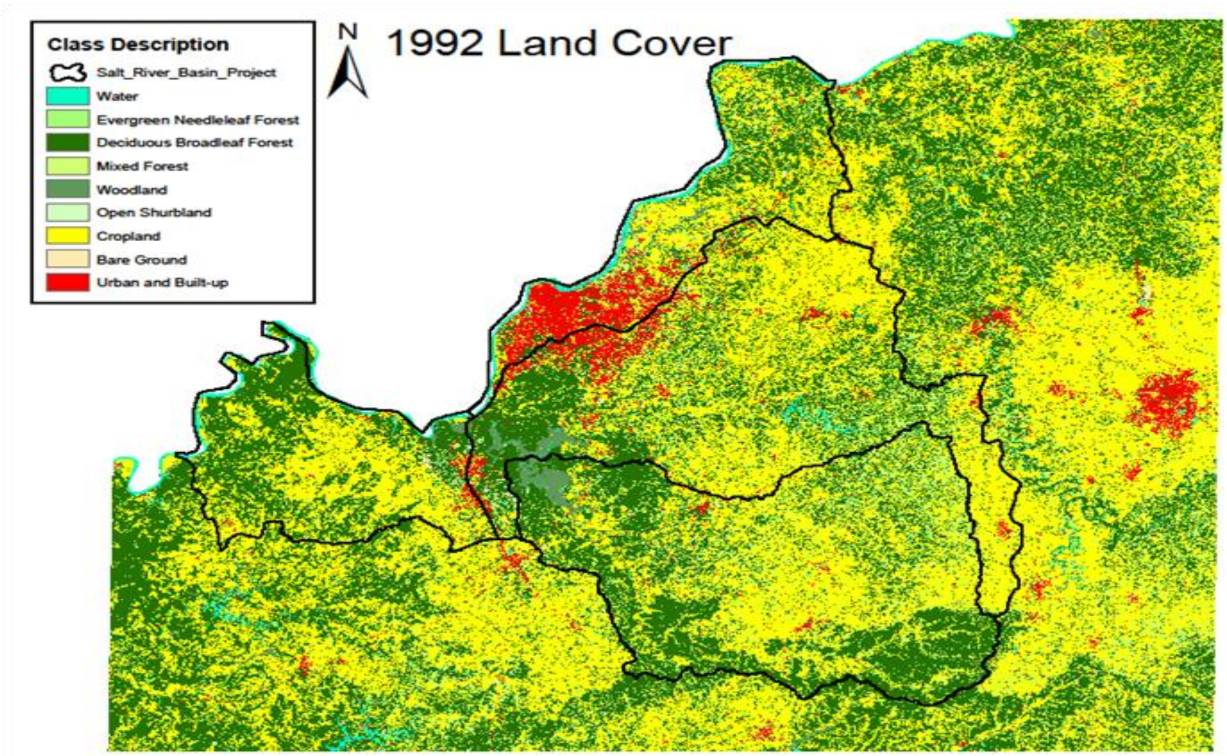


Figure 7.Land Cover for 1992 using the National Land Cover Dataset (NLCD).

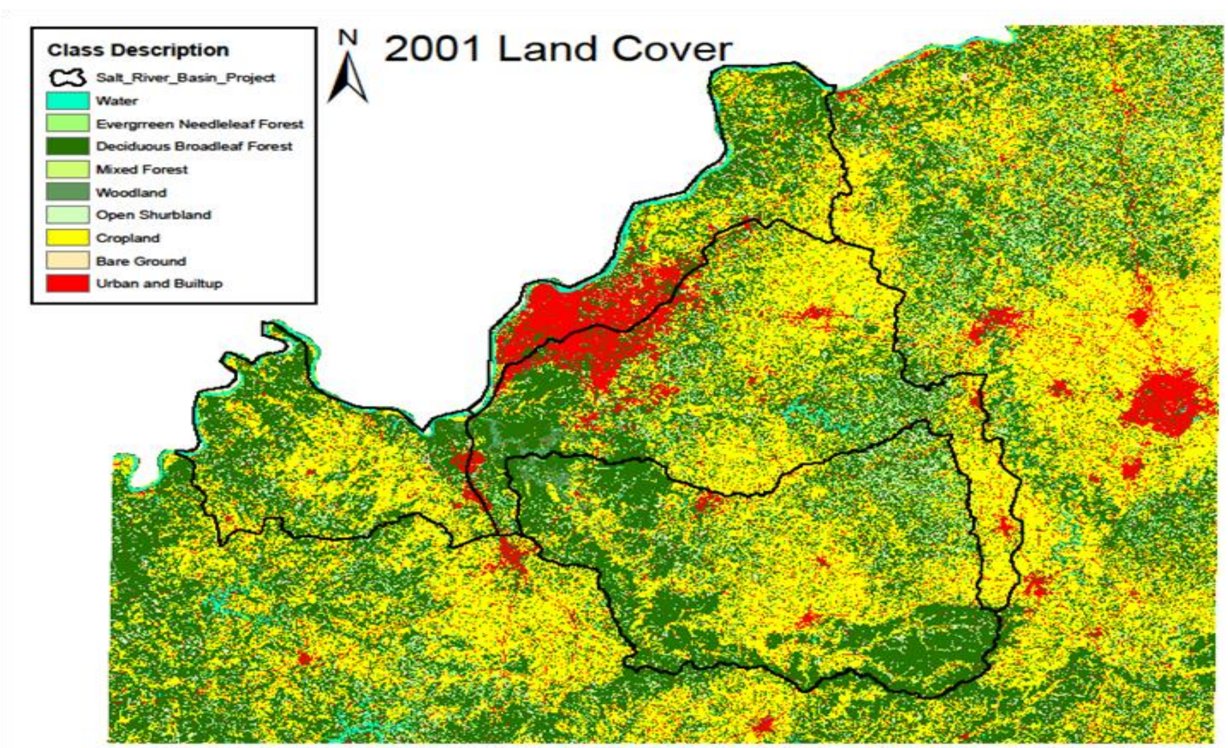


Figure 8.Land Cover for 2001 using the National Land Cover Dataset (NLCD).

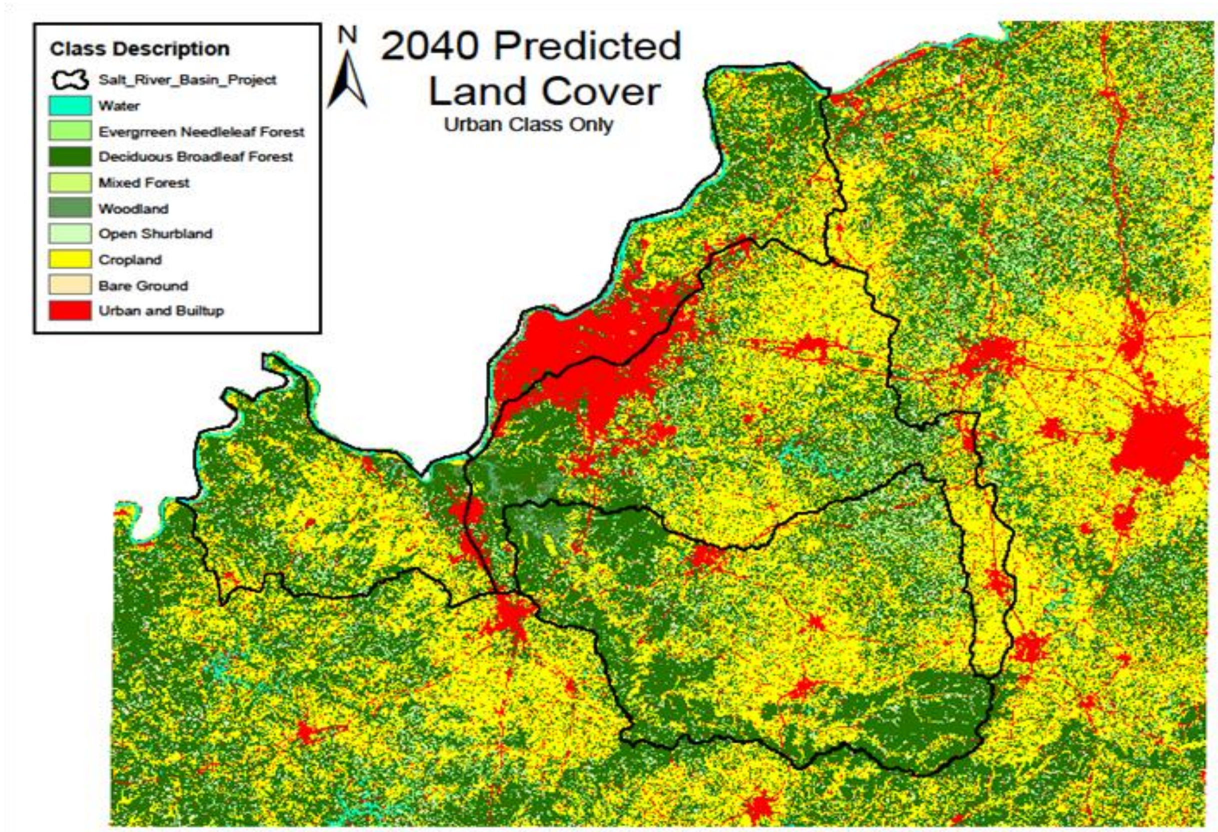


Figure 9.Predicted land cover for 2040 using urban growth for previous nine years.

Impervious surface change (Table 2) between the two datasets for urban areas shows a 4.75% increase over the period between 1992 (Figure 6) and 2001 (Figure 7). Using this rate of change, a predicted land cover dataset was derived for year 2040 (Figure 8). This predicted landuse dataset assumes that the rate of urban growth in the basin will be a constant over time. Note that in this approach, the drivers of land cover change are entirely implicit, as model output is based solely on observed data that represents the landscape, not any socioeconomic or biophysical variables. The datasets employed serve as a guide to modify the data so that it more closely matches known relationships between land use and land cover. Despite the simplified focus on land cover, change analysis of model output is possible. 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).

Table 2. Land Cover change between 1992 and 2001 for the Salt River Basin.

Land Cover Type	1992	2001	Δ over time
Water	1.53%	1.64%	0.10%
Evergreen Needle Leaf Forest	2.89%	2.71%	-0.18%
Deciduous Broadleaf Forest	38.28%	43.77%	5.49%
Mixed Forest	9.82%	4.12%	-5.70%
Open Shrub Land	1.65%	0.74%	-0.90%
Crops	40.45%	36.08%	-4.37%
Bare Ground	0.38%	0.19%	-0.19%
Urban	5.01%	10.76%	4.75%

5.3 Soils data

Soils data for VIC were obtained from the State Soil Geographic (STATSGO) data set website (USDA-NRCS, 2009). The SATASGO data were created by Soil Conservation Service (SCS) from soil surveys with the USGS 1:250,000-scale topographic quadrangles as base maps. All the surfaces are at a resolution of 1 km. These data have been extensively attributed and documented by other model developers (Anderson and Reed, 2005; Williamson and Odom, 2007; Zhang et al., 2006).

The data retrieved include sand fraction, clay fraction, bulk density, field capacity, and saturated hydrologic conductivity (Ksat) respectively. These data were used to determine the soil texture class for each of the grid cells. Once the soil texture for each of the soil type was identified, conversion to actual soil hydraulic properties was needed in running the VIC model. The following is needed for the proper development of the soils input data used to operate VIC; percent sand, silt, clay and the soils bulk density.

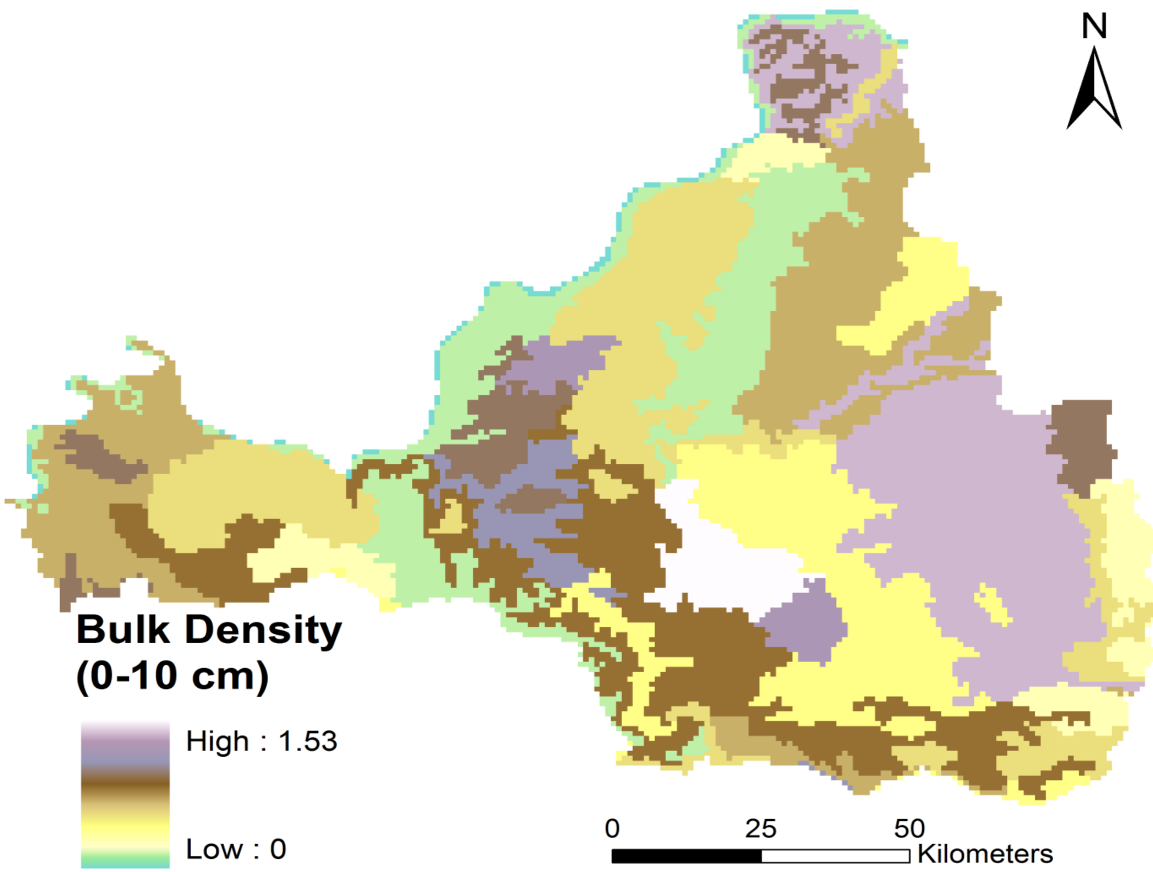


Figure 10.Salt River Basins Soils from the STATSGO dataset.

5.4 Meteorological forcing data

The VIC model in water balance mode is forced with observed surface meteorological data which include precipitation, temperature, wind, and shortwave radiation. North American Regional Reanalysis (NARR) data were used as the atmospheric forcing data (Table 4). NARR data is gridded climatalogical data at a 32km resolution

(Mesinger et al. 2003). NARR is a long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain (Mesinger et al. 2006). The regional reanalysis was developed with the 2003 version of the Eta model and its associated Eta Data Assimilation System (EDAS). The Eta model is coupled to the Noah land surface model (Ek et al. 2003) that simulates land surface temperature, the components of the surface energy balance and the surface water balance, and the evolution of soil temperature and soil moisture, both liquid and frozen. The NARR computational grid has a 32-km horizontal resolution, with 45 layers in the vertical (Mesinger et al. 2006). NARR was created at NCEP. [Data for this study were obtained from the NOAA/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD), in Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov.] For this study NARR 3-hourly data was obtained and compiled into a temporal resolution of 3 hours and downscaled to a spatial resolution of 0.00833 degrees (1km) for the entire basin over the period 1979 - 2008. For all simulation in this study, 1979 -1984 was used to calibrate the model and the remaining years were used for validation and analysis.

Table 3. Climatalogical forcing data used in the VIC model.

Variables for Climatalogical Forcing from NARR		
	Unit	**Time**
Accumulated total precipitation	kg m^{-2}	3-hourly accumulation
Air temperature at 2m	K	3-hourly value
Relative Humidity at 2m	%	3-hourly value
Uwind at 10 m	m s^{-1}	3-hourly value
Vwind at 10 m	m s^{-1}	3-hourly value
Downward Shortwave Radiation	Wm^{-2}	3-hourly value

5.3 Model Calibration

Model calibration has one main objective. The model variables must be adjusted to match the overall volume of water discharged from the watershed with the observed discharge at the USGS stream gauge – Salt River near Shepherdsville, Kentucky (gauge number 3298500)(Figure 9). Calibration proceeded roughly as described in Nijssen et al. 1997. Overall volumes were generally increased by the calibration of six parameters: a) the infiltration parameter (bi), which controls the partitioning of rainfall (or snowmelt) into infiltration and direct runoff (a higher value of bi gives lower infiltration and yields higher surface runoff); b) D2 and D3, which are the second and third soil layer thicknesses (D1, the top soil layer depth, is usually specified a priori) and affect the water available for transpiration and baseflow respectively (thicker soil depths have slower runoff response — baseflow dominated —with higher evapotranspiration, but result in longer retention of soil moisture and higher baseflow in wet seasons); c) Dsmax, Ds, and Ws, which are baseflow parameters and also are estimated via calibration. Dsmax is the maximum baseflow velocity, Ds is the fraction of maximum baseflow velocity, and Ws is the fraction of maximum soil moisture content of the third soil layer at which non-linear baseflow occurs. These three baseflow parameters determine how quickly the water stored in the third soil layer is evacuated as baseflow (Liang et al. 1994). The three baseflow parameters and the third soil layer depth (d3) (Nijssen et al., 2001a, Su et al., 2005) are used with only minor adjustment during the calibration, while the infiltration parameter (bi) and the second soil depth (d2) are targeted for intensive calibration. Parameters bi and d2 are calibrated independently.

Adjustment of the Dsmax variable away from the default settings (0.95 respectively) had relatively little effect. In the absence of a direct physical measurement, judging between competing estimates is difficult. Soil layers remained constant (10 mm, 30 mm, and 150 mm respectively) during the duration of the model calibration. A listing of the various fitted model parameters can be found in Table 4 with the parameter calibrations used in bold.

Table 4. Parameters used in the calibration of the VIC model.

b infil	Ds	Ws	Ds max	r2	NS
10	**0.5**	**35**	**0.95**	**0.783**	**0.537**

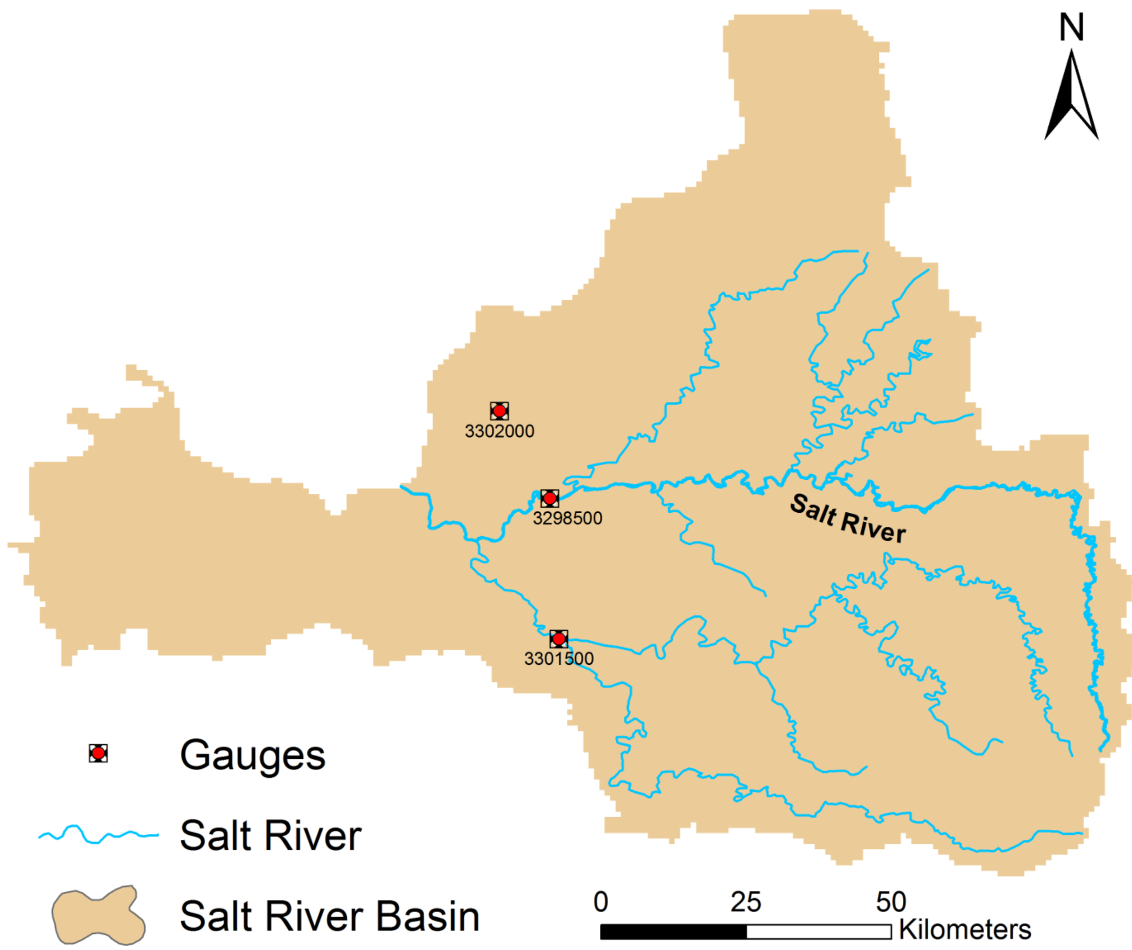


Figure 11.Gauges used for calibration and validation of the VIC model.

Table 5. Land cover for each of the Basins.

Gauge	Land Cover Type	1992	2001	2040
USGS 03298500	Water	0.78%	0.73%	0.70%
AT SHEPHERDSVILLE, KY	Evergreen Needle Leaf Forest	3.21%	2.75%	2.73%
Drainage area: 1,197 square miles	Deciduous Broadleaf Forest	32.89%	31.30%	28.63%
	Mixed Forest	5.51%	4.59%	6.10%
	Open Shrub Land	0.30%	0.41%	0.28%
	Crops	55.49%	53.29%	53.45%
	Bare Ground	0.05%	0.08%	0.07%
	Urban	1.77%	6.85%	8.05%
USGS 03301500	Water	0.24%	0.19%	0.30%
NEAR BOSTON, KY	Evergreen Needle Leaf Forest	4.55%	3.99%	2.95%
Drainage area: 1,299 square miles	Deciduous Broadleaf Forest	41.70%	41.81%	41.43%
	Mixed Forest	12.57%	10.99%	9.64%
	Open Shrub Land	0.29%	0.28%	4.84%
	Crops	39.70%	38.78%	36.40%
	Bare Ground	0.14%	0.17%	0.07%
	Urban	0.82%	3.80%	4.37%
USGS 03298000	Water	5.40%	5.58%	5.11%
AT FISHERVILLE, KY	Evergreen Needle Leaf Forest	2.13%	2.41%	1.21%
Drainage area: 138.0 square miles	Deciduous Broadleaf Forest	29.14%	29.66%	25.45%
	Mixed Forest	9.48%	9.42%	6.37%
	Open Shrub Land	2.13%	2.96%	1.99%
	Crops	34.22%	26.30%	29.83%
	Bare Ground	0.33%	0.27%	0.52%
	Urban	17.16%	23.41%	29.52%

Land cover data for the watershed for 1992 (Table 5) was input into the model and the resulting daily and monthly streamflow (calculated as the average daily streamflow over each month in the period of interest) was compared to historical flows.

The calibration of these parameters is conducted via a trial and error procedure that leads to an acceptable match of model-predicted discharge with observations. Besides visual comparison of monthly simulated and observed hydrographs, two objective functions are often used. One is the Nash-Sutcliffe efficiency (*E*) which describes the prediction skill of the modeled streamflow as compared to the observed value. The Nash-Sutcliff model efficiency was used as a measure of model performance (Nash and Sutcliffe, 1970). These statistics were calculated for average monthly streamflow over the period and reported in table 4. The Nash-Sutcliffe model efficiency coefficient is commonly used to assess the predictive strength of hydrological models, and is given by:

The other is the relative error (*Er*), reported as r^2 in this study, between simulated and observed mean annual runoff, and is given by:

It s calculated as where Q_o is observed discharge, and Q_m is modeled discharge. Q_{ot} is observed discharge at time t. Nash–Sutcliffe efficiencies can range from to 1. An efficiency of 1 (E = 1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model or, in other words, when the residual variance (described by the nominator in the expression above), is larger than the data variance (described by the denominator).Essentially, the closer the model efficiency is to +1, the more accurate the model is. The threshold that separates an acceptable model from one that is not is often arbitrarily chosen, but ranges from 0.46 to 0.53 in several treatments (Freer et al., 1996; Muleta and Nicklow, 2005; Beven and Freer, 2001).

Additionally, mean absolute error (MAE) was utilized to assess the modeled outcomes versus observations. The mean absolute error measures the average magnitude of the errors in a set of forecasts, without considering their direction. It measures accuracy for continuous variables. The mean absolute error (MAE) is given by:

– –

The mean absolute error is an average of the absolute errors $e_i = f_i - y_i$, where f_i is the prediction and y_i the true value. Expressed in words, the MAE is the average over the verification sample of the absolute values of the differences between forecast and the corresponding observation. The MAE is a linear score which means that all the individual differences are weighted equally in the average (Willmott, 1981).

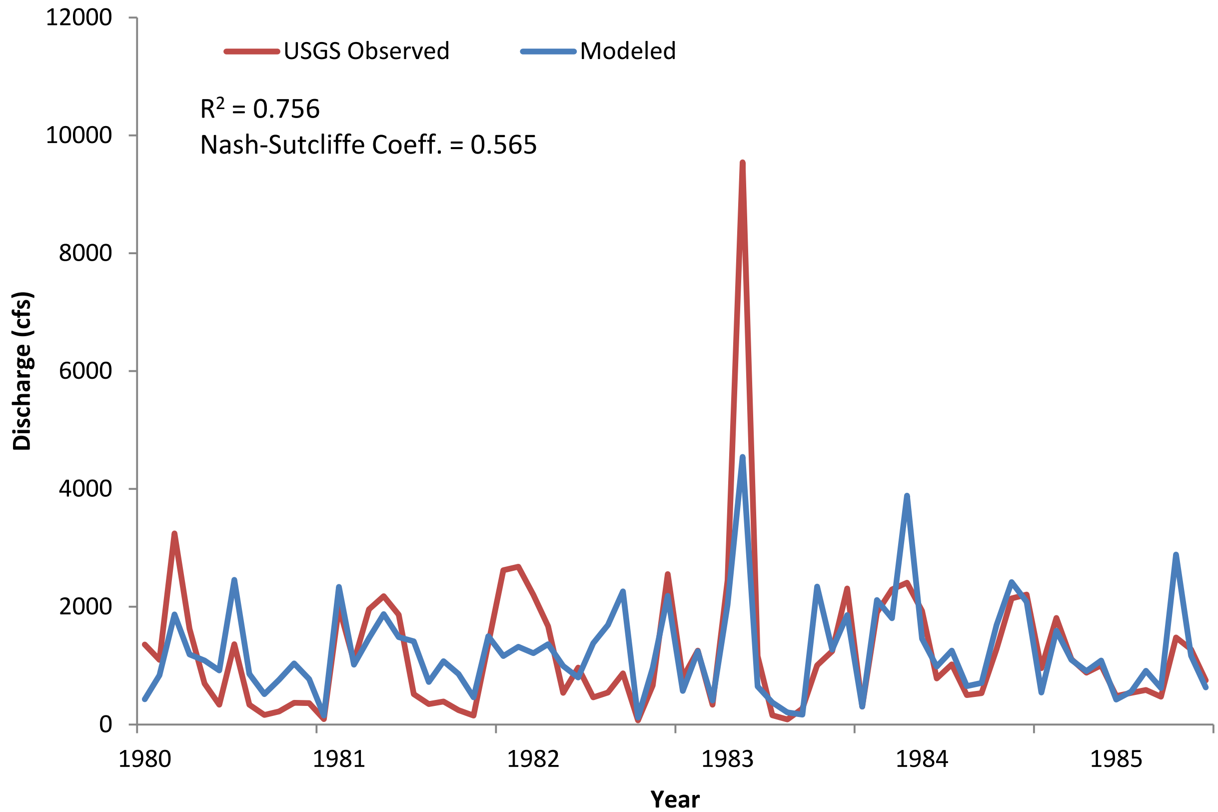


Figure 12.Calibration results for the Shepardsville Basin.

5.3.1 Soil Parameter Modification

In Figure 12 it can be seen that overall the discharge is temporally simulated quite well, although some peaks are underestimated and conversely some low-flow periods are over estimated when utilizing the standard soils. While this study attempts to improve the representation of urban areas, methods of improving the results were needed. Impervious surface has a strong influence on the overall discharge of a watershed. The land cover classification used was conservative such that the amount of impervious cover represented in the model is most likely less than the actual impervious cover for that cover type.

The primary characteristic of the land cover that affects the hydrologic fluxes simulated by the VIC model is LAI. Solely modifying landuse in the model does not properly alter the behavior of water entering the watershed. This is because VIC uses soil parameters to partition available water into runoff and infiltration. Soil hydraulic conductivity (K-sat) is the primary factor for this partitioning. The landcover is primarily used to calculate the energy flux over the grid based on leaf area index (LAI) values for each representative landcover type.

The saturated hydraulic conductivity (K-sat) values used in the formation of the soils data used by VIC are given in table 6.

Table 6. USDA Index of Soil Hydraulic Properties used in VIC.

USDA Class	Soil Type	% Sand	% Clay	Bulk Density g/cm3	Fieldd Capacity g/cm3	Wilting Point cm3/cm3	Porosity Fraction	Saturated Hydraulic Conductivity cm/hr	Slope of Retention Curve (in log space)
1	Sand	94.83	2.27	1.49	0.08	0.03	0.43	38.41	4.1
2	Loamy sand	85.23	6.53	1.52	0.15	0.06	0.42	10.87	3.99
3	Sandy loam	69.28	12.48	1.57	0.21	0.09	0.4	5.24	4.84
4	Silt loam	19.28	17.11	1.42	0.32	0.12	0.46	3.96	3.79
5	Silt	4.5	8.3	1.28	0.28	0.08	0.52	8.59	3.05
7	Sandy Clay	60.97	26.33	1.6	0.27	0.17	0.39	2.4	8.66
8	Silty Clay	9.04	33.05	1.38	0.36	0.21	0.48	4.57	7.48
9	Clay loam	30.08	33.46	1.43	0.34	0.21	0.46	1.77	8.02
10	Sandy Clay	50.32	39.3	1.57	0.31	0.23	0.41	1.19	13
11	Silty Clay	8.18	44.58	1.35	0.37	0.25	0.49	2.95	9.76
12	Clay	24.71	52.46	1.39	0.36	0.27	0.47	3.18	12.28

When these values are modified for the input during model simulations, one can see that as the value for K-sat increases from the lower values, i.e. 1.17, to higher values, i.e. 3.18, resulting average runoff increases, baseflow correspondingly decreases for this relationship (Figure 13).

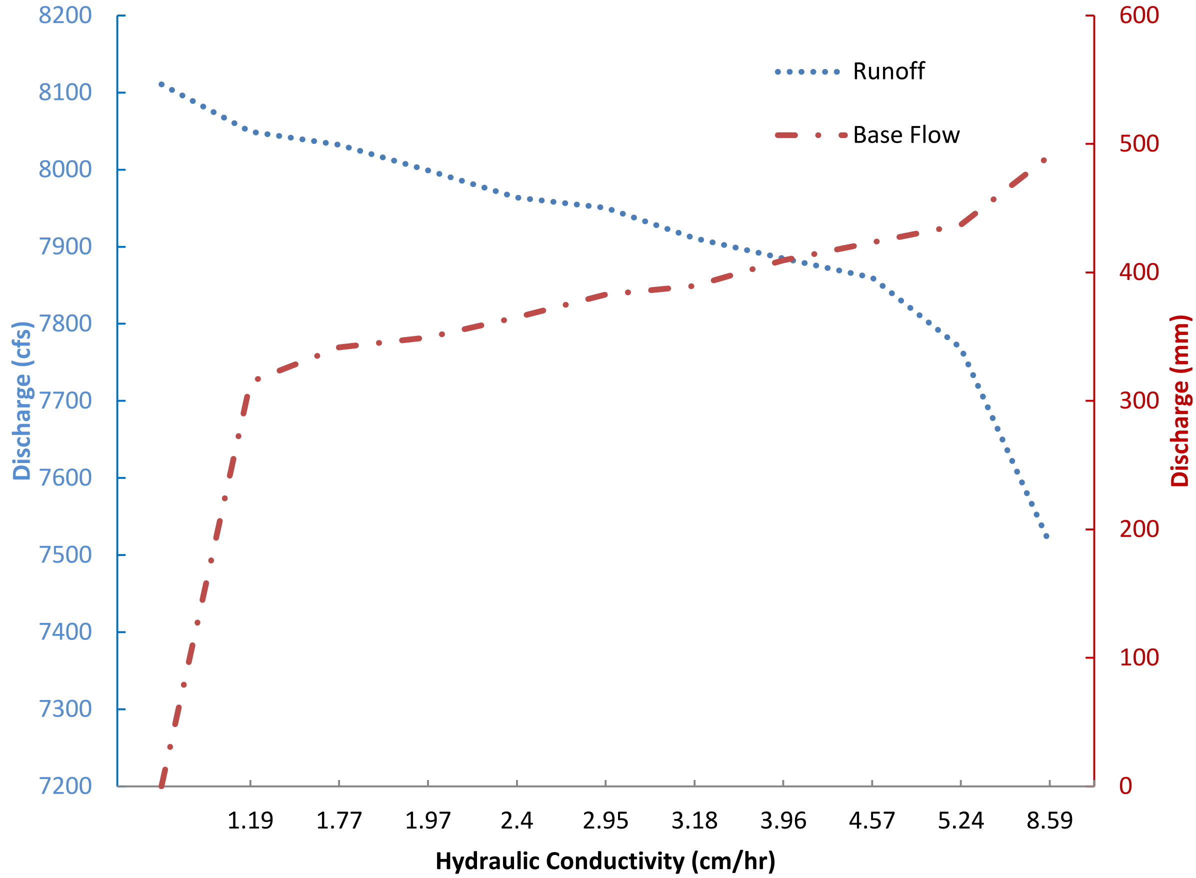


Figure 13. Sensitivity analysis of Hydraulic Conductivity on runoff and baseflow for urban landcover.

In order to represent urban landcover appropriately, adjustments were made to the K-sat values in order to partition the water properly for runoff and baseflow. In order to achieve these adjustments, the percentage impervious surface of each grid cell was used to modify the K-sat value using the following conceptual model:

Where is derived from the landcover datasets for 1992, 2001 and the 2040 projection and cannot be below zero. These adjustments allow for a more accurate modeled output with respect to the observations collected at USGS gauging stations.

5.3.2 Recalibration and Validation of Results

The preliminary investigation discussed above suggested a recalibration of the soil parameters was necessary. Two subbasins (Shepardsville 3298500 and Boston 3301500, shown in Figure 11) were used during recalibration in the current study. Results of the Shepardsville calibration are shown in Figure 13. The period 1979- 1984 was used for calibrating the model, with 1979 being used for model spin-up. Spin-up is the time taken for a model to reach a state of statistical equilibrium under the applied forcing. For this study the model reached equilibrium after one year. After the application of the modifications to the soil data, the overall fit of the calibration improve considerably. The Nash-Sutcliffe coefficients (0.88 and 0.57 respectively), for the modified soils shows improvement over the standard soils. An occasional overestimation of peak flow occurs, however the agreement between modeled and observed values is significantly improved (Figure 14).

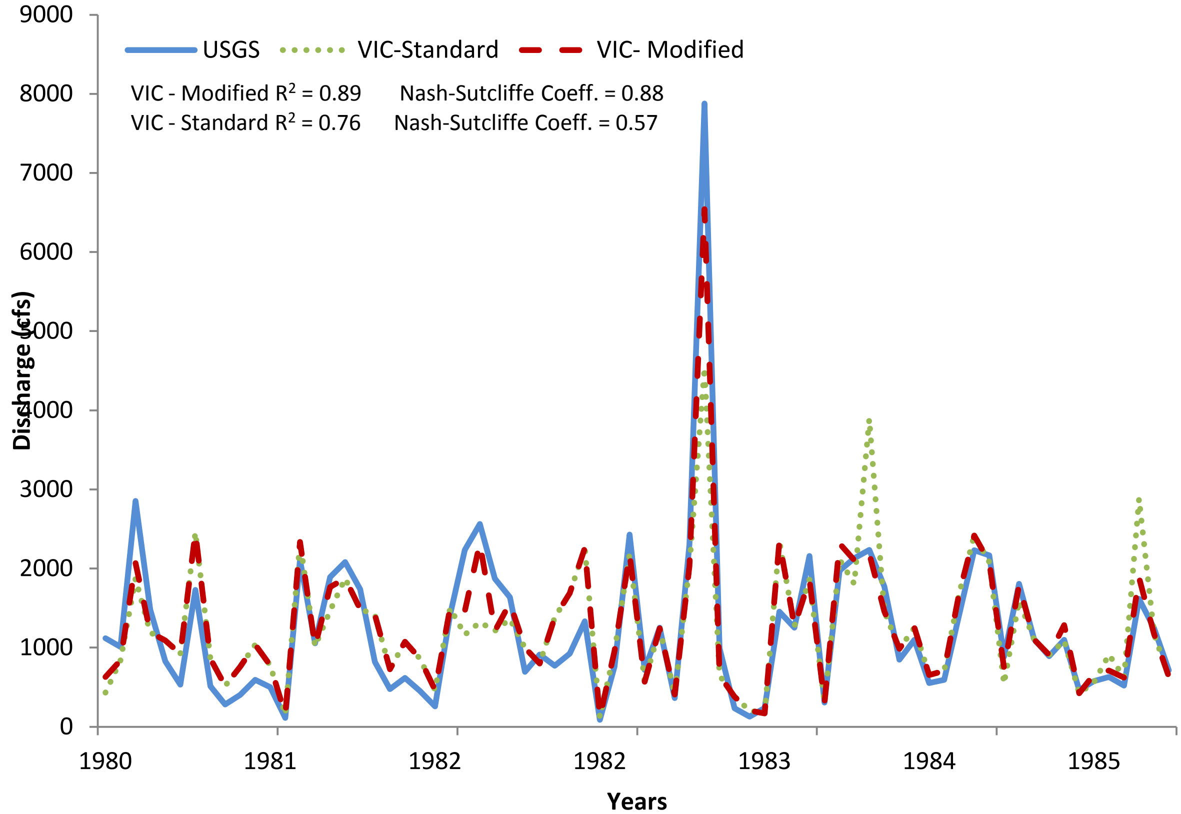


Figure 14.Comparison of the calibration results for the Shepardsville Basin after the K-sat adjustment.

In order to confirm that the model parameters achieved a better overall fit, the model was validated using the calibrated parameters and climate forcing data form 1985-1995. The results (Figure 14) show a r^2 value of 0.78 and a Nash Sutcliffe coefficient of 0.72 for the validation period. The improvement of the modified soils over the standard soils parameters allowed for a more accurate representation of the soil conditions for urban landcover. The results can be seen in tables 7 and 8. There was an overall improvement for all the study watersheds within the Salt River Basin. The greatest improvement occurred within the Fisherville watershed for the 1995 – 2005 study periods. The Nash-Sutcliffe coefficient improved from a negative value, which indicated that the mean of the observations were a better fit, to a positive value. While it was not as well fit as the other basin, this may be explained by the Fisherville watershed having the largest amount of urban landcover within the Basin at 23.4 %.

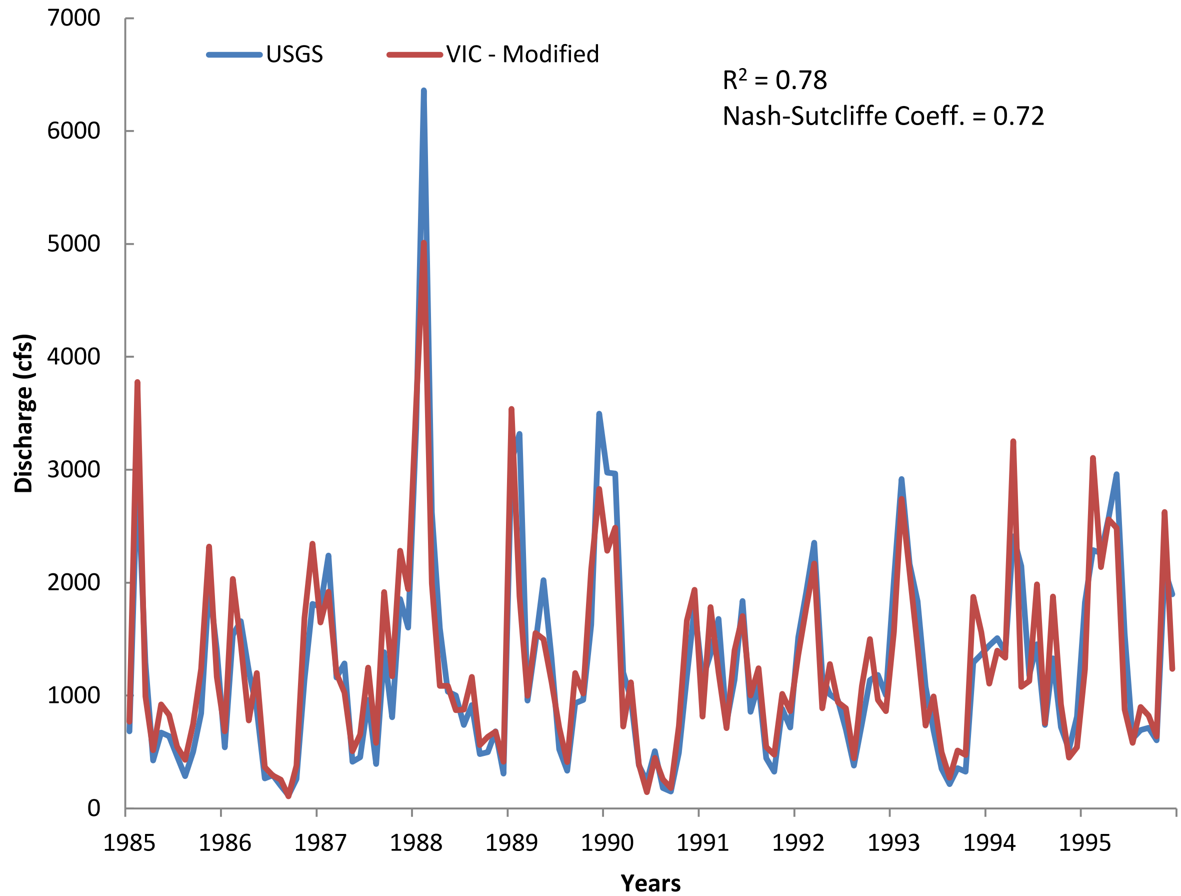


Figure 15.Validation of the parameters using the Shepardsville outlet compared with USGS observations for the period 1985 - 1995.

Validation was conducted using historic stream flow data from three separate basins, each undergoing differing degrees of increasing urbanization. The basin that experienced the greatest increase in urban land cover is gauged at Fisherville, KY (Figure 11); it has experienced a 6.3% increase between 1992 and 2001. VIC simulations indicated a successful temporal correlation between the simulated and observed discharge for the basin (Figure

16). However the model did over estimate discharge for the 2001 landcover investigations. This is possibly due to the fact that VIC does not have the capacity to account for underground drainage pipes and urban retention ponds that are used as flood controls in the city. This could lead to a possible over representation of surface runoff in the model which would result in higher total discharge.

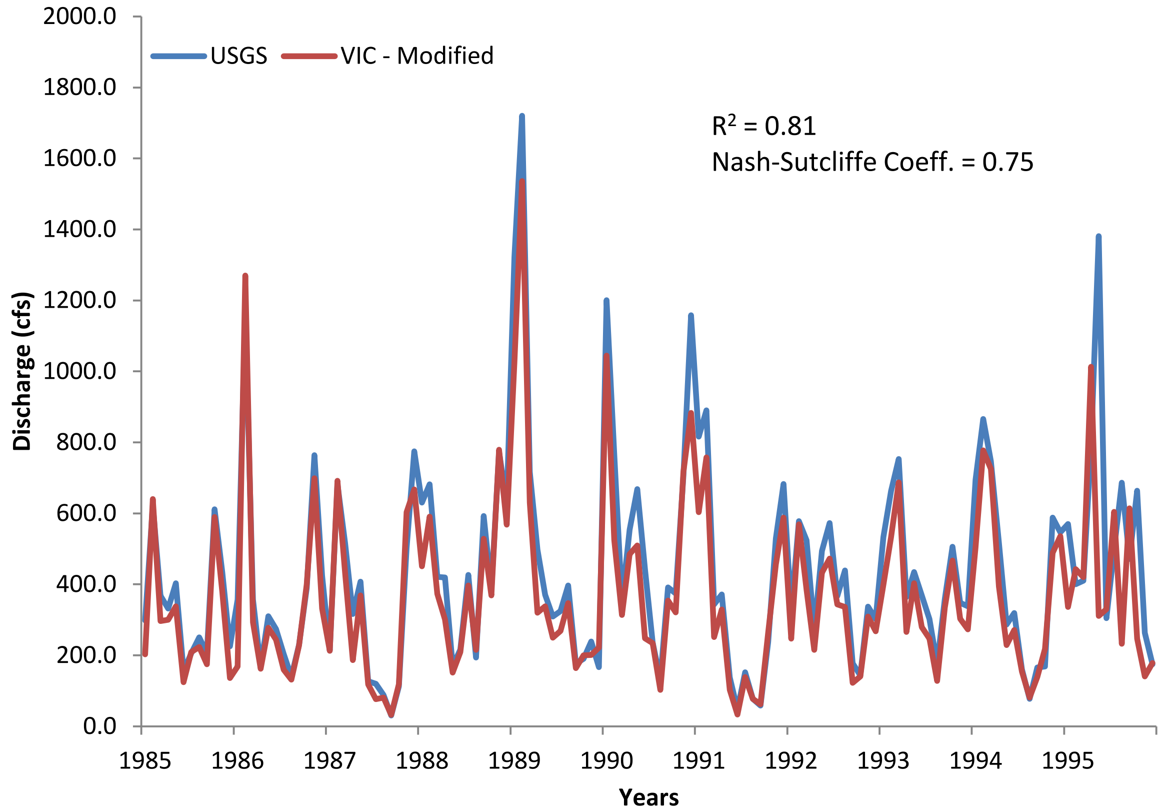
A similar temporal pattern can be seen in the basin gauged near Boston, KY (Figure 17). This catchment has the least urban land cover of the three validation basins. The model displayed a generally good fit for this basin, though it tended to underestimate the peak flows. The basin that is gauged at Shepardsville, KY displayed the best overall results (R2 0.78 and 0.84 respectively) for the periods 1992 and 2001 land cover investigations (Figure 18). The moderate increase in urban land cover (5.1%) is near the average for the entire basin.

Table 7. Summary of validation statistics for 1985 -1995

	Observed Mean	Mean	Diff in Mean	Standard error of mean	Standard Deviation	R2	RMSE	MAE	Nash-Sutcliffe Coeff.
Shepardsville									
USGS	1188.67								
Soils -Standard		884.05	304.62	152.31	215.40	0.88	439.91	300.07	0.76
Soils - Modified		1218.10	-29.43	20.81	20.81	0.84	151.63	28.99	0.84
Boston									
USGS	656.99								
Soils -Standard		334.91	322.08	161.04	227.75	0.87	428.74	317.27	0.34
Soils - Modified		499.50	157.49	111.36	111.36	0.85	853.79	155.16	0.67
Fisherville									
USGS	420.30								
Soils -Standard		270.89	149.41	74.70	105.65	0.78	197.18	147.18	0.51
Soils - Modified		370.95	49.35	34.90	34.90	0.81	511.98	48.61	0.75

Table 8. Summary of validation statistics for 1995 - 2005

	Observed Mean	Modeled Mean	Diff in Mean	Standard error of mean	Standard Deviation	R2	RMSE	MAE	Nash-Sutcliffe Coeff.
Shepardsville									
USGS	1274.54								
Soils -Standard		975.98	298.55	149.28	211.11	0.82	469.81	294.10	0.68
Soils - Modified		1310.81	-36.27	25.64	25.64	0.78	436.18	35.73	0.72
Boston									
USGS - Observations	711.12								
Soils -Standard		376.39	334.73	167.36	236.69	0.77	406.22	329.73	0.28
Soils - Modified		540.87	170.25	120.39	120.39	0.75	293.31	167.71	0.62
Fisherville									
USGS	359.15								
Soils -Standard		298.00	61.15	149.28	43.24	0.14	305.36	60.24	-0.37
Soils - Modified		400.04	-40.89	25.64	28.91	0.36	338.07	40.28	0.06


2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
USGS
VIC - Modified
R² = 0.81
Nash-Sutcliffe Coeff. = 0.75
Discharge (cfs)
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
Years

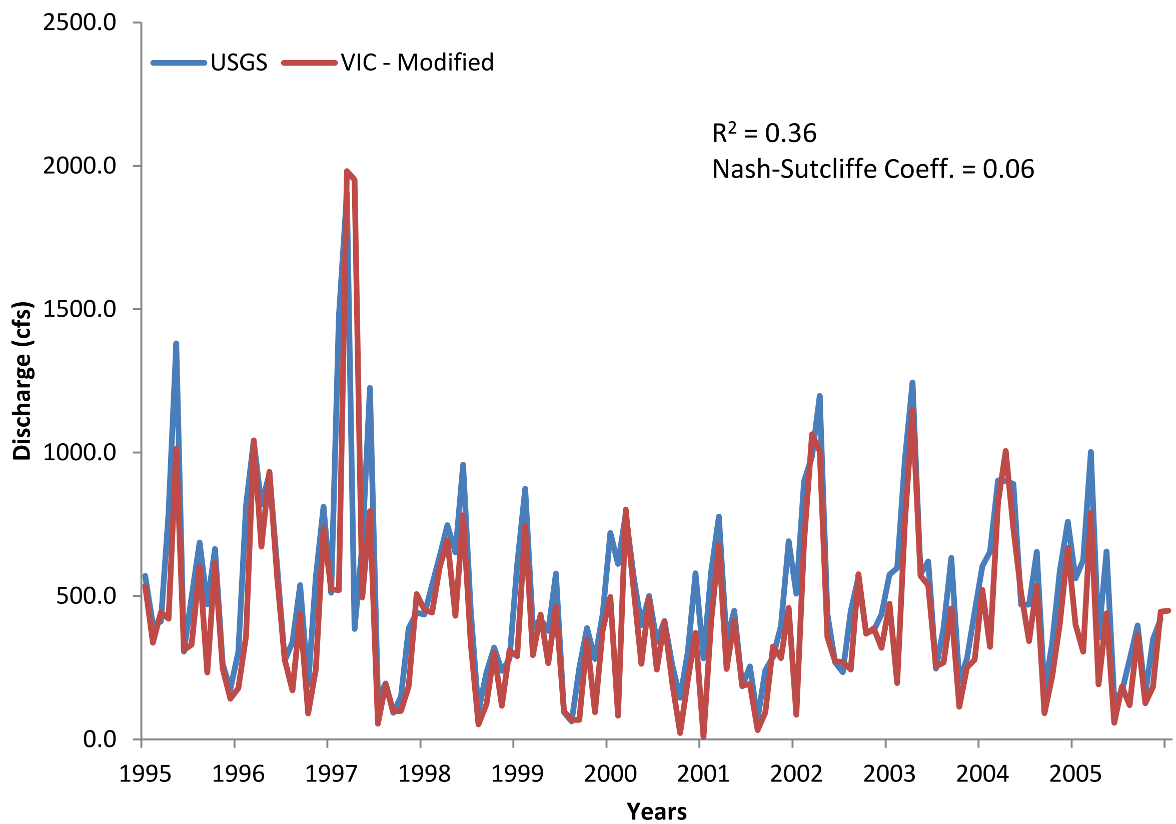
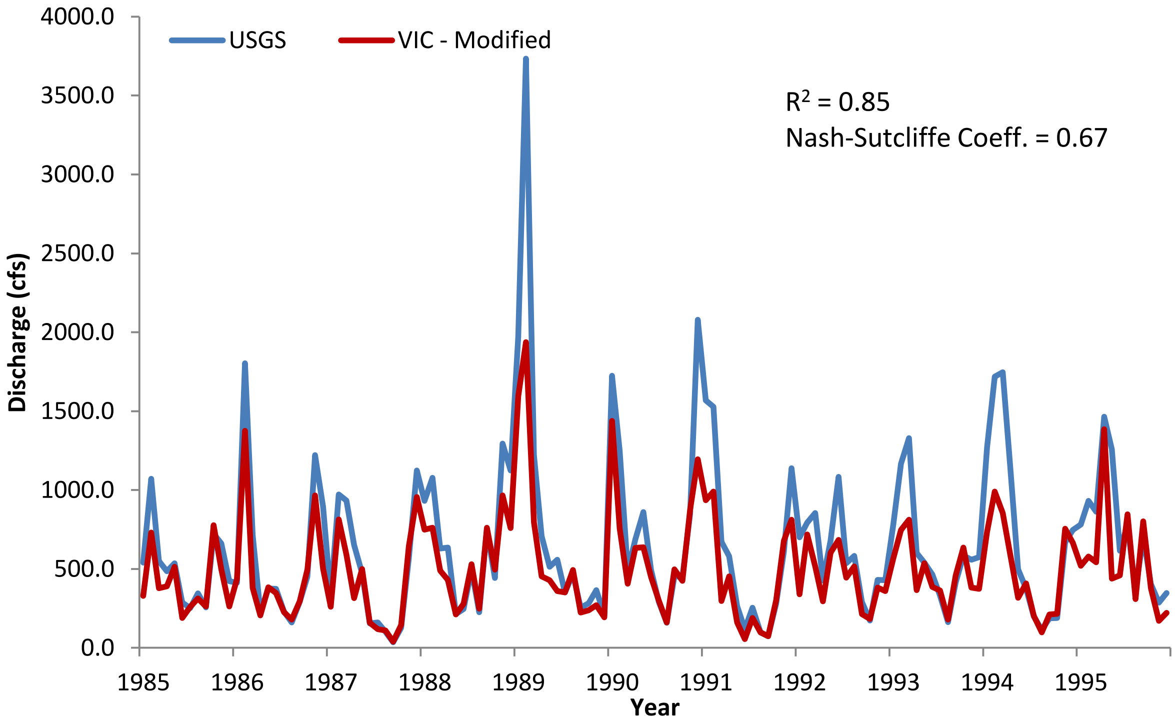

2500.0
2000.0
1500.0
1000.0
500.0
0.0
USGS
VIC - Modified
R² = 0.36
Nash-Sutcliffe Coeff. = 0.06
Discharge (cfs)
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
Years

Figure 16. Comparison of observed and simulated monthly mean streamflow for the Fisherville gauge.



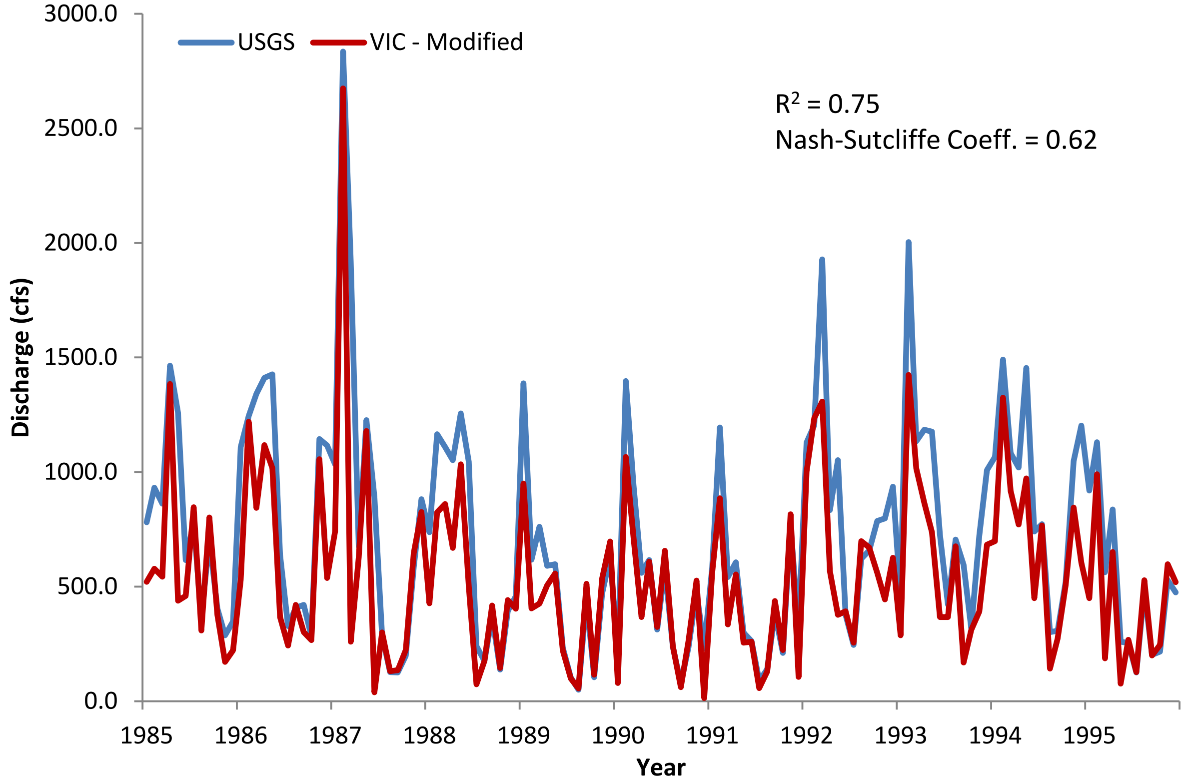
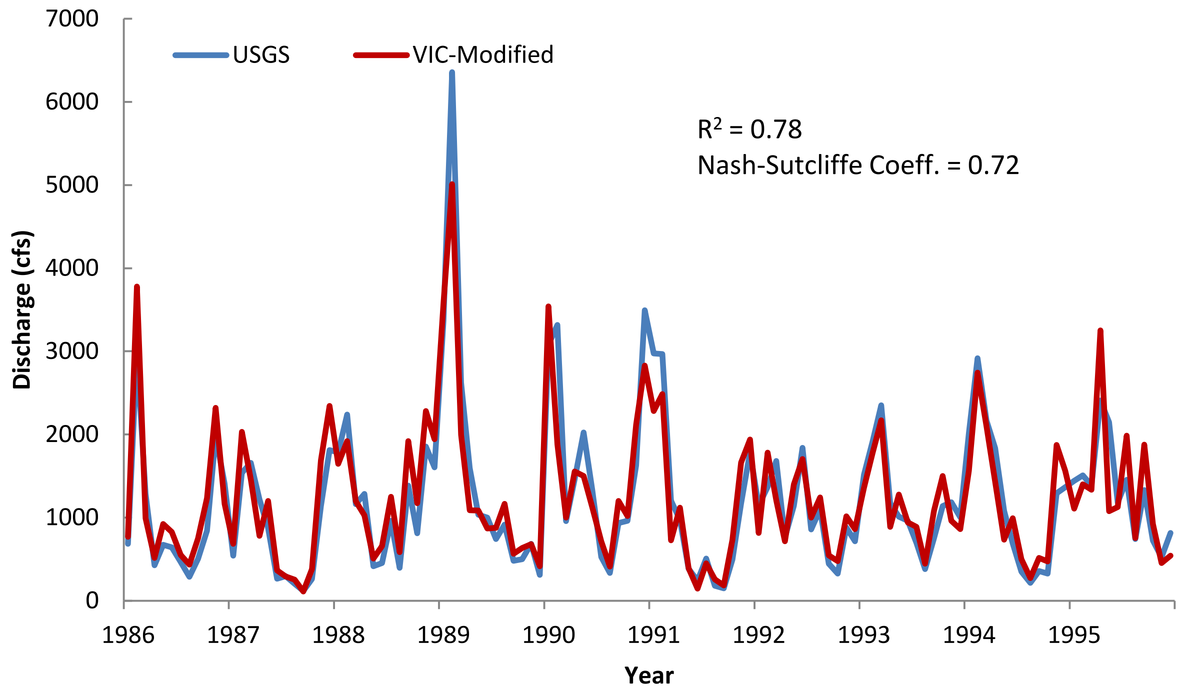


Figure 17. Comparison of observed and simulated monthly mean streamflow for the gauge near Boston, KY.



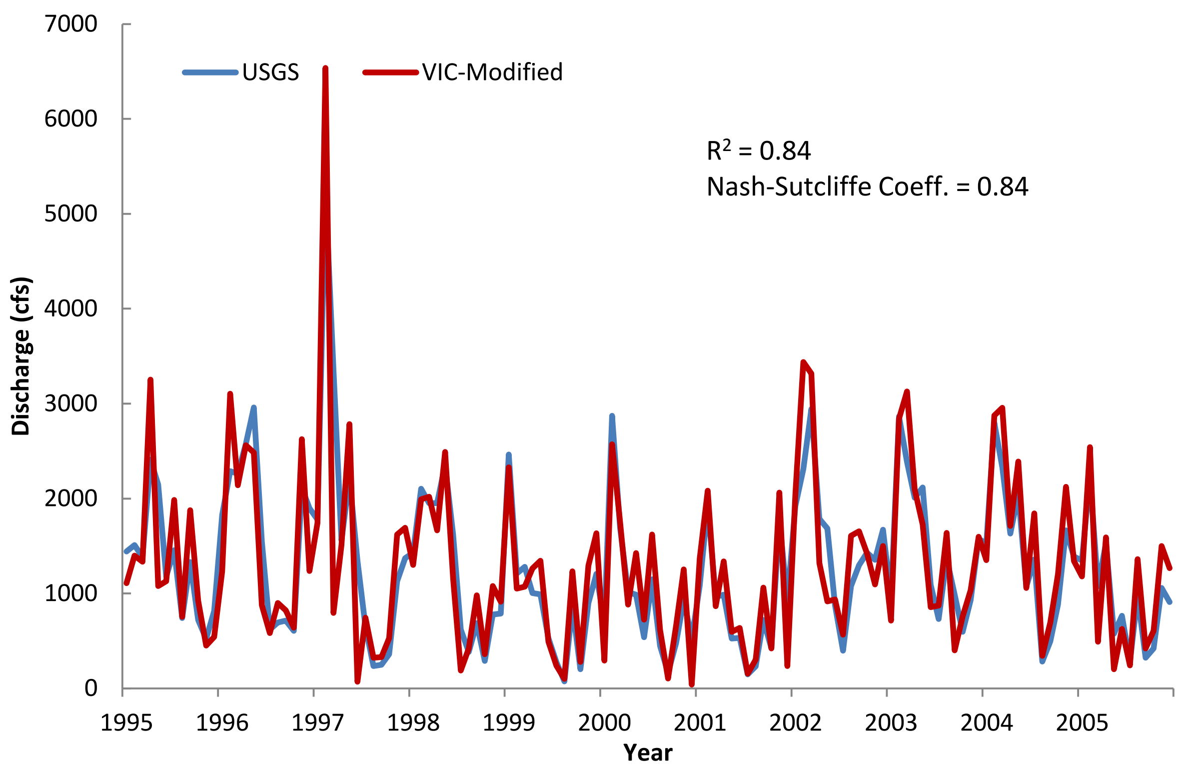


Figure 18. Comparison of observed and simulated monthly mean streamflow for the Shepardsville gauge.

5.3.3 Confirmation of Landcover Validation Results

In order to investigate the effects of altered landscapes on hydrology, the VIC model validation was run using fixed period landuse configurations. Using the time period immediately around the NLCD landcover data, the VIC model validation was confirmed (Figures 19 and 20). Nash-Sutcliffe values of 0.73 and 0.80 respectively indicated a good fit and proper working model. With VIC performing well under these input parameters, we investigated the effects of future alterations to the Basin's landcover.

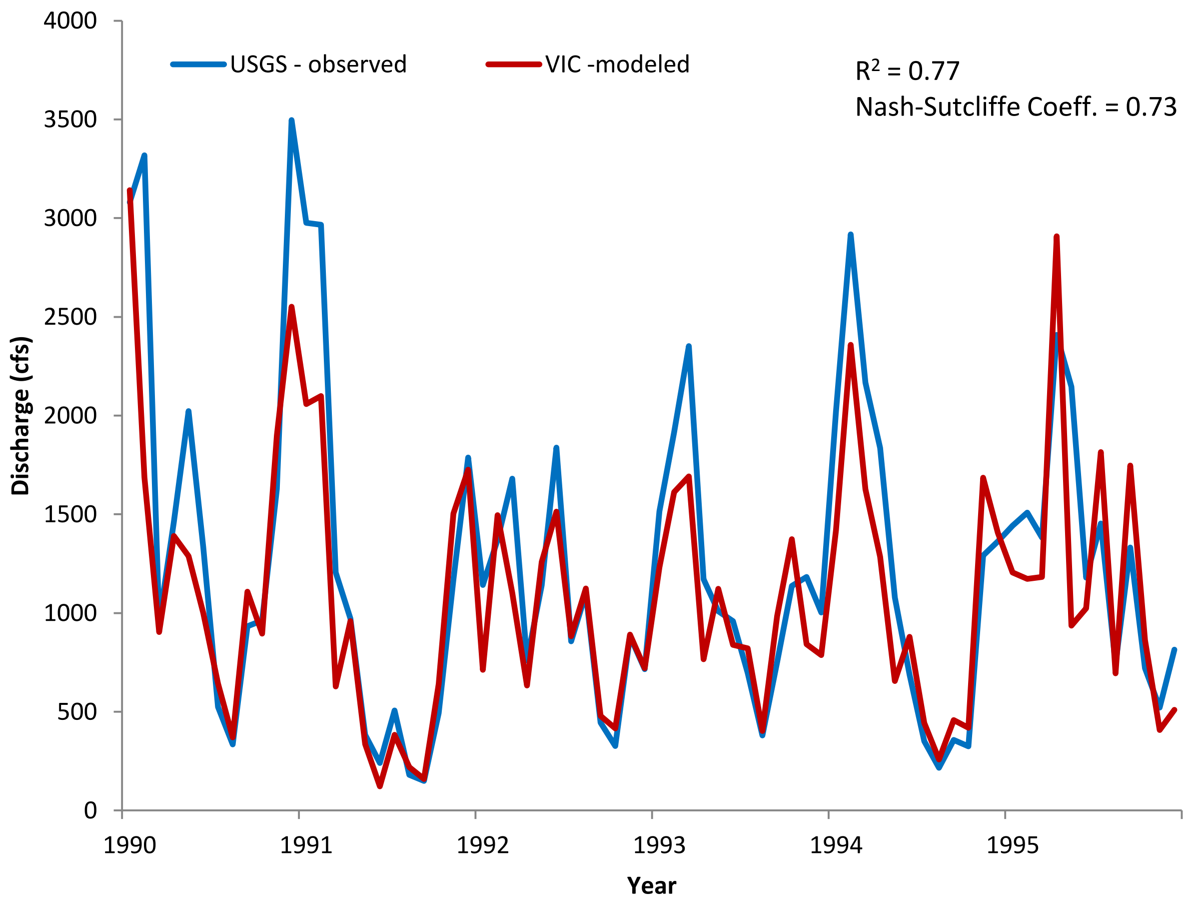


Figure 19. Shepardsville Basin modeled discharge with 1992 NLCD Landcover dataset.

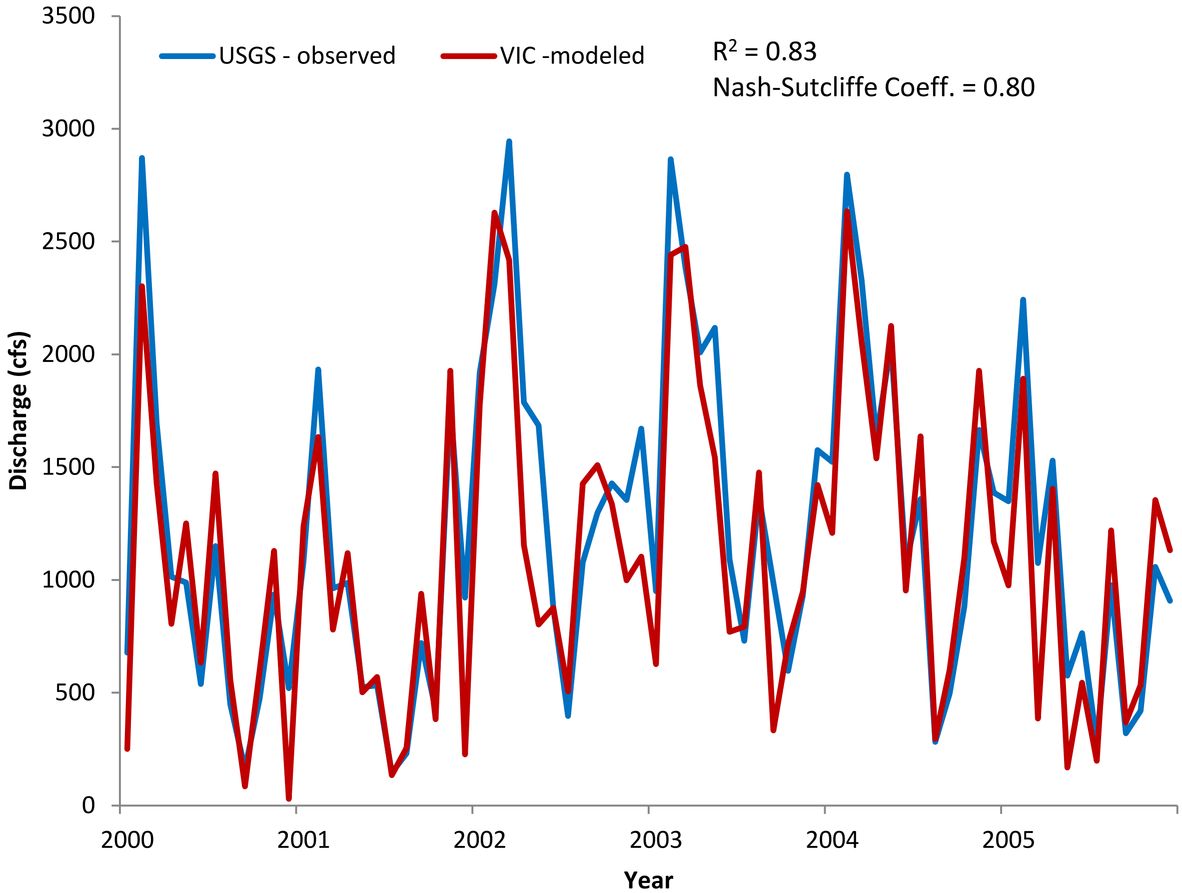


Figure 20. Shepardsville Basin modeled discharge with 2001 NLCD Landcover dataset.

6.0 Hydrologic variability within the Salt River Basin

6. 1 Climate variability within the Salt River Basin

To fully understand the implications of land use change on water resources we must establish a baseline understanding of the climate variability within the region as it effects the hydrologic cycle. In order to investigate the effects of climate variability on surface runoff and base flow measurements we isolated land use change by implementing the VIC model with a fixed land cover dataset. The 1991 land cover data were used during these investigations. VIC model output was generated using the climate data for the entire period of record in this study 1979 through 2008 with 1979 - 80 being excluded to allow for model spin-up.

Figure 21 show the results of average surface runoff comparisons between the periods 1981 – 1990 and 2000 – 2008 for April. We can see an overall increase in the surface runoff due to climate variability. The largest increase occurring in the southern portions of the basin, with moderate increases occurring in the north-central region where landscape changing is occurring rapidly. This variability is further seen when we look at the surface runoff for September (Figure 22). The average surface runoff within the basin is decreasing for September, with a similar decrease being seen in the southern portion of the basin and a large decrease in the urbanized portion in north central regions of the basin.

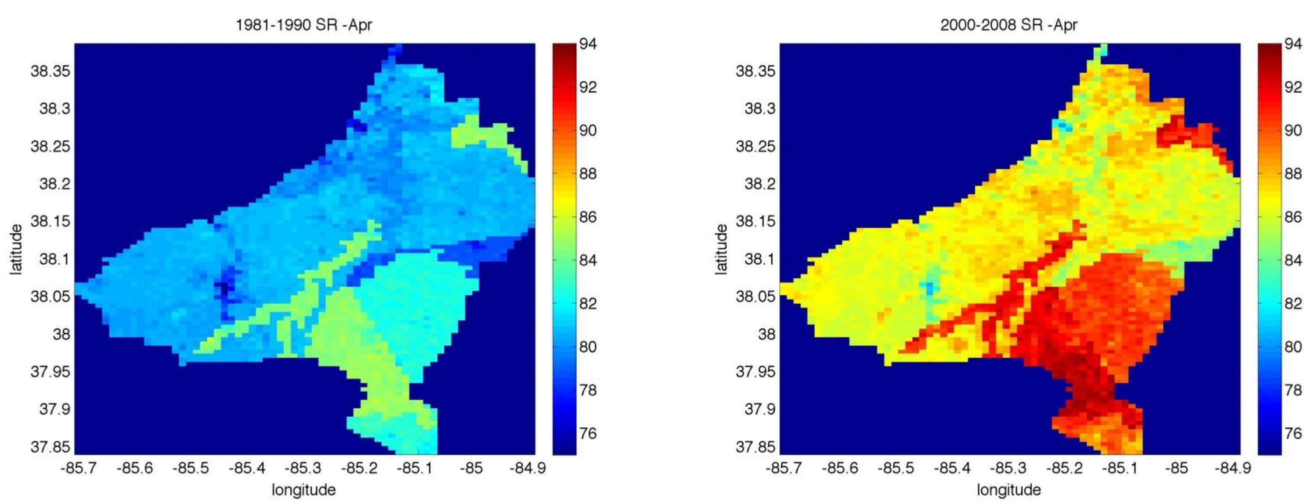


Figure 21. Comparison of April 1981-1990 and 2000-2008 average surface runoff for the Salt River Basin

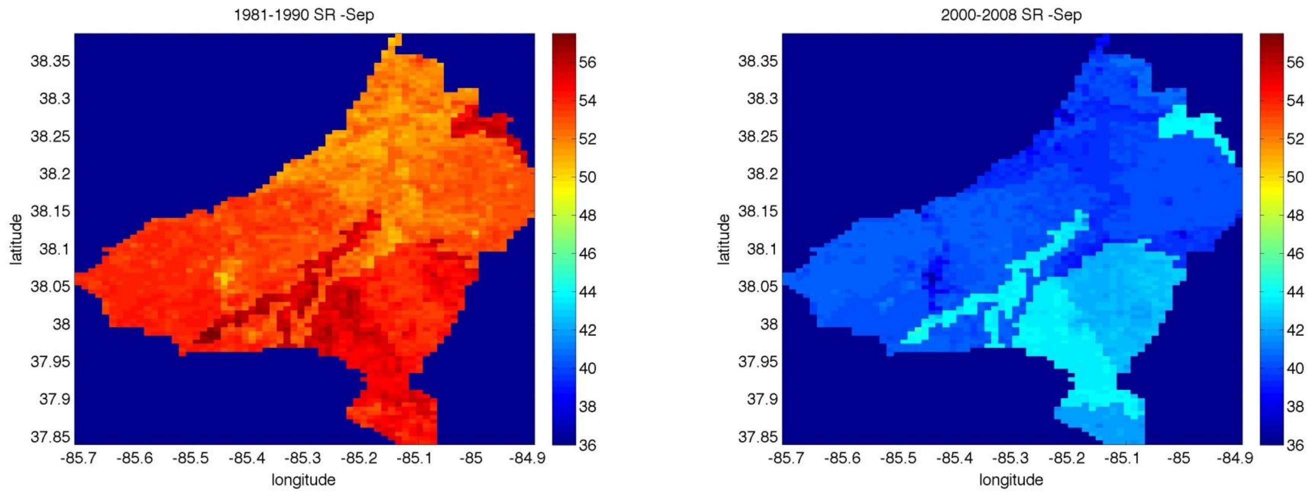


Figure 22. Comparison of September 1981-1990 and 2000-2008 average surface runoff for the Salt River Basin

Similar fluctuations in base flow can be seen under climate variability in the basin. Figure 23 shows the comparisons of average baseflow during the month of April. We can see an overall decrease in the average base flow between the periods; the largest differences being seen in the north central regions. This pattern is not universal throughout the year, figure 24 shows moderate increase in the base flow for the basin with little to no change occurring over the region.

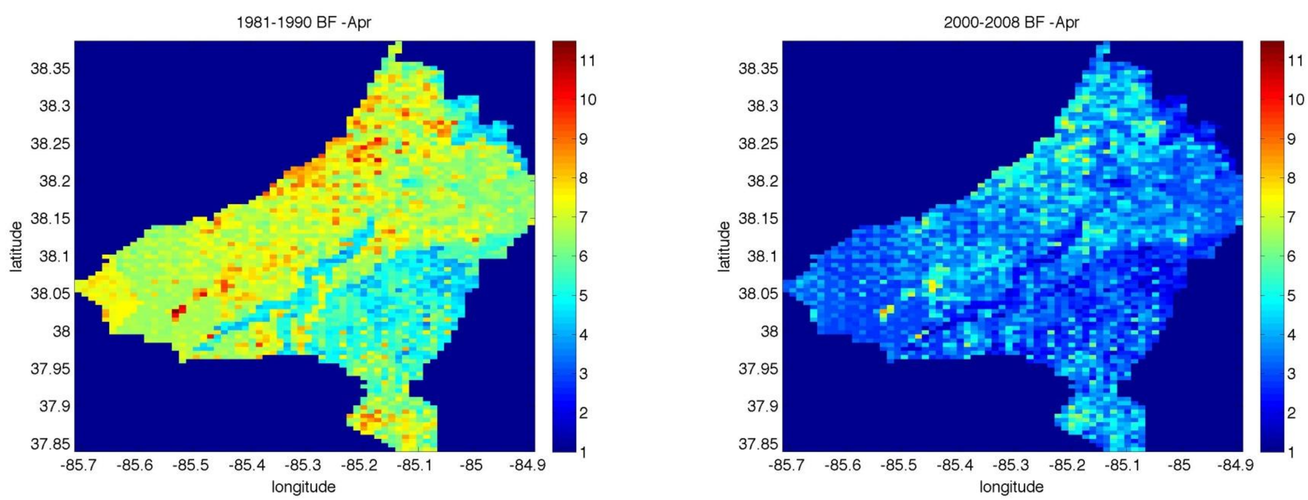


Figure 23. Comparison of April 1981-1990 and 2000-2008 average base flow for the Salt River Basin

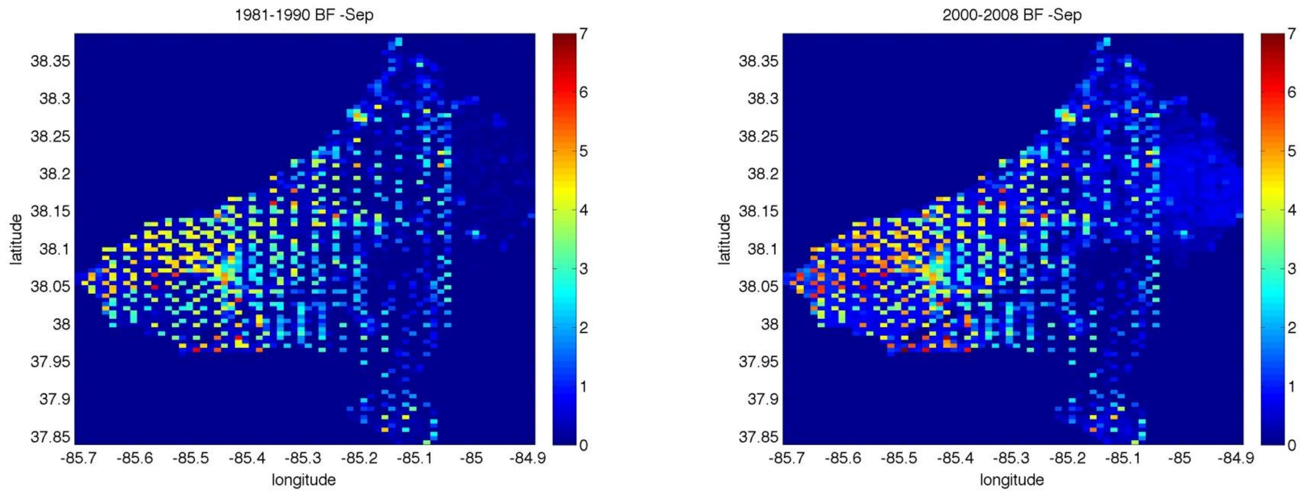


Figure 24. Comparison of September 1981-1990 and 2000-2008 average base flow for the Salt River Basin

It is important to set a baseline understanding of the stream flow fluctuations due to climate variability before we can fully investigate the impact of landscape changes on the hydrologic regime. This disproportionate change can be attributed to more intense precipitation events in climates and the non-linear nature of hydrologic budget components. Our results also suggest that the relationship of annual streamflow to annual precipitation may change in a future climate in that a unit increase in precipitation will cause a larger increase in streamflow. It is known (Anderson et al. , 2003) that regional models capture mesoscale events more accurately than global models, strengthening the case for fine-scale resolution of the dynamics of the hydrological system as being essential for driving hydrological impacts models.

6. 2 Impact of land use change on the hydrologic cycle

In order to isolate the effects of changing landscapes within the basin, the climate forcing data was held constant. This means that we only altered the model by adjusting the landcover data used during experiments, while utilizing the same climate forcing period. Using parameters estimated for each grid cell as described in the previous section, the VIC model was implemented.

Infiltration and interflow were predicted to decrease due to an increase in impervious surfaces (Calder, 1993). Percolation was expected to decrease because an increase in impervious surfaces would limit locations in which recharge can occur (Shi et al., 2007). Evapotranspiration is limited by the lack of vegetation in recently developed urban areas, but evaporation could increase due to the construction of reservoirs and detention ponds, as well as the generally warmer temperatures in urban areas due to lower albedo and other factors. However, these factors were not considered in this study. Streamflow and runoff were expected to increase due to impervious surfaces (Dunne and Leopold, 1978). Stream peak flows are predicted to generally be larger and earlier (Hornberger et al., 2001).

The investigations resulted in an increase in stream discharge for the basin as expected in the face of increasing urbanization occurring across the study region. Tables 9 & 10 show the ANOVA results of VIC simulations for model runs where the climate forcing data was held constant and land cover inputs were modified to use 1992 and 2001 land cover dataset respectively. For each analysis the comparison was done between 1992 and 2001 data, while only changing the climate forcing.

Table 9. ANOVA for 1992 and 2001 Landcover data and 1995 - 2005 Forcing.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Monthly Discharge	2.09E+08	119	1756585	63314.95	4.9473E-252	1.35361
Landcover Year	835.5712	1	835.5712	30.11761	2.33072E-07	3.920795
Error	3301.49	119	27.74361			
Total	2.09E+08	239				

Table 10. ANOVA for 1992 and 2001 Landcover data and 1985 - 1995 Forcing.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Monthly Discharge	1.67E+08	131	1271697	44017.9	6.6E-267	1.334383
Landcover Year	444.0167	1	444.0167	15.36898	0.000142	3.913428
Error	3784.648	131	28.89044			
Total	1.67E+08	263				

Total stream discharge increased for the corresponding change in land cover (Figure 25). The corresponding P-value for the 2001 experiment was 0.0001, indicating a significant difference in discharge between the two landcover scenarios. The total simulated flow for 1992 landcover was 0.29km^3 and total simulated stream discharge for the 2001 land cover was 0.30 km^3; an increase of 0.007 km^3. The mean simulated flow for the 1992 land cover was 900.93 cfs and for 2001 was 923.30 cfs.

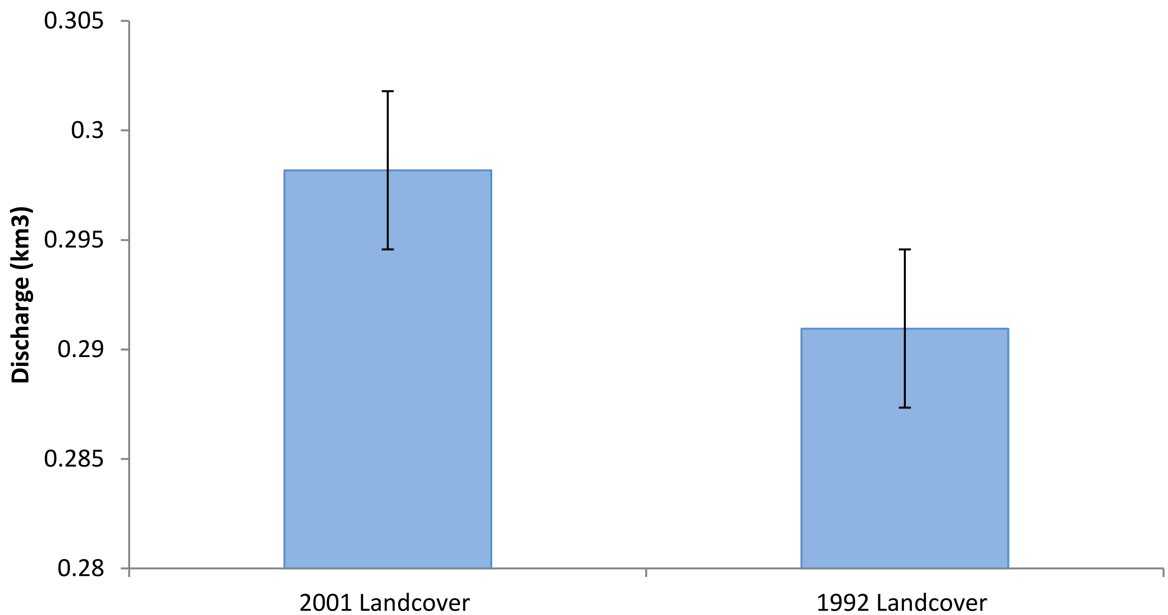


Figure 25. Results of land cover change on stream discharge for the Salt river Basin with 1985 -1995 climate forcing data.

Similar results were observed when using climate forcing data for the period 1995 – 2005. Figure 26 shows the results for these experiments. Total stream discharge increased for the change in land cover. 1992 total simulated flow was 0.30 km^3 and total simulated flow for the 2001 land cover was 0.31 km^3; an increase of 0.009 km^3. The difference between the 1992 experiment and the predicted land cover for 2040 showed a decrease in discharge of 5279.12 cfs for the period. The mean simulated flow for the 1992 land cover was 931.72 cfs and for 2001 was 959.33 cfs.

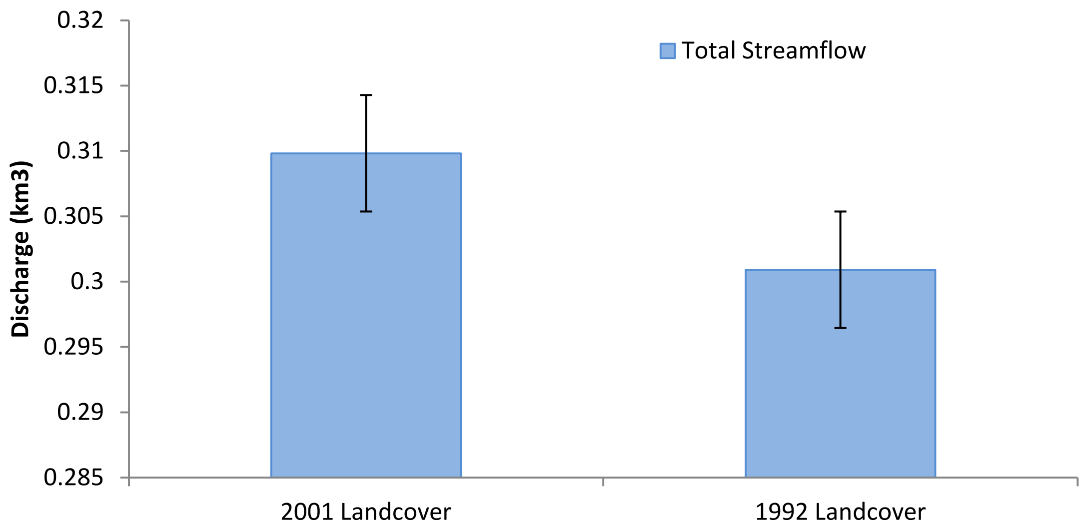


Figure 26. Results of land cover change on stream discharge for the Salt River Basin with 1995 -2005 climate forcing data.

7.0 Increasing impervious surface simulations

After the model calibration and validation, a basin-wide analysis was conducted using different increases in impervious surface (30%, 50%, 75% and 90% respectively) scenarios. Soil and impervious surface parameters for all scenarios were modified based on the simulated percentage of impervious values. A detailed description of data and scenarios are presented in Table 11. The projected landcover dataset for the year 2040 was represented by the 30% impervious surface scenario and represents the most likely possible outcome due to increased growth in the watershed given the population projections and previous urban expansion. The distributions of impervious surface were the only land cover changed in order to assess their impact on the regional water cycle, climate forcing was held constant across all simulations. Impervious surface was increased adjacent to existing impervious areas to achieve the desired increase scenarios.

Table 11. Scenarios used to study the impact of land cover change on regional hydrology.

Scenario	% Increase	Meteorology	Forcing Period	Impervious surface
Projected impervious cover	30	Gridded data at .008°/1km from NARR	1984–2005	
Projected impervious cover	50	Gridded data at .008°/1km from NARR	1984–2005	
Projected impervious cover	75	Gridded data at .008°/1km from NARR	1984–2005	
Projected impervious cover	90	Gridded data at .008°/1km from NARR	1984–2005	

Regional simulations were conducted for the period of 1994–2005 for the land cover change scenarios. In all cases, the initial year was not used in the analysis and was treated as the model spin-up period; we were able to use this model to predict possible trajectories of hydrologic regime under various increased impervious surface change scenarios. Simulations indicated that average annual discharge increased with the increase in impervious surface (Figure 27). In the comparison of the monthly discharge differences between the 30% increase scenario and the 90% increase scenario, we found an increase in the total discharge across the basin (Figure 28).

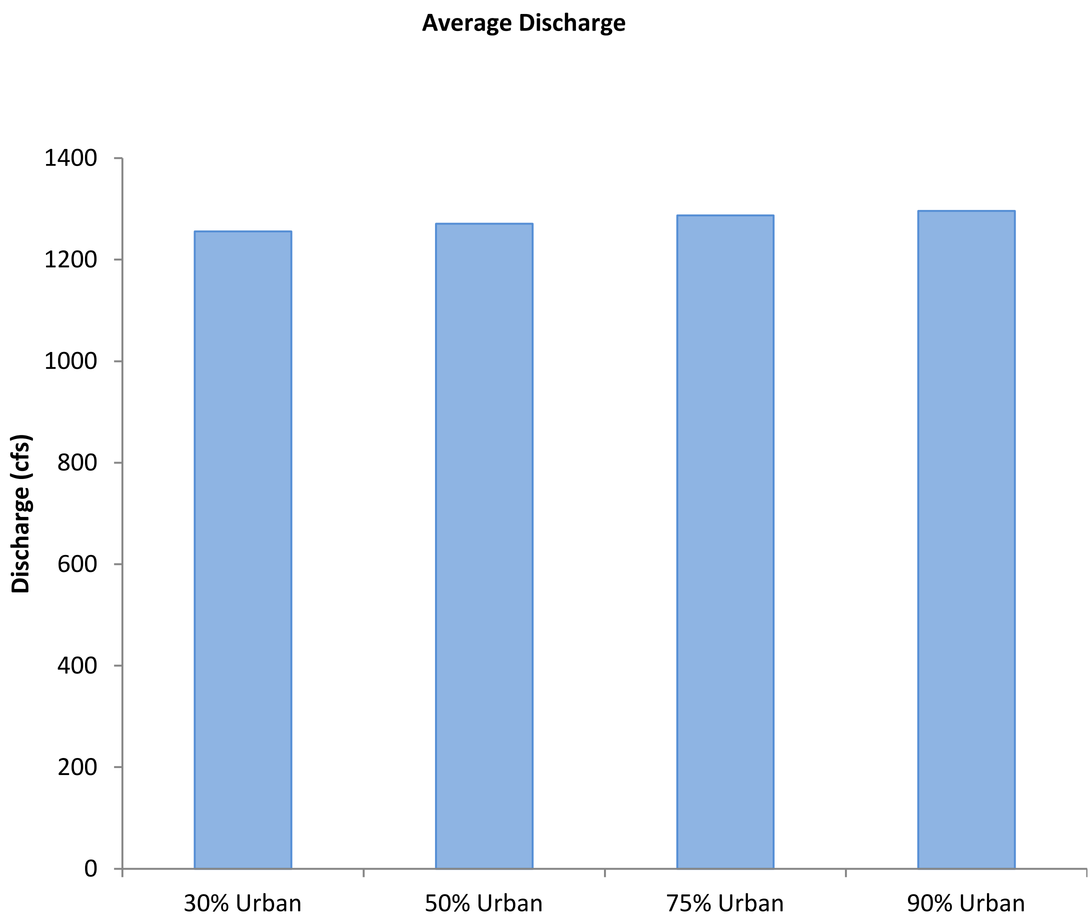


Figure 27. Average discharge under the impervious surface increase simulations.

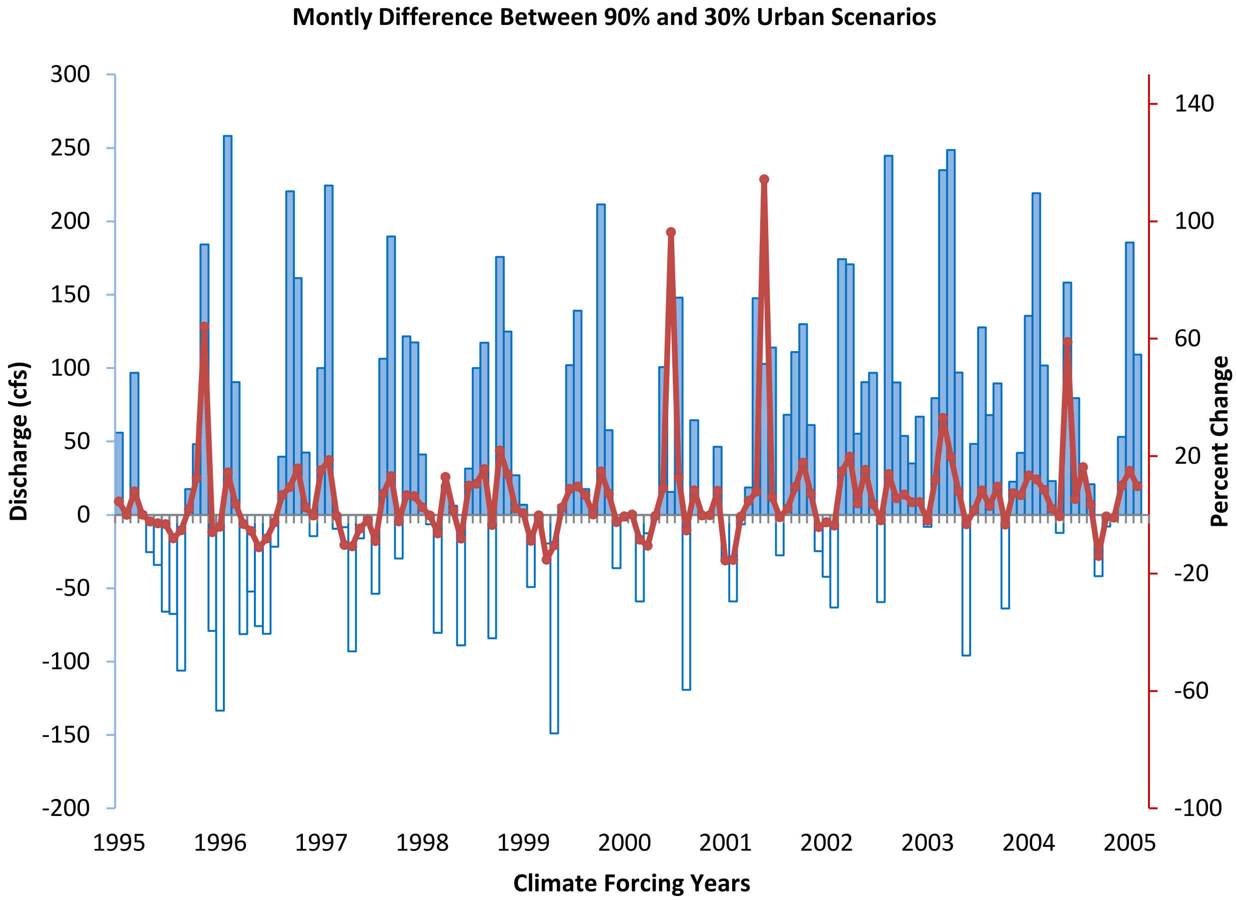


Figure 28. Total discharge differences between the 90% and 30% scenarios.

While in some years we see a decrease, an ANOVA test between these populations revealed that over the ten year simulation there was an increase in the total basin discharge(F = 1216.66, P-value= 0.00082). The maximum percent change was 114% increase and a 15% decrease between the two scenarios. These results are consistent with previous work indicating an expected increase in overall basin discharge under increased impervious surface areas.

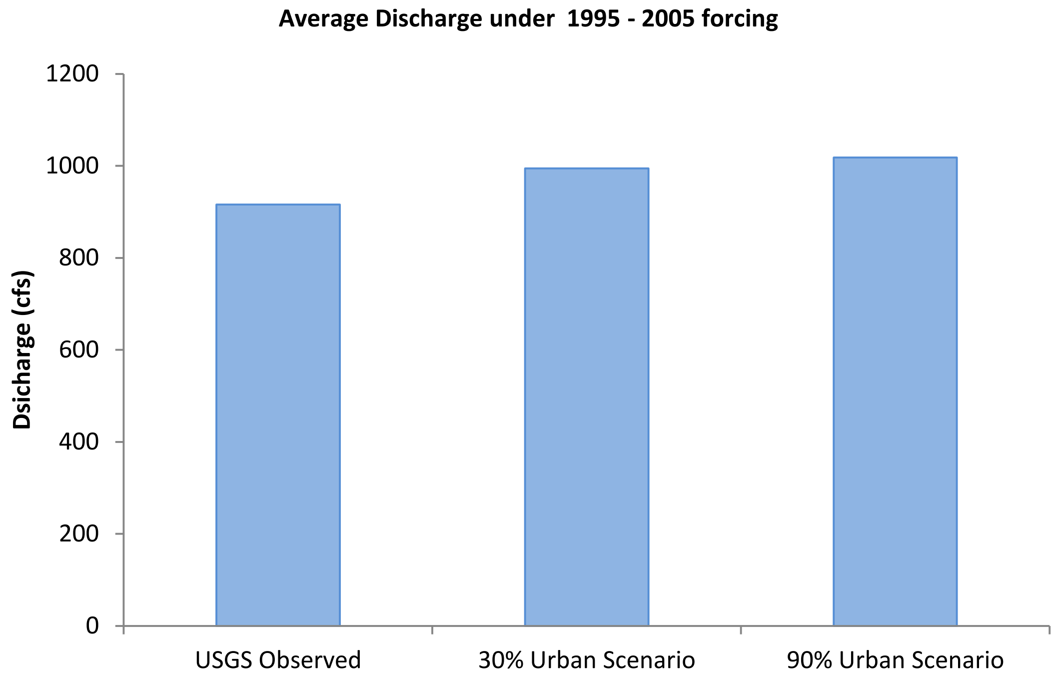


Figure 29. Comparison of monthly average discharge under increasing impervious surface scenarios.

When comparing total average monthly discharge using the 10 year climate forcing data 1995 through 2005, total discharge increases in each scenario. Urbanization has significantly affected flow regime of the Salt River Basin. Results from hydrology simulation under future land use scenarios produced an increase of mean annual flow across the basin (Figures 29). The flow of Salt River Basin under the 30% impervious surface scenario resulted in 8.58 % increase compared to Base Case Scenario (from 916 cfs to 995 cfs); while an 11.12% increase over current observations are seen under the 90% impervious surface scenario (from 916 cfs to 1018 cfs). Increase in the proportion of urban area in the watershed disrupts and changes the natural water balance that causes alterations in seasonal flow regime. Primarily it is reflected in increased flood peaks due to increased stormwater runoff. Also, increased bankfull flows are typical for urbanized watersheds.

8.0 Summary and Conclusions

The first objective of this thesis research was to determine the appropriateness of an existing model to simulate hydrologic processes in an urbanizing watershed. The second objective was to modify an existing model to better simulate these hydrologic processes in an urbanizing basin. The final objective was to predict possible trajectories of hydrologic regime under various landscape change and climate change scenarios in the Salt River Basin.

In order to better understand the hydrologic impacts of landscape transformation, hydrologic response to land cover change must be identified and evaluated. The VIC model was found to be appropriate to be modified and used in the basin due to its strength in simulating the hydrology and water balance of a watershed. The VIC model was modified to simulate hydrologic processes in urbanized environments. The modified VIC version used percent urbanization to modify the soil infiltration properties across the basin. Using the newly modified VIC model allows for simulating the hydrology by capturing its unique landuse and soil characteristics.

The interactions between land cover change and water fluxes across spatial scales are intricate, especially as the scale of the modeled basin increases. The relative impact of land cover change on water fluxes is by nature less significant as you move down a watershed relative to the streamflow. Less than a millimeter more runoff per month in the headwaters will have a greater relative impact on streamflow than a grid cell near the outlet because of increasing stream discharge as one moves downstream. Increasing runoff by one millimeter per month may increase streamflow in a small, local watershed by 10%, but could have an undetectable impact on streamflow in a regional scale watershed. This phenomenon is more apparent in larger watersheds. Because of larger discharge values, it is not as easy to detect the impact of land cover change on hydrology simply by examining streamflow.

While this research has shown that through modeling the response of a region's water dynamics to land cover change can be simplified, the relationship between these two systems is too complex to be emulated exclusively with modeling. Therefore, it is important for researchers employing the land cover change and hydrologic tools presented here to have an understanding of both trends in land cover change and hydrologic change throughout their basin of interest, so that they may be able to interpret model results more effectively.

Conceptually, modified VIC is an improvement and enables a better representation of urbanization effects on the portioning of water across the Basin. In the Salt River Basin, modified VIC using the urban modifications had a more notable impact in the watershed hydrology than the original VIC model. The difference might be related to the modified VIC's detailed representation of the characteristics of change experienced when converting land to impervious surfaces by using the percentage of change to modify the hydrologic conductivity rate.

In the Salt River Basin, model simulation statistics showed that modified VIC performed better than original VIC in predicting streamflow in an urban-influenced watershed. The modified VIC model offers the flexibility to represent the unique relationship between increases in impervious surface and total discharge across a watershed.

The urban percentage modification to soil infiltration provides a new and appropriate mechanism to represent the partitioning of water across the watershed. The new modification can be used for model calibration and to represent the surface and ground water partitioning to regions outside the watershed boundary.

The results presented here are evidence that well-documented hydrologic impacts of land cover change are identifiable in regional scale watersheds. However, the magnitude of effect can be attenuated by the geographic scale of the basin analyzed. While the most obvious impacts of land cover change are the direct and immediate effects on runoff and streamflow, an examination of one component of the water cycle is not comprehensive enough to capture the mechanisms by which land cover change can influence hydrology. Examining any one result in isolation could provide a false sense of security (or unsubstantiated concern) about the relative impacts that land cover change is having on the water balance of an area. It is important, especially in larger watersheds where water cycle dynamics are poorly understood, to utilize tools such as modeling that can elucidate impacts humans are having on water resources through land cover/use change.

8.1 Areas of Further Research

The key to reliable estimation of the landscape, is the identification of precise datasets. While this has been significantly advanced for residential and agricultural land uses, other types have not been addressed through this model. It is highly likely that areas converted to impervious surface in the model presented here, in reality converted to other uses like shrub lands or forests.

A weakness of this research is that it is heavily dependent on patterns of change in the period that high-resolution remotely-sensed data exist (in this case 1992 and 2001). It emulates this change for all future time steps. Through developing the ability to replicate changes in land cover over decadal time scales through models, the response of environmental systems to these changes can be more fully understood. Any type of modeling of natural landscapes is by nature generalized. Key to effective modeling is ensuring that assumptions and simplifications are as close to reality as can be supported by data. For the Variable Infiltration Capacity (VIC) model, this means adequate consideration of the parameters that make up the land surface including both the types of vegetation as well as the amount and characteristics of urban coverage.

A better understanding of the amount of impervious cover in an area is crucial, because it may have a significant hydrologic impact. Because it was shown through this research (and others before it) that small changes in impervious cover can have dramatic impacts on hydrologic fluxes, a more specific description of urban areas, that includes varying levels of impervious cover for classes such as high-density residential, low-density residential, and industrial land uses should be created for the Variable Infiltration Capacity model. Also an analysis of how the characteristics of urban areas may have changed over the time of simulation is necessary. Urban cover in 1990 was undoubtedly different from urban cover in 2010. Also, a method for distinguishing connected from not connected impervious would be an important modification to VIC. Currently, any precipitation that strikes an impervious surface contributes to streamflow.

One component of the water balance not explicitly identified within this study is water storage. Changes in moisture storage capacity in the soil or in lakes through the construction or destruction of dams should be analyzed. Also, wetlands in this area are not represented within this version of the VIC model and may have an impact on water flux output. An existing VIC lake and wetlands algorithm could be employed to represent changes in lake/wetland levels within the watershed (Cherkauer et al., 2003).

In light of the recommended modifications to land cover modeling as well as the parameterization of hydrologic model inputs, it is important to consider the initial purposes for providing simplified methods based on widely available datasets. While the modifications presented here will likely improve the land cover change and hydrologic models' ability to recreate actual changes, the further investigation necessary to acquire additional information about a study area may prohibit potential users from adopting this method.

Another important consideration when gauging the usability of the land cover change and hydrologic modeling approach presented here is the ability of land use planners to understand and appreciate model results. It is difficult for land use planners in large watersheds to glean information about the impacts of land cover change on their municipal area from the analysis presented here. Therefore, a means by which areas can be identified as hydrologically sensitive to certain types of change should be developed. In a watershed such as the Salt River watershed, that covers several counties and includes many municipalities, it is vital to provide pertinent information to those whom it applies. Analysis at the watershed scale is sufficient for presentation to regional and state officials, but is not adequate for informing decision-making at lower levels. Therefore, decision makers must be provided tools appropriate for a variety of spatial and temporal scales. Developing models at every hierarchy helps to meet the needs of decision makers such as land use planners and government officials.

8.1.2 Future Climate Research

An assessment of peak annual flows and low flows would enhance the value of this study for understanding potential future impacts on the area due to climate change. For example, the Salt River has a large recreational value due to its thriving fish population. Understanding the impact of climate change on low flows could support sustainability and management schemes to maintain this industry. In the same way, an analysis of flood potential could support engineering design structures to prevent negative economic impacts due to changes in the water balance of the area caused by land cover and climate change. Incorporating projected forecasts of climate would help to identify the sensitivity of the watershed to changes in temperature and precipitation in the future.

Future climate projections for the region indicate that precipitation will increase and summers will be drier but punctuated with more intense convective storms leading to an increase in the flashiness of summer streamflow .The increased urbanization that is projected in the 2040 land cover is also likely to produce more flashiness with greater magnitude flood peaks. Projections of increased precipitation and increased urbanization will have additive impacts on surface temperature. Urbanization results in elevated surface temperatures (the urban heat island effect), which will be further enhanced under projected future climate, resulting in an additive impact.

References

Abdulla, F. A., D. P. Lettenmaier, E. F. Wood, and J. A. Smith. 1996. Application of a macroscale hydrologic model to estimate the water balance of the Arkansas Red River basin. *Journal* of Geophysical Research-Atmospheres 101 (D3):7449-7459.

Anderson, C. J., et al. 2003, Hydrological processes in regional climate model simulations of the central United States flood of June–July 1993, J. Hydrometeorol., 4, 584– 598.

Anderson, R. Koren, V.I., Reed, S.M., 2005. Using SSURGO data to improve Sacramento model a priori parameter estimates. Submitted to MOPEX Special Issue of 'MODEL PARAMETER ESTIMATION' in Journal of hydrology.

Arnell, N. W. 1999. Climate change and global water resources. Global Environmental Change-Human and Policy Dimensions 9:S31-S49.

Arnold, J., P. Allen, and G. Bernhardt. 1993, A comprehensive surface-groundwater flow model, Journal of Hydrology, 142, 47-69.

Arnold, C. L., and C. J. Gibbons. 1996. Impervious surface coverage - The emergence of a key environmental indicator. Journal of the American Planning Association 62 (2):243-258.

Bates, C. G., and A. J. Henry. 1928. Forest and streamflow experiment at Wagon Wheel Gap, Colorado. Mon. Weather Rev. 56:79-97.

Beven, K. J., M. J. Kirkby, N. Schofield, and A. F. Tagg. 1984. Testing A Physically-Based Flood Forecasting-Model (Topmodel) For 3 Uk Catchments. Journal of Hydrology 69 (1-4):119-143.

Beven, K. 1989. Changing ideas in hydrology -- The case of physically-based models. Journal of Hydrology 105 (1-2):157-172.

Beven, K.J. and Freer, J., 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems, Journal of Hydrology, 249,11–29.

Blondin, C. 1991, Parameterization of land-surface processes in numerical weather prediction, in Land Surface Evaporation: Measurements and Parameterization, edited by T. J. Schmugge and J. C. Andre, pp. 31-54, Springer-Verlag, New York.

Booth, D. B. 1991. Urbanization And The Natural Drainage System - Impacts, Solutions, And Prognoses. Northwest Environmental Journal 7 (1):93-118.

Bonan, G. 1996, A Land Surface Model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide, Tech. Rep. NCAR/TN-417+STR, NCAR Technical Note.

Bosch, J. M., and J. D. Hewlett. 1982. A Review Of Catchment Experiments To Determine The Effect Of Vegetation Changes On Water Yield And Evapo-Transpiration. Journal of Hydrology 55 (1-4):3- 23.

Bowling, L. C., J. W. Pomeroy, and D. P. Lettenmaier. 2004. Parameterization of blowing-snow sublimation in a macroscale hydrology model. Journal of Hydrometeorology 5 (5):745-762.

Bowling, L. C., P. Storck, and D. P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. Water Resources Research 36 (11):3223-3240.

Brabec, E., S. Schulte, and P. L. Richards. 2002. Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. Journal of Planning Literature 16 (4):499-514.

Bradshaw, C.J.A., N.S. Sodhi, K.S.-H. Peh, and B.W. Brook. 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. Global Change Biol. 13: 2379-2395.

Brooks, R. H., A. H. Corey. 1988, Hydraulic properties of porous media, Hydrol. Pap., Colorado State University, 3.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310 (1-4):28-61.

Burnash, R.J.C. 1995, The NWS River Forecast System - Catchment model in: Computer models of Watershed Hydrology, edited by V.P. Singh, pp.311-366.

Burt, T. P., and W. T. Swank. 1992. Flow frequency responses to hardwood-to-grass conversion and subsequent succession. Hydrological Processes 6 (2):179-188.

Calder, I. R. (1993), Hydrological effects of land-use change. Handbook of Hydrology, D.R. Maidment, Ed., McGraw-Hill, 3.1-3.50.

Carle, M. V., P. N. Halpin, and C. A. Stow. 2005. Patterns Of Watershed Urbanization And Impacts On Water Quality . Journal of the American Water Resources Association 41 (3):693-708.

Carter, R.W. 1961, Magnitude and Frequency of Floods in Suburban Areas, in Short Papers in the geologic and hydrologic sciences: U.S. Geological Survey Professional Paper 424-B, p.B9-Bl 1.

Cherkauer, K. A., L. C. Bowling, and D. P. Lettenmaier. 2003. Variable infiltration capacity cold land process model updates. Global and Planetary Change 38 (1-2):151-159.

Chow, V. T. 1952, Hydrologic Studies of Urban Watersheds, Rainfall and Runoff of Boneyard Creek, Champaign-Urbana Illinois, Illinois University: Civil Engineering Studies, Hydraulic Engineering Series, Number 2, 66p.

Claussen, M., V. Brovkin, . and A. Ganopolski. 2001. Biogeophysical versus biogeochemical feedbacks of large-scale land cover change. Geophysical Research Letters 28: 1011-1014.

Crawford, N., and R. Linsley .1966, Digital simulation in hydrology: Stanford Watershed Model IV, Stanford University Department of Civil Engineering, Tech Report 39, Palo Alto, CA.

Cuffney, T. F., M. R. Meador, S. D. Porter, and M. E. Gurtz. 2000. Responses of Physical, Chemical, and Biological Indicators of Water Quality to a Gradient of Agricultural Land Use in the Yakima River Basin, Washington. Environmental Monitoring and Assessment 64 (1).

Deardorff, J. W. 1978, Efficient prediction of ground surface-temperature and moisture, with inclusion of a layer of vegetation, Journal of Geophysical Research-Oceans and Atmospheres, 83(NC4), 1889-1903.

DeFries, R. S., and J. R. G. Townshend . 1994, NDVI-derived land cover classification at global scales, International Journal of Remote Sensing, 15(17), 3567-3586.

DeVries, J.J., and Hromadka, T.V., 1993, Computer models for surface water, in Maidment, D.R. (ed) Handbook of Hydrology, McGraw-Hill, NY.

Dickinson, R. E., A. Henderson-Sellers, P. J. Kennedy, M. F. Wilson (1986), Biosphere-atmosphere transfer scheme(BATS) for the NCAR community climate model, NCAR Tech. Note TN-275 +STR.

Dow, C. L. 2007. Assessing regional land-use/cover influences on New Jersey Pinelands streamflow through hydrograph analysis. Hydrological Processes 21 (2):185-197.

Dougherty, M., Dymond, R.L., Goetz, S.J., Jantz, C.A., and Goulet, N., 2004, Evaluation of Impervious Surface Estimates in a Rapidly Urbanizing Watershed: Photogrammetric Engineering and Remote Sensing, v.70(l l)p. 1275-1284.

Ducoudre, N. I., et al. 1993, SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land-atmosphere interface within the LMD atmospheric general circulation model, J. Clim.,6(2), 248-273.

Dumenil, L., and E. Todini. 1992. A rainfall-runoff scheme for use in the Hamburg climate model, in Advances in theoretical hydrology, A tribute to James Dooge. P. O'Kane, ed., European Geophysical Society Series on Hydrological Sciences 1, Elsevier: Amsterdam.

Dunn, S. M., and R. Mackay. 1995. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. Journal of Hydrology 171 (1-2):49-73.

Dunne, T., and Leopold, L.B., 1978, Water in Environmental Planning, W.H. Freeman and Co., New York, New York

Ek et al. 2003, Implementation of Noah Land surface model advances in the National Centers forEnviornmental Prediction operational Mesoscale Eta Model, J. Geophys. Res., 108, 8851,doi:10.1029/2002JD003296.

Engel, B. A., J.-Y. Choi, J. Harbor, and S. Pandey. 2003. Web-based DSS for hydrologic impact evaluation of small watershed land use changes. Computers and Electronics in Agriculture 39 (3):241-249.

Feldman, D., ed. (2000), Hydrologic modeling system HEC-HMS, Technical Reference Manual: Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers, Davis, Calif.

Franchini, M., and M. Pacciani. 1991, Comparative-analysis of several conceptual rainfall runoff models, Journal of Hydrology, 122(1-4), 161-219.

Freer, J., Ambroisc, B. & Beven, K. J. (1996) Bayesian estimation of uncertainty in runoff prediction and the value of data: an application of the GLUE approach. Wat. Resour. Res. 32(7), 2161-2173.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch. 2004. Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model. Journal of Hydrology 286 (1-4):249-270.

Grace, J.M. 2004. Forest operations impact on forest soil and water on poorly drained organic soil watersheds in North Carolina. Dissertation. North Carolina State University.

Harris, E.E., and Rantz, S.E., 1964., Effect of Urban Growth on Streamflow Regimen of Permanente Creek, Santa Clara County, California, U.S. Geological Survey Water Supply Paper 1591-B, 18p.

Hornbeck, J. W., C. W. Martin, and C. Eagar. 1997. Summary of Water Yield Experiments at Hubbard Brook Experimental Forest, New Hampshire. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 27 (12):2043-2052.

Hogue, T. S., H. Gupta, and S. Sorooshian. 2006. A 'User-Friendly' approach to parameter estimation in hydrologic models. Journal of Hydrology 320 (1-2):202-217.

Hood, M. J., J. C. Clausen, and G. S. Warner. 2007. Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development. JAWRA Journal of the American Water Resources Association 43 (4):1036-1046.

Hooper, R. P., A. Stone, N. Christophersen, E. de Grosbois, and H. M. Seip. 1988. Assessing the Birkenes Model of Stream Acidification Using a Multisignal Calibration Methodology. Water Resour. Res.24 (8):1308-1316.

Hornbeck, J. W., S. W. Bailey, D. C. Buso, and J. B. Shanley. 1997. Streamwater chemistry and nutrient budgets for forested watersheds in New England: Variability and management implications. Forest Ecology and Management 93 (1-2):73-89.

Hornberger, G. M., T. M. Scanlon, and J. P. Raffensperger. 2001. Modelling transport of dissolved silica in a forested headwater catchment: the effect of hydrological and chemical time scales on hysteresis in the concentration-discharge relationship. Hydrological Processes 15 (10):2029-2038.

Hsu, M. H., S. H. Chen, and T. J. Chang. 2000. Inundation simulation for urban drainage basin with storm sewer system. Journal of Hydrology 234 (1-2):21-37.

Jakeman, A. J., and G. M. Hornberger. 1993. How Much Complexity Is Warranted in a Rainfall-Runoff Model? Water Resour. Res. 29 (8):2637-2649.

Johanson, R.C., Imhoff, J.C., and Davis, H.H., 1980, Users Manual for the Hydrologic Simulation Program - FORTRAN (HSPF), EPA-600/9-80-105.

Kaufman, M. M., and W. M. Marsh. 1997. Hydro-ecological implications of edge cities. Landscape and Urban Planning 36 (4):277-290.

Klein, R.D., 1979, Urbanization and Stream Water Quality impairment, Water Resources Bulletin, v.l5(4)p.948-963.

Laurance, W.F. 2007. Forests and floods. Nature. 449: 409-410.

Leopold, L. B. 1991. Lag times for small drainage basins. CATENA 18 (2):157-171.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. A Simple Hydrologically Based Model Of Land-Surface Water And Energy Fluxes For General-Circulation Models. Journal of Geophysical Research-Atmospheres 99 (D7):14415-14428.

Liang, X., et al .1996, Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification, Global Planet Change, 13(1-4), 195-206.

Liang, X., et al. 1999, Modeling ground heat flux in land surface parameterization schemes, J. Geophys. Res.-Atmos., 104(D8), 9581-9600.

Liang, X., and Z. H. Xie. 2003, Important factors in land-atmosphere interactions: surface runoff generations and interactions between surface and groundwater, Global Planet Change, 38(1-2), 101-114.

Liang, X., et al. 2003, A new parameterization for surface and groundwater interactions and its impact on water budgets with the variable infiltration capacity (VIC) land surface model, J. Geophys. Res.-Atmos., 108(D16).

Liang, X., et al. 2004, Assessment of the effects of spatial resolutions on daily water flux simulations, Journal of Hydrology, 298(1-4), 287-310.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G. 1983, Precipitation- Runoff Modeling System: Users manual, U.S. Geological Survey Water Resources Investigation Report 83-4238,126 p.

Leopold, L. B., 1968, Hydrology for Urban Land Planning - A guidebook on the Hydrologic Effects of Urban Land Use, U.S. Geological Survey Circular 554,18 p.

Lohmann, D., R. Nolte-Holube, And E. Raschke. 1996. A large-scale horizontal routing model to be coupled to land surface parametrization schemes. Tellus A 48 (5):708-721.
Lohmann, D., et al. (1998), Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, Hydrol. Sci. J.-J. Sci. Hydrol., 43(1), 131-141.
Louis, J. F. 1979, Parametric Model of Vertical Eddy Fluxes in the Atmosphere, Bound-Lay Meteorol, 17(2), 187-202.
Mahrt, L., and H. Pan.1984, A 2-Layer Model of Soil Hydrology, Bound-Lay Meteorol, 29(1), 1-20.
Martens, L.A., 1968, Flood Inundation and Effects of Urbanization in Metropolitan Charlotte, North Carolina: U.S. Geological Survey Water Supply Paper 1591-C, 60p
Marsh. W. M.. and N. L. Marsh. 1995. Hydrogeomorphic considerations in development planning and stormwater management, central Texas hill country, USA. Environmental Management 19:693- 702.
Maurer, E. P., D. P. Lettenmaier, and N. J. Mantua. 2004. Variability and potential sources of predictability of North American runoff. Water Resour. Res. 40 (9):W09306.
McCray, J. E., and T. B. Boving. 2007. Introduction: Urban Watershed Hydrology. JAWRA Journal of the American Water Resources Association 43 (4):839-840.
McMahon, G., J. D. Bales, J. F. Coles, E. M. P. Giddings, and H. Zappia. 2003. Use Of Stage Data To Characterize Hydrologic Conditions In An Urbanizing Environment . Journal of the American Water Resources Association 39 (6):1529-1546.
McMahon, G., and T. F. Cuffney. 2000. Quantifying Urban Intensity In Drainage Basins For Assessing Stream Ecological Conditions. Journal of the American Water Resources Association 36 (6):1247-1261.
Mesinger, F, G. DiMego, E. Kalnay, P. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, M. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, K. Mitchell, D. Parrish, E. Rogers, W. Shi, 2004: NCEP North American Regional Reanalysis. Paper P1.1 in 15th Symposium On Global Change and Climate Variations, Combined Preprints CD-ROM, American Meteorological Society, Seattle, WA, 11-15 January.
Mesinger, F., et al. (2006), North American regional reanalysis, Bull. Am.Meteorol. Soc., 87, 343–360.
Meybeck, M. 2002. Riverine quality at the Anthropocene: Propositions for global space and time analysis, illustrated by the Seine River. Aquatic Sciences 64 (4):376-393.
Meybeck, M. 2004. The global change of continental aquatic systems: dominant impacts of human activities. Water Science and Technology 49 (7):73-83.
Monteith, J. L., and M. H. Unsworth (1990), Principles of Environmental Physics, 2nd ed., Routledge, Chapman and Hall, New York.
Muleta, M.K. and Nicklow, J.W. (2005). "Decision support for watershed management using evolutionary algorithms." J. of Water Resources Planning and Management, ASCE, 131(1): 35-44.
NRCS, 1986, Urban Hydrology for Small Watersheds: Natural Resources Conservation Service Technical Release 55, 160p.
Nijssen, B., D. P. Lettenmaier, X. Liang, S. W. Wetzel, and E. F. Wood. 1997. Streamflow simulation for continental-scale river basins. Water Resources Research 33 (4):711-724.
Nijssen, B., et al. 2001, Predicting the discharge of global rivers, J. Clim., 14(15), 3307-3323.

Nilsson, C., J. E. Pizzuto, G. E. Moglen, M. A. Palmer, E. H. Stanley, and N. E. Bockstael, and L. C. Thompson. 2003. Ecological forecasting and the urbanization of stream ecosystems:

challenges for economists, hydrologists, geomorphologists, and ecologists.Ecosystems 6:659-674.

Oelsner, G. P., P. D. Brooks, and J. F. Hogan. 2007. Nitrogen Sources and Sinks Within the Middle Rio Grande, New Mexico. JAWRA Journal of the American Water Resources Association 43 (4):850-863.

Pielke, R., R. Avissar, M. Raupach, J. Dolman, X. Zeng, and S. Denning. 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Global Change Biology 4 (5):461-475.

Poeter, E. 2007. All Models are Wrong, How Do We Know Which are Useful? Ground Water 45 (4):390-391.

Postel, S., and B. Richter. 2003. Rivers for Life: Managing water for people and nature. Island Press, Washington.

Rhoades, B.L., 1995, Stream power: a unifying theme for urban fluvial geomorphology,in: Herricks, E.E., (ed) Stormwater Runoff and Receiving Systems Impact,monitoring, and assessment, CRC Press,Boca Raton, FL.

Savini, J., and Kammerer, J.C., 1961, Urban Growth and the Water Regimen: U.S.Geological Survey Water Supply Paper 1591-A, 39p

Sauer, V.B., Thomas, W.O., Strieker, V.A., and Wilson, K., 1983, Flood Characteristics of Urban Watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 36 p.

Schuster, W.D., Bonta, J., Thurston, H., Wamemuende, E., and Smith, D.R., 2005, Impacts of Impervious surface on watershed hydrology - a review: Urban Water Journal, v.2(4)p. 263-275.

Serengil, Y., F. Gökbulak, S. Özhan, A. Hizal, K. Sengönül, A. Nihat BalcI, and N. ÖzyuvacI. 2007. Hydrological impacts of a slight thinning treatment in a deciduous forest ecosystem in Turkey. Journal of Hydrology 333 (2-4):569-577.

Shi, X. G., et al. (2008), How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting?, Journal of Hydrometeorology, 9(6), 1350-1363.

Shuttleworth, W. J. (1993), Evaporation, in Handbook of Hydrology, edited by D. R. Maidment, pp. 4.1-4.53, McGraw-Hill, Inc., New York.

Singh, V.P., 1995 (ed), Computer Models of Watershed Hydrology: Water Resources Publications, Highlands Ranch.

Singh, V.J., and Frevert, D.K., 2006 (eds), Watershed Models: Taylor and Francis, New York.

Silvert, William. 2001. Modelling as a Discipline. Int. J. General Systems 30: 261-282. A Polish translation was published in the "Projektowanie i Systemy" volume XVII in 2004.

Sloenecker, E.T., and Tilley, J.S., 2006, An assessment of Impervious-surface Measurement Methods, in: Acevedo, W., et al. (eds) Rates, Trends, Causes, and Consequences of Urban Land-use Change in the United States: U.S. Geological Survey Professional Paper 1726, pp.65-78.

Smakhtin, V. U. 2001. Low flow hydrology: a review. Journal of Hydrology 240 (3-4):147-186.

Snyder, F.F., 1938, Synthetic Unit Hydrographs: Transactions of the American Geophysical Union, v.l9(l)p.447-454.

Stamm, J. F., E. F. Wood, and D. P. Lettenmaier. 1994. Sensitivity Of A GCM Simulation Of Global Climate To The Representation Of Land-Surface Hydrology. Journal of Climate 7 (8):1218-1239.

Su, F. G., et al. (2005), Streamflow simulations of the terrestrial Arctic domain, J. Geophys. Res.-Atmos., 110(D8).

Todini, E. 1996. The ARNO rainfall-runoff model. Journal of Hydrology 175 (1-4):339-382.

Toon, O. B. 2000. Atmospheric science - How pollution suppresses rain. Science 287 (5459):1763.
Turner, M.G., O'Neill, R.V., Gardner, R.H., and Milne, B.T., 1989, Effects of changing spatial scale on the analysis of landscape pattern: Landscape Ecology, v.3(3-4)p.l53-162.
Van Genuchten, M.T., 1991, Progress and opportunities in hydrologic research, 1987- 1990: Reviews in Geophysics, v.25, p.189-192.
Verry, E. S. 1986. Forest harvesting and water: the Lake States experience. Water Resources Bulletin 22 (6):1039-1047.
Vice, R.B., Guy, H.P., and Ferguson, G.E., 1969, Sediment Movement in an Area of Highway Construction, Scott Run Basin, Fairfax County, Virginia, 1961-64: U.S. Geological Survey Water Supply paper 1591-E, 41 p.
Vogel, R. M., and N. M. Fennessey. 1995. Flow Duration Curves Ii: A Review Of Applications In Water Resources Planning . Journal of the American Water Resources Association 31 (6):1029-1039.
Vogelmann, J.E., S.M. Howard, L. Yang, C.R. Larson, B.K. Wylie, and J.N. Van Driel, 2001A. Completion of the 1990's National Land Cover Data Set for the conterminous United States, Photogrammetric Engineering & Remote Sensing 67:650–662.
Vörösmarty, C.J., B. Moore III, M.P. Gildea, B. Peterson, J. Melillo, D. Kicklighter, J. Raich, E. Rastetter, and P. Steudler. 1989. A continental-scale model of water balance and fluvial transport: Application to South America. Global Biogeochemical Cycles 3: 241-65.
Vörösmarty, C.J., P. Green, J. Salisbury, R.B. Lammers. 2000. Global water resources:vulnerability from climate change and population growth. Science 189: 284-288.
Vrugt, J. A., H. V. Gupta, S. C. Dekker, S. Sorooshian, T. Wagener, and W. Bouten. 2006. Application of stochastic parameter optimization to the Sacramento Soil Moisture Accounting model. Journal of Hydrology 325 (1-4):288-307.
Wardlow, B. D., & Egbert, S. L. (2003). A state-level comparative analysis of the GAP and NLCD land-cover data sets. Photogrammetric Engineering & Remote Sensing, 69 (12), 1387–1397.
Wagener, T., and H. S. Wheater. 2006. Parameter estimation and regionalization for continuous rainfall- runoff models including uncertainty. Journal of Hydrology 320 (1-2):132-154.
Werkhoven, K., T. Wagener, P. Reed, and Y. Tang. 2008. Characterization of watershed model behavior across a hydroclimatic gradient. Water Resour. Res. 44 (1):W01429.
Wickham JD, Stehman SV, Fry JA, Smith JH, Homer CG (2010) Thematic accuracy of the NLCD 2001 land cover for the conterminous United States. Remote Sens Environ 114:1286–1296
Wigmosta, M. S., et al. 1994, A Distributed Hydrology-Vegetation Model For Complex Terrain, Water Resour Res, 30(6), 1665-1679.
Williams J.R., A.D. Nicks, & J.G. Arnold. Simulator for Water Resources in Rural Basins. ASCE Hydr. Div. III(6):970-986. 1985.
Williamson, T. and K.R. Odom. 2007. Implications of SSURGO vs. STATSGO data for modeling daily streamflow in Kentucky. In ASA-CSSASSSA 2007 International Annual Meetings. New Orleans, LA.
Willmott, C. J. (1981). On the validation of models. Physical Geography, 2(2), 184–194.
Winter, T. C. 2001. The Concept Of Hydrologic Landscapes . Journal of the American Water Resources Association 37 (2):335-349.
Wood, E. F., D. P. Lettenmaier, and V. G. Zartarian. 1992. A Land-Surface Hydrology Parameterization With Subgrid Variability For General-Circulation Models. Journal of Geophysical Research-Atmospheres 97 (D3):2717-2728.

Yang, X. J., and Z. Liu. 2005. Using satellite imagery and GIS for land-use and land-cover change mapping in an estuarine watershed. International Journal of Remote Sensing 26 (23):5275-5296.

Zhang, Z., V. Koren, S. Reed, M. Smith, F. Moreda. 2006. Comparison of simulation results using SSURGO-based and STATSGO-based parameters in a distributed hydrologic model. In Third Federal Interagency Hydrologic Modeling Conference. Reno, NV.

Zhao, R.-J., et al. 1980, The Xinanjiang model, Hydrological Forecasting Proceedings Oxford Symposium, IASH 129, 351-356.

Zhao, W. W., B. J. Fu, O. H. Meng, Q. J. Zhang, and Y. H. Zhang. 2004. Effects of land-use pattern change on rainfall-runoff and runoff-sediment relations: a case study in Zichang watershed of the Loess Plateau of China. Journal of Environmental Sciences-China 16 (3):436-442.