

# Baseflow signatures of Sustainable Water Resources

An Analysis of Maryland Streamflow

## **FINAL REPORT**

Prepared for the Hughes Center for AgroEcology

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September 2011  
Revised September 2012

## Acknowledgements

The authors gratefully acknowledge the support from the Hughes Center for Agroecology that made this work possible. The exceptional efforts of Sarah Taylor-Rogers in navigating logistic, administrative, and grants management mazes with characteristic grace and good humor are gratefully acknowledged. This work was motivated and built upon work on the fragmentation of Maryland's working lands and we acknowledge the generous contribution of Dr. Bernadette Hanlon in its development. The final analysis benefited from thoughtful comments and careful review by three external reviewers whose comments and suggestions significantly improved the final manuscript. At the Center for Urban Environmental Research and Education where every project is a special case, we acknowledge the dedicated effort of Amy Rynes in navigating grants routing and approval, and Sabrina Strohmeir's assurance of reliable grants management and accounting.

Producing figures in this report (specifically plots of the Kendall Tau surfaces) that retained their fidelity, resolution, and clarity in both digital and hardcopy proved to be a significant challenge. The final figures contained in this report were generated in a vectorized format that can be accurately viewed and enlarged in digital format. Readers interested in carefully extracting trend information for individual years from the Kendall tau surfaces are encouraged to zoom into these figures in the digital version of this document and its appendices.

The intellectual pedigree of this work is grounded in the enthusiasm, delight, and essential need for interdisciplinary policy-relevant research inspired by the late Red Wolman. Those who had the privilege of knowing him are richer for the experience and poorer for his passing.

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## Abstract

Increasing trends in suburban and exurban development are fragmenting Maryland's agricultural and forested lands, amplifying the cumulative stresses on the State's water resources. This project developed methods to evaluate the effects of landscape fragmentation on the sustainability of Maryland's water resources through regional analysis of low flow characteristics of gauged stream flow. A consistent set of heuristic baseflow metrics, representing hydrologic and hydraulic characteristics of baseflow response, provided a multimetric signature of human alteration of Maryland's water resources. The methods developed in this project demonstrate clear consistent insights into the interaction of human activities and sustainable water resources, and are directly transferable to other gauged watersheds of the Chesapeake Bay watershed. Where available, streamflow information can provide a rich reliable diagnostic tool to quantify human impacts to the hydrologic system and the baseflow signatures of sustainable water resources.

## Executive Summary

### Baseflow Signatures of Sustainable Water Resources

#### Overview

Increasing trends in suburban and exurban development are fragmenting Maryland's agricultural and forested lands, amplifying the cumulative stresses on the State's water resources. This project developed methods to evaluate the effects of landscape fragmentation on the sustainability of Maryland's water resources through regional analysis of low flow characteristics of gauged stream flow.

***Baseflow Metrics*** Multimetric baseflow indices were developed and applied to USGS streamflow records to derive consistent quantitative measures of baseflow characteristics. Baseflow characteristics from developed watersheds and watersheds with minimal human influence (the USGS Hydroclimatic Data Network<sup>1</sup> or HCDN) demonstrated a multimetric fingerprint of human hydrologic alteration. Along a rural to urban gradient, multimetric baseflow analysis of Piedmont streams in Central MD revealed clear endpoints, identifiable as rural forest and agricultural watersheds, and urban watersheds. These endpoints bounded the response of intermediate mixed and developing watersheds, as well as the HCDN gauges in the Piedmont of Chesapeake Bay.

Multimetric fingerprinting also distinguished hydrologic changes – (changes in runoff and recharge) from hydraulic changes (changes in the hydraulic *response* of aquifer drainage). Characteristics of quickflow and slowflow derived from USGS streamflow records revealed clear signatures of hydrologic alteration along the rural to urban landuse gradient in the watersheds of the Baltimore Ecosystem Study<sup>2</sup> (an NSF Urban Long Term Ecological Research site in the Baltimore Metropolitan area).

- Taken together, **multiple baseflow indices provide a more refined characterization of changes in the dominant hydrologic processes resulting from urban/suburban land transformation than single metrics such as the baseflow index or estimated recharge.**

***Baseflow Trend Analysis***- Trend analysis of multiple baseflow metrics further elucidated the baseflow signatures of human hydrologic alteration. We developed and implemented robust trend analysis using consistent non-parametric tests for *all feasible sub-periods* within the period of record of *every gauged watershed in Maryland* for which sufficient data are available. These multi-metric trend analyses enabled us to distinguish significant trends that were dominated by anomalous extreme events (such as the drought of the 1960s) from long-term persistent secular shifts in baseflow characteristics, controlling for hydrometeorological variability.

- For Maryland's urban/suburban watersheds, we consistently found **highly significant decreasing trends in the fraction of annual streamflow attributed to baseflow (i.e. the**

<sup>1</sup> HCDN: <http://water.usgs.gov/GIS/metadata/usgswrd/XML/hcdn.xml>

<sup>2</sup> BES: <http://beslter.org/>

**baseflow index or BFI) closely associated with the period of maximum historical urban/suburban development.**

Declining baseflow is consistent with traditional expectations that suburban land conversion increases runoff and decreases infiltration, recharge, and hence baseflow. Remarkably, many of Maryland's suburban watersheds with declining BFI trends also showed consistent *increasing* trends in baseflow, recharge and surface runoff. This apparent paradox resulted from baseflow trends that increased *less than* the increase in discharge, yielding a smaller fraction of annual discharge derived from baseflow and thus a lower BFI. The combination of declining BFI and increasing discharge and baseflow trends suggests the signature of interbasin transfers through leaky infrastructure and return flows in altering the urban water budget. We found consistent *differences* in baseflow characteristics identified through hydrologic baseflow metrics (BFI, recharge etc.) and hydraulic metrics (baseflow recession constant,  $K_b$ ), strongly validating a multimetric approach to diagnose baseflow changes. One postulated effect of urban/suburban land transformation is a hydraulic response associated with infiltration and inflow to storm sewers.

- **At the watershed scale captured in Maryland's stream gauge network, *we found no significant evidence of hydraulic changes in baseflow response due to suburban land transformation.***

### Findings

Observed baseflow response to land transformation is more complex than traditional conceptual models, with confounding signals from interbasin transfers (of both drinking water and wastewater); changes in effective drainage (from infiltration and inflow to sewer systems); and hydroclimatic variation.

- Where high quality long-term streamflow records are available, multimetric baseflow analysis (combining non-parametric trend analysis and controls for hydrometeorological forcings and non-stationarity) provides a robust cost-effective tool to characterize Maryland's water resources.
- Within the existing Maryland stream gauge network we found no watersheds in which exurban fragmentation represented the *dominant* watershed-scale landuse change. For the streamflow records available in Maryland, a quantitative estimate of the specific hydrologic effect of exurban fragmentation could not be uniquely distinguished from the other dominant processes affecting observed streamflow.
- Landsat images did not correspond to – and were generally unavailable for- historical periods with the most significant changes in baseflow characteristics. MD Property View data provided useful information quantifying the watershed-scale development history of Maryland's landscapes.

- Hydrometeorological water balances at the scale of Maryland's climate divisions captured the dominant hydrometeorological forcings in Maryland streamflow, enabling the inherent hydroclimatic signal in baseflow to be distinguished from non-climatic forcings (such as the effects of land transformation and water infrastructure).
- Clear non-stationarity was identified in the stream record from Seneca Creek at Dawsonville, one of the reference gauges used by MDE for groundwater allocation. Ironically, both baseflow and streamflow for Seneca Creek showed a strong statistically significant increasing trend. This "apparent" increase in groundwater availability (as MD currently allocates its groundwater resources) is associated with increases in the discharge of treated wastewater from municipal supply originating outside the basin, combined with the operation of Little Seneca Reservoir for minimum instream flows.

### Significance

This analysis is targeted for the use of operational and regulatory water resource managers making risk-based decisions about the sustainability and appropriation of limited water resources impacted by human modification. The results have direct applicability and significance for the current regulatory approach to ground water appropriation in the State of Maryland. Current regulatory practice relies on recharge estimated from gauged streamflow. Non-stationarity of reference gauges used for this purpose suggests the need to revisit these regulatory resource assessments. The ability of multimetric trend methods developed in this project to distinguish human alteration of baseflow characteristics (including effects from infrastructure and interbasin transfers) identifies a regulatory paradox in allocating groundwater resources. In watersheds that may have significant "artificial recharge" from leaking water infrastructure, the decoupling of heuristic baseflow (derived from gauged streamflow), from the functional recharge of groundwater, highlights the *limitations* of streamflow analysis alone. The limitations and potential risks from appropriating groundwater based only on the characteristics of observed streamflow highlight the value of a more process-based understanding of Maryland's coupled surface water- groundwater resource.

The methods developed in this project demonstrate clear consistent insights into the interaction of human activities and sustainable water resources, and are directly transferable to other gauged watersheds of the Chesapeake Bay watershed. Where available, streamflow information can provide a rich reliable diagnostic tool to quantify human impacts to the hydrologic system and the baseflow signatures of sustainable water resources.



## Introduction

Increasing trends of “rural suburbanization” – exurban development and suburban residential development in previously rural landscapes- are fragmenting Maryland’s agriculture and forested lands. This land transformation alters the sustainability of water resources by (a) altering the hydrologic response of the land via changes in vegetation, impervious landcover, and drainage; (b) increasing withdrawals from surface and groundwater to support increased demands; and (c) altering the hydrologic cycle via water and wastewater infrastructure that can alter both recharge and subsurface drainage. Collectively these effects can interact to amplify the cumulative stresses on the State’s water resources.

This project evaluated the effects of land transformation and fragmentation on the sustainability of water resources using regional low flow analysis of gauged streamflow. Linking regional low flow characteristics to spatial patterns and trends in land transformation could establish benchmark sustainability measures for managing the growing competition for the State’s limited water resources.

### 1. Background

#### Maryland’s Working Lands –

Hanlon et al. [1] have documented the expansion of urban-suburban lands in Maryland – largely at the expense of Maryland’s working lands. For example, from 1986-2001 Montgomery County lost approximately 21,000 acres of agricultural/open land and 15,000 acres of forest. Nearly one quarter of the statewide decline in farmland between 1978 and 2002 occurred in the Washington, DC area with 72,000 acres lost in Montgomery and Prince Georges County alone. Despite the growth boundary defined by its Urban Rural Demarcation line, Baltimore County lost 42,000 acres of working lands, with 95,000 acres lost in Southern Maryland during this same period. Beyond the loss of Maryland’s working lands, Hanlon et al. [1] identified the likely predictors of future land transformations. The innovative combination of the MdProperty View database and processing of LANDSAT imagery identified the fragmentation of Maryland’s working lands as a key predictor of the probability of working land urbanization. This quantitative risk of conversion, complements the relative vulnerability estimates and amplifies the significance the Chesapeake Bay Program’s Resource Lands Assessment.

#### Maryland’s Water Resources.

Growing competition for the State’s limited water resources was dramatically highlighted by the droughts of 1999 and 2002, and continuing constraints on accelerating growth including current water supply limitations on development in Westminster, and growing interest and feasibility analysis of desalination to expand increasingly strained water supplies. The hydrologic impact of urban and suburban development is increasingly recognized [2-5] although the complex interactions of land transformation, water withdrawals and water infrastructure can be highly variable [6, 7] and are not well understood. Older cities with aging water infrastructure may experience significant increases in recharge due to leaking water mains [8-10]. Nevertheless the need for more systematic evaluation of water resource sustainability is pressing, clearly recognized, and unequivocally recommended by the Governor’s Advisory Committee on the Management and Protection of the State’s Water Resources.

### Sustainability – A Policy Decision

Reconciling regional water balances is central to policy formation to resolve the sustainability of Maryland's regional water resources - and the goals of this project. The water balance reflects the dynamic steady state of the hydrologic cycle in which hydrometeorological fluxes are filtered and transformed by land surfaces processes. Historically, closure of the water budget - balancing inputs and outputs- led to an operational criterion considering groundwater withdrawals as *sustainable* as long as they did not exceed recharge. This view of sustainable groundwater exploitation has been widely operationalized as a groundwater "safe yield", more recently coming to be referred to as the "Water Budget Myth" [11-14] . From a systems perspective we recognize the need to manage groundwater and surface water as a single resource. The hydrologic fluxes and natural variability of the water balance are, by definition "fully allocated" between evapotranspiration (ET) , lateral flow, recharge, surface runoff, etc. No new demand can be accommodated without altering some of these fluxes. Sustainable water appropriations must therefore be viewed not as a "zero impact" withdrawal, but in terms of *acceptable* impacts – i.e. acceptable degradation of the baseline allocations of precipitation and groundwater storage to runoff, ET, infiltration, recharge, and baseflow discharges from groundwater. Thus any alteration of hydrometeorological fluxes must propagate through the water balance, motivating our focus on the baseflow signature of sustainability in Maryland's water resources.

### *Sustainability and Reliability*

In the broadest sense the sustainability of Maryland's water resources will be defined by the ability to meet both human and ecosystem demands for vital water-based services: potable, sanitary and firefighting uses, commodity uses of water in commercial and industrial activities, cooling water for industrial processes, manufacturing and electric power generation, dry-land and irrigated agriculture, and instream flows and ecosystem services. The sustainability challenge is to match supplies and demands in time and space, with acceptable impacts among uses. The sustainability of water resources is directly linked to the reliability with which the demands for water can be satisfied. Increased pressure on limited supplies threatens sustainability through both shortages – decreased reliability- and through increased competition to appropriate growing shares of a limited supply.

Sustainability also has substantial economic and equity dimensions as increased appropriations of surface water supplies reduce the resilience of the system for all users. Diversions of both potable supply and stormwater alter regional water budgets, lower groundwater tables and impair the broad reliability of Maryland's supplies. Supplies may also be enhanced – at cost- through interbasin transfers, technologies for the recycling and reuse, and ultimately desalination of brackish groundwater and estuarine surface water supplies and aggressive treatment and reuse of wastewater. Given these economic alternatives, sustainability is not simply a hydrologic metric such as "safe yield". Rather, the hydroclimatic reliability of Maryland's surface and groundwater supplies is essential – but not sufficient - information supporting sustainable policies to manage Maryland's water resources and allocate the services these resources provide while equitably allocating the risks and consequences of shortage.

### Prior Work

Though naturally well-endowed and long viewed as a water-rich region, demographic trends, land fragmentation [1] and the Chesapeake Bay Program Resource Land Assessment's (RLA) identification of vulnerable lands, highlight growing challenges to the sustainability of Maryland's water resources. Recent drought emergencies, limitations on water use appropriations, and serious exploration of desalination to expand water supplies highlight the growing competition for Maryland's water resources and the need to quantify and manage the sustainability of finite water supplies [15]. Regional water resource assessments are best based on full evaluation of the dynamic regional water balance, for which regional baseflow provides an integrative signature [16-20]. A number of automated algorithms for "baseflow separation" provide consistent automated estimates of the fraction of runoff derived from baseflow (baseflow index, or BFI) using long-term stream monitoring records [21-25]. These heuristic estimates of runoff components are often referred to as 'quickflow' and 'slowflow' to emphasize their identification with respect to the time scale of response, rather than the source or hydraulic mechanism of their origin. Though heuristic, these consistent measures of slowflow can be analyzed regionally and used to estimate groundwater recharge [26-29], for low flow prediction [30, 31], estimating flow statistics at ungauged watersheds [19, 32, 33], and related to regional geology, topography and other basin characteristics [26, 34, 35].

In combination with hydraulic groundwater theory, careful analysis of baseflow recessions can also provide estimates of the effective parameters, storage, and response times of regional groundwater systems [36-40]. For an unconfined aquifer, idealized Dupuit-Boussinesq aquifer theory predicts the nonlinear decline of the water table due to drainage to a fully penetrating stream, as well as a sharp predictable change in the rate of decline when the drawdown of the water table is extensive enough to be affected by the groundwater drainage divide (*sensu* Brutsaert and Nieber [35]) [35, 36]. This prediction can be tested through recession analysis from observed streamflow records [41-46] and even used to estimate storage half-lives for regional aquifers [36]. Beyond hydraulic analysis, the use of stream chemistry, including isotopes [47-50], and conservative solutes [50-56] and even contaminant transport [57, 58] provide process-based insight into the interaction of surface water and groundwater, and human impacts on the sustainability of water resources [59-61]. Together these tools provide the means to assess the signature of development and early warning indicators of declining water resource sustainability, through regional investigation of land fragmentation and regional baseflow characteristics.

The following section provides a background on baseflow analysis and the complex interacting effects of human landscape modification on baseflow response, with a more detailed description of the baseflow indices derived from gauged streamflow that are used in this work. Section 2 examines multiple baseflow metrics as consistent quantitative measures of baseflow characteristics from developed watersheds and watersheds with minimal human influence (the USGS Hydroclimatic Data Network<sup>3</sup>). The endpoints and multimetric pattern of baseflow response along a rural-to-urban gradient of the watersheds of the Baltimore Ecosystem Study<sup>4</sup>

<sup>3</sup> HCDN: <http://water.usgs.gov/GIS/metadata/usgswrd/XML/hcdn.xml>

<sup>4</sup> BES: <http://beslter.org/>

(an NSF Urban Long Term Ecological Research site in the Baltimore Metropolitan area) is examined in section 3. Section 4 develops robust consistent methods for the analysis of trends in multiple baseflow metrics. Nonparametric trend analyses is used to distinguish significant trends that were dominated by anomalous extreme events (such as the drought of the 1960s) from long-term persistent secular shifts in baseflow characteristics, providing a framework to control for hydroclimatic variability. Section 5 discusses the significance of these analyses and the implications for their use in sustainable management of Maryland water resources. The findings and results of this work are summarized in Section 6 with conclusions for the sustainable management of MD's water resources.

## 2. Baseflow Metrics

### 2.1 Methodology

Low flow characteristics of gauged streamflow were used to characterize basin response for Maryland's coupled groundwater-surface water resources. The analysis of low flow basin response is grounded in applied methods of estimating groundwater recharge using data from stream gauges. Multiple methods of regional hydrologic analysis are used to establish baseline signatures of sustainable water resources using streamflow records from Maryland's HydroClimatic Data Network (HCDN) stations [62]. Tiered analysis of the HCDN station records use (i) automated baseflow separation to derive the empirical baseflow index (BFI) [21, 42, 43, 63-65]; (ii) physically based dimensionless baseflow recession constants [20, 29, 66]; (iii) gauge-based recharge estimated using recession curve displacement [67-69]; and (iii) water balance fluxes estimated with a simple one-layer soil moisture accounting model used in operational forecasting at the National Centers for Environmental Prediction [70]. Kroll et al. [16] have shown that the hydrogeologic indices used here consistently improve regional estimation of low flow statistics in all regions of the country, bolstering their potential to consistently elucidate changing response to land transformation.

Our original study plan framed the analysis of Central Maryland streamflow characteristics, with a second growth area (such as southern Maryland or the Maryland Eastern Shore) to be selected in consultation with regional water resource managers. As the project evolved we automated much of the streamflow analysis, enabling us to perform consistent multimetric analysis for all Maryland stream gauges for which sufficient data are available (summarized in Appendix 3. This consistent characterization of Maryland's gauged streamflow enables us to identify watersheds with significant distinctive multimetric slowflow fingerprints for further analysis. The following section describes the individual baseflow metrics used in this analysis, framed by heuristic baseflow separation and the characteristics of the "slowflow" signal in gauged streamflow.

### 2.2 Heuristic Baseflow Separation

Baseflow separation and recession analysis are widely used in the analysis of event runoff, recharge estimation, low flow forecasting, hydrogeologic parameter estimation, hydrologic model calibration, and the identification of source areas and dominant processes producing runoff. Traditional engineering hydrology utilizes baseflow separation in the analysis of storm hydrographs and the transformation of effective precipitation to runoff with a unit hydrograph (Chow 1964). In this context, baseflow separation refers to the disaggregation of quick flow (generally interpreted as surface runoff) from slow flow (interpreted as subsurface flow or drainage from groundwater). Conventional distinctions between surface runoff and baseflow (as groundwater discharge) reflect a process-based interpretation of flow components. Quickflow and slowflow in contrast, refer to relative time constants for characteristic components of observed basin-scale response. Interpretations of "old water" and "new water" imply distinct origins for sources of discharge, differentiating precipitation inputs and direct runoff from pre-storm water that has been resident in the subsurface. These source differences may be manifested in differential chemical signatures of streamflow and precipitation.

The relationships among these commonly employed conceptualizations are not unique. Baseflow is varyingly conceptualized as drainage from a saturated aquifer [71], discharge from groundwater and other delayed sources [72, 73], and basin-scale drainage under conditions of no recharge. [28, 74, 75]. Quick flow (reflecting characteristic hydrograph response time) can be dominated by subsurface flow (reflecting source origins of observed flow) [29, 34, 74] with the chemical signature of old water [76-78]. Rapid response of through flow, [34] as well as the intermediate response of interflow [71], blur operational inferences of basin response based on gauged streamflow. This ambiguity led Hall [73] to conclude:

*“baseflow should either be defined in a meaningful way, or the term should be abandoned and the same should be done for what is commonly called interflow. A more useful way of defining the hydrograph might be in terms of the delay or lag times of the components, without implication of origin”*

In general the unique flow paths, dominant flow processes, and sources of runoff in a particular basin cannot be unambiguously identified from the analysis of the discharge hydrograph alone [34]. The expanding set of analytical tools for baseflow separation includes the use of stream chemistry, environmental isotopes, and hydraulic groundwater theory. The variety of separation algorithms reflects differences in both the conceptualization and intended uses of derived baseflow. For example, Hall [73] notes that recession analysis for low flow forecasting should not be confused with analysis to understand groundwater flow regimes. Anderson and Burt [34] similarly observe that graphical separation for low flow forecasting has limited value as an indicator of flow processes. The growing suite of baseflow separation techniques (reflecting diverse applications and formulations) nevertheless remains useful when applied in context and properly matched to the intended application.

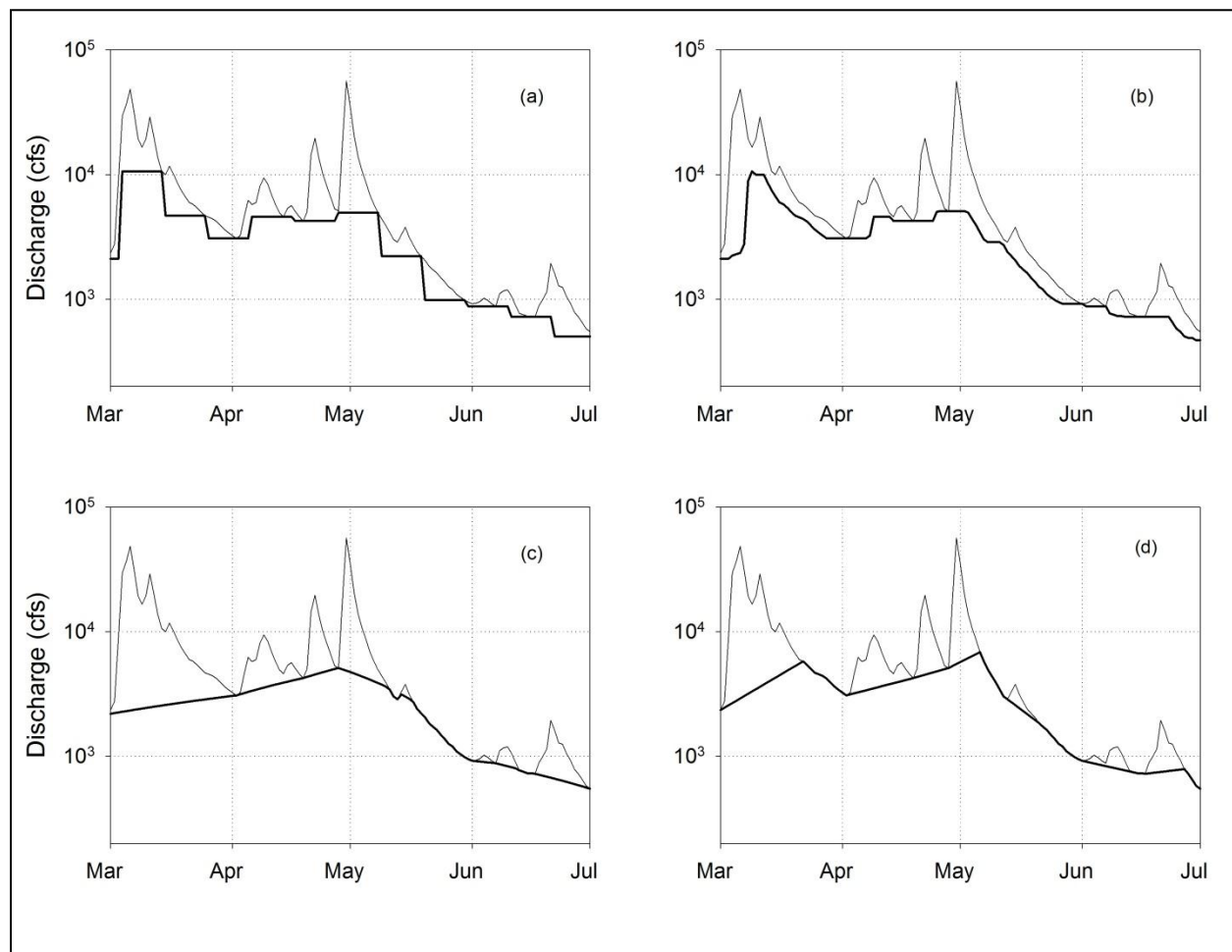
### 2.2.1 Automated Heuristic Baseflow Separation

The subjective nature of graphical baseflow separation along with the utility of baseflow time series derived from continuous gauge records motivates the interest in techniques to automate heuristic baseflow separation. Most automated baseflow separation algorithms are neither constructed nor intended to disaggregate or identify the unique processes, sources, or flow paths contributing to streamflow. These techniques are primarily employed to derive a consistent reproducible estimate of slowflow from gauged streamflow. They have in common the absence of calibration against “observed baseflow”, and are primarily judged subjectively by the “reasonableness” of the resulting baseflow time series. They use no information about hydrologic fluxes (e.g. precipitation, evapotranspiration) other than gauged streamflow data, and make no assumptions regarding the relative timing of the baseflow and runoff peaks. Nor do they impose any physically-based structure on the functional form of the recession hydrograph as in Vogel and Kroll [20], Brutsaert and Lopez [36] or Szilagyi and Parlange [43]. Nevertheless the rapid consistent separation of slowflow from stream hydrographs has utility in basin-scale studies of seasonal and interannual water balances, recharge estimation, hydrologic model calibration, and regional low flow analysis. Five automated baseflow separation algorithms, described by Sloto and Crouse [21], Rutledge [79], and Nathan and McMahon [22] were

automated, implemented, compared, and used to characterize heuristic baseflow from Maryland's stream gauge records.

### 2.2.2 USGS Baseflow Separation Algorithms

Sloto and Crouse [21] describe three algorithms to automate heuristic baseflow separation from streamflow records. These algorithms and their automated implementation in the MATLAB programming environment are described in detail in Appendix 1. Appendix 1 also describes the USGS PART algorithm [79] and its implementation for heuristic baseflow estimation. Figure 1 contrasts heuristic baseflow separation by the four USGS algorithms for the spring and summer of 1964 for the Potomac River at Hancock [65].



**Figure 1** Heuristic Baseflow separation (a) Fixed Block; (b) Sliding Block; (c) Sliding Minimum; (d) PART

### 2.2.3 Digital Filter

The so-called digital filter [22] (Nathan and McMahon 1990) is used to heuristically separate quickflow  $q_q(t)$  from observed discharge,  $Q_t$ , as:

$$\begin{aligned} q_q(t) &= \alpha q_q(t-1) + \frac{(1+\alpha)}{2} [Q_t - Q_{t-1}] \\ q_b(t) &= Q_t - q_q(t) \end{aligned} \quad (1)$$

with the constraints:

$$0 \leq q_b(t) \leq Q_t \quad t = 1, 2, \dots, T \quad (2)$$

Nathan and McMahon [22] recommended estimating the baseflow time series by filtering the observed streamflow time series with three successive passes of (1) using a recommended filter parameter of  $\alpha = 0.925$ . They note the phase shift introduced by each pass of the discrete filter, and implement the second pass of the filter running backwards from time  $t = T-1, T-2, \dots, 2, 1$ , to offset this effect.

The digital filter is commonly interpreted as filtering the high frequency response of quickflow from the low frequency response of baseflow. While baseflow has a low frequency response, Spongberg [24] observes that quickflow is not just a high frequency signal, but rather a white noise pulse. The broad spectrum frequency content of quickflow includes low frequency components common to baseflow. For this reason filtering to remove quickflow (including its low frequency components) will also remove some of the overlapping frequency response of baseflow. Spongberg [24] also notes that while the filter (1) introduces a phase shift as described by Nathan and McMahon [22], reversing the direction of successive filter passes does not completely correct this phase shift, due to the intermediate differencing between successive passes. Spongberg [24] considered the subjective tradeoffs between the choice of filter parameter and the number of filter passes, recommending fewer filter passes -to minimize phase distortion- with a larger filter parameter.

Although automated separation algorithms have most frequently been evaluated by comparison to manual or graphical baseflow estimates, several studies compare automated separation to baseflow estimated from field observations [55, 77]. Arnold et al. [80] compared baseflow separation with the digital filter to field estimates from six well instrumented temperate climate watersheds. The observed fraction of baseflow in annual discharge was estimated from groundwater monitoring wells using empirical stage-discharge curves. The fraction of annual discharge observed as baseflow was found to consistently lie between the values estimated from the first and second passes of the digital filter. For this reason, Arnold et al. (1995) used only 1 pass of (1) to automate baseflow separation used to estimate groundwater recharge with the Rohrbaugh [81] method.



The digital filter, like the techniques in Sloto and Crouse [21] and Rutledge [79], has proven useful and reliable even though the resulting baseflow does not exhibit exponential recession or any inherent structure (such as log-linear recession). The lack of “calibration” or other intervention makes these algorithms particularly useful for regional studies that require consistent reproducible comparisons between basins. Nathan and McMahon [22] observe that the digital filter generally yields heuristic baseflow time series that appear “realistic” (in conforming to our intuitive idea of what a baseflow time series *should* look like).

Although three passes of the digital filter were recommended by Nathan and McMahon [22], the pragmatic choices of one pass by Arnold et al. [26], or two passes recommended by Spongberg [24] highlights the need to match baseflow separation algorithms to the intended application. This variability reinforces Nathan and McMahon’s [22] observation that:

*“Hydrograph separation techniques based solely on the analysis of streamflow hydrographs are inherently arbitrary in nature, and without field observation data the true base flow contribution cannot be confidently determined.”*

Though consistent and reproducible, each algorithm engenders a subjective abstraction of baseflow.

### 2.3 Tiered Low Flow Analysis

As uniformly recommended in the analysis of groundwater recharge [82] we use multiple low flow metrics derived from gauged streamflow to detect and characterize changes in the water balance affecting recharge and groundwater sustainability. Heuristic baseflow separation is commonly used to compute the baseflow index (BFI) and graphical baseflow recession constant  $K$  ( $dt / d(\ln(Q))$ ) with the interpretation of the time for baseflow to decrease by one log cycle. We automate these common procedures as well as the computation of Vogel and Kroll’s [66] recession constant  $K_b$ , and recession displacement estimation of recharge after the USGS RORA algorithm.

#### 2.3.1 Baseflow Index (BFI)

The simplest estimate of groundwater recharge from streamflow data derives from the baseflow index (BFI). Under long-term dynamic steady state conditions the expected value of groundwater storage is unchanging, and groundwater inflow and outflow are in balance. If lateral flow and ET from groundwater are negligible, long-term recharge is approximately equal to long-term baseflow [63, 69]. Automated algorithms for heuristic baseflow separation yield time series of daily baseflow, from time series of daily streamflow. The ratio of baseflow to total discharge is referred to as the baseflow index (BFI) and offers an initial estimate of regional baseflow characteristics and long-term average recharge. The BFI for the HCDN gauge records then represents a baseline recharge estimate, that can be compared with similar BFI computations for locations and time periods experiencing the loss of agricultural and forest lands due to rural suburbanization. The gauge-derived BFI lends itself to regionalization [83, 84] and Wolock [64] has derived a national digital map of BFI—at 1km resolution. This approach to estimating regional recharge has been refined by Szilagyi [63], with an energy-balance estimate

of ET, to estimate long-term recharge for the State of Nebraska. For the full set of Maryland stream gauges considered in this report, BFI values were computed and compared using each of the heuristic baseflow separation methods described above. The results (summarized in Appendix 3) show small but consistent differences in the relative magnitude of estimated BFI, with values generally lower for the digital filter and higher for PART. For consistency and computational efficiency, the BFI results presented here are computed using the third pass of the digital filter as described by Nathan and McMahon [22].

### 2.3.2 Recession Analysis ( $K_b$ ) Hydraulic baseflow

The steady state assumption inherent in estimating recharge from BFI avoids the estimation of aquifer parameters such as the effective distance to drainage divide or the recharge area. Of course baseflow estimated from stream gauge observations represents a lower bound on groundwater recharge. The water balance is modulated by both changes in hydrologic fluxes (e.g. precipitation, ET) and soil and aquifer characteristics such as hydraulic conductivity and the volume and release rate of stored groundwater – the dimensionless storativity. Using a conceptual model of recharge and discharge from an idealized aquifer, the “effective” characteristics of aquifer systems may be inferred and estimated from the characteristics of observed baseflow [20, 66] and recession analysis of gauged streamflow. Using the Dupuit-Boussinesq representation of a saturated aquifer draining to a fully penetrating stream, the recession constant  $K_b$  can be related to basin-scale effective aquifer characteristics. For unimpaired recharge, we expect  $K_b$  to provide a regional signature of effective basin characteristics such as soil porosity and hydraulic conductivity. Physical properties of regional flow systems such as hydraulic conductivity and thickness and extent of unconfined aquifers are not normally expected to change with development, thus significant changes in streamflow response are inferred to result from changes in forcings (e.g. infiltration, runoff, ET) representing the baseflow signature of development. Following the notation of Vogel and Kroll [20] consider the Dupuit – Boussinesq unit discharge to a fully penetrating stream (after an initial transient decay of the water table) can be given by:

$$q = \left[ \frac{2kD(D - D_c)}{B} \right] \exp \left[ \frac{-\pi^2 kDt}{4fB^2} \right] \text{ where } k \text{ is hydraulic conductivity, } D \text{ and } B \text{ are}$$

respectively the thickness and breadth of the aquifer, and  $D_c$  is the flow depth in the receiving channel;  $f$  is the drainable porosity of the soil and  $t$  is time after the initial saturation of the aquifer. The unit discharge  $q$  may be extended to the entire watershed to estimate groundwater drainage as  $Q = 2Lq$  where the drainage per unit length of channel,  $q$ , is multiplied by the total length of all streams  $L$ , and doubled to capture drainage to each bank of a stream segment. If  $\alpha$  is the fraction of the total basin drainage area,  $A$ , contributing to baseflow, then the mean breadth (i.e. distance to drainage divide) of the aquifer contributing to a stream can be approximated as  $B = \alpha A / 2L = \alpha / 2d$  where  $d$  is the drainage density (defined as the ratio of total stream length to watershed area). Note that  $\alpha = 1$  implies the coincidence of surface water and ground water drainage basins, while small basins with groundwater discharged from aquifers extending (and recharged) far beyond the surface water drainage divide would imply  $\alpha > 1$ , or would require the aquifer breadth (i.e. distance to the no-flow groundwater boundary) to be estimated independent of drainage density. For a water table parallel to the land surface with slope  $S$ , the water table

depth at the drainage divide can be approximated as  $D \cong SB$ . Assuming low flow stream depth is much smaller than aquifer depth  $D_c \ll D \Rightarrow D - D_c \approx D$ , the watershed-scale groundwater discharge can be estimated as:

$$Q = \alpha k A S^2 \exp\left[\frac{-\pi^2 k S d t}{2 f \alpha}\right] \text{ which can be written in the familiar form } Q = Q_0 K_b^t, \text{ and the}$$

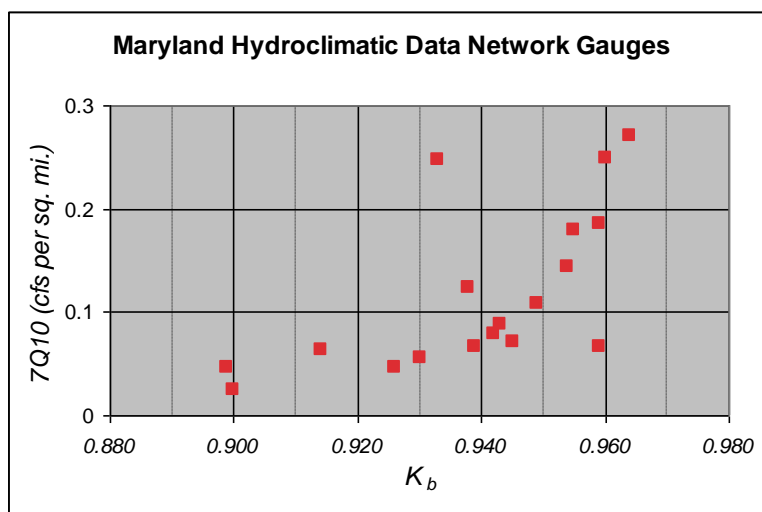
dimensionless baseflow recession constant can be related to physical characteristics of the idealized watershed as  $K_b = \exp\{-\pi^2 k S d / 2 f \alpha\}$ .

*Linear Reservoir Theory* For an idealized aquifer with basin storage  $V$  continuity requires  $dV/dt = I - Q$ , where recharge increases aquifer storage as its inflow, and aquifer discharge supports baseflow (assuming negligible groundwater evapotranspiration). Baseflow recession conditions can be considered as having zero inflow with the discharge related to storage as  $Q = aV^n$ . Then  $dQ/dt = -na^{1/n}Q^{(2n-1)/n} \Leftrightarrow -na^{1/n}Q^b$  where  $b = (2n-1)/n$ . Under the linear reservoir hypothesis  $n = 1 \Rightarrow b = 1$  and  $a = -\ln(K_b)$ . Then in general  $dQ/dt = -aQ$  under conditions of no recharge, and  $\ln[-dQ/dt] = \ln[a] + \ln[Q]$ . Following Vogel and Kroll [20] we estimate these terms from observed discrete streamflow observations using the approximations:  $-dQ/dt = Q_{t-1} - Q_t$  and  $Q = (Q_{t-1} + Q_t)/2$  and average these values over all recession periods to yield:

$\ln[a] \cong \frac{1}{m} \sum_{i=1}^m \ln(Q_{t-1} - Q_t) - \ln((Q_{t-1} + Q_t)/2)$ . Since  $K_b = \exp(-a)$  this gives the operational estimator of the dimensionless recession constant from  $m$  pairs of daily discharge observations during baseflow recession segments of stream gauge records:

$$K_b = \exp\left\{-\exp\left\{\frac{1}{m} \sum_{i=1}^m \ln(Q_{t-1} - Q_t) - \ln((Q_{t-1} + Q_t)/2)\right\}\right\} \quad (3)$$

Values of  $K_b$  have been computed in this way for each of the stream gauge records in the USGS HCDN records reported in Kroll et al. [16]. For the HCDN gauge records in Maryland the 7-day 10-year low flow ( $7Q_{10}$ ) is plotted here versus the baseflow recession constant,  $K_b$ , estimated as in (3) above. To facilitate comparison across widely varying drainage areas, the  $7Q_{10}$  values are normalized by the basin drainage area, and therefore expressed in cfs per square-mile. The strong consistent relationship - even with one conspicuous outlier - with  $7Q_{10}$  increasing nonlinearly with  $K_b$ , illustrates the physically-based information inherent in observed streamflow data, suggesting its utility in consistently characterizing low flow characteristics for these unimpaired flow records.

Figure 2  $K_b$  and 7Q10 for MD HCDN gauges

### 2.3.3 Recession Displacement-

As a check and comparison, groundwater recharge is also estimated with standard recession displacement methods [67, 85]. These methods incorporate comparable Dupuit-Boussinesq assumptions [68], with additional assumptions on the timing and extent of recharge [67]. These well-known traditional methods have been used to characterize recharge from stream records in Mid-Atlantic Appalachian physiographic provinces and the USGS RASA study [69, 86] and compared with a suite of hydrologic measures -as we do- on a well-studied experimental watershed [87] in Pennsylvania. Although the idealized assumptions underlying these methods are infrequently fully realized, they nevertheless offer consistent readily interpreted measures of groundwater fluxes and response that can be meaningfully compared as “effective” basin-scale metrics. Recession displacement methods are traditionally implemented with manual user selection of “representative” recession periods, used to estimate a single empirical recession constant for the watershed. These methods were modified to automate estimation of each watershed baseflow recession constant. The basin-specific recession constant was in turn used to derive consistent recession displacement recharge estimates for every streamflow record in this study. Implementation of the automated algorithm for recession displacement parameterization and computation are described in Appendix 1.

### 2.3.4 Regional Water Balance –

As an added dimension of our tiered hydrologic analysis, the hydrometeorological forcing driving each gauge is estimated from a simple regional water balance at the scale of state climate divisions, maintained at the National Centers for Environmental Prediction (NCEP). Regional baseline water balances are established using the simple 1-d soil moisture model described by Huang et al. [70]. This water balance model is also used by NCEP to track and estimate spatially averaged conceptual soil moisture as part of NOAA’s national soil moisture monitoring system. Model-derived soil moisture estimates yield physically meaningful regional estimates of available soil moisture – independent of the direct effects of landuse change and

infrastructure- and add meaningful forecast skill in NCEP air temperature forecasts (as a predictor of the likely partition of latent and sensible heat) over forecast horizons of several weeks. This simple physically-based soil moisture accounting model provides an independent estimate of the major terms of the regional water balance, independent of direct watershed-specific influences of landuse and infrastructure changes. In this way, the divisional water balance serves as a baseline hydrometeorological reference signal against which systematic anomalies associated with land transformation can be detected.

Together, these hydrologic metrics provide a structured approach to analyze baseflow characteristics from gauged streamflow, enabling us to quantify trends, interventions, and anomalous deviations in basin-scale hydrologic response associated with land transformations.

## Summary

The implementation of these baseflow metrics is described in greater detail in Appendix 1. Baseflow separations using each of the heuristic algorithms was compared for the full set of stream gauges used in this study. Small systematic differences among the methods were consistently observed –as expected and reported elsewhere- but these differences were not significant for our use of heuristic baseflow separation to estimate the baseflow index -BFI. We therefore chose to implement the digital filter as our primary heuristic algorithm for computing BFI due to its ease of implementation, absence of arbitrary discontinuities in the derived BF time series, and the recommendation and empirical validation of digital filter baseflow time series in measured field estimates of groundwater recharge [26, 80]. For completeness and comparability, we also consistently implemented the USGS PART algorithm and duplicated baseflow computations with PART as a check for reasonableness, and as a bound on the range of variation contained in the simple choice of heuristic baseflow algorithm. The parallel derivation of PART baseflow estimates also supports the State of Maryland’s groundwater planning process which allocates ground water appropriations based on a baseflow-derived estimate of drought recharge with a 10-year recurrence interval computed using the USGS PART algorithm [88]. The full comparisons of BFI for the reference gauges used by MDE can be found in Appendix 3. This institutionalized use of baseflow analysis for regulatory and planning purposes in the State of Maryland highlights the applications and significance of this work.

Taken together the baseflow metrics described in this section provide a consistent quantitative framework to characterize the low flow response of any watershed with high quality continuous streamflow records. The following section illustrates the use of these baseflow metrics to examine the baseflow fingerprints of land transformation using the watersheds of the Baltimore Ecosystem Study as a case study.

### 3 Slowflow Fingerprints of Urbanization

#### Overview

Land transformation drives profound alterations to the urban water budget. Predicted changes in runoff, infiltration, recharge and evapotranspiration can be manifested in the observed characteristics of quickflow and slowflow derived from gauged streamflow. Characteristics of quickflow and slowflow derived from USGS streamflow records are used to examine the patterns of hydrologic alteration across the rural to urban landuse gradient in the watersheds of the Baltimore Ecosystem Study, an NSF Urban Long Term Ecological Research site in the Baltimore Metropolitan area. Metrics characterizing slowflow, recharge, and hydraulic drainage are compared to regional characteristics of Piedmont streams in the Chesapeake Bay watershed from the U.S. Geological Survey's Hydroclimatic Data Network (HCDN). Anomalies in multiple drainage characteristics are framed by a conceptual model of urban hydrologic alteration, and used to discern the slowflow fingerprints of urbanization in the Baltimore Ecosystem Study. Together, multiple hydrologic indices provide a more nuanced and consistent signature of changes in the dominant hydrologic processes driving urban hydrologic systems than any single index, motivating a multi-metric approach to identifying the baseflow signatures of sustainable water resources.

#### 3.1. Hydrologic Effects of Urbanization

The transformation of forested landscapes to agricultural, suburban, and urban land uses is associated with a shift in catchment water budgets, increasing runoff from impervious surfaces and concentrating runoff in efficient drainage infrastructure, with accompanying decreases in infiltration, recharge, soil moisture, and baseflow [89]. The direct effects of these landuse transformations are accompanied by secondary effects of development associated with the distributed construction of water and waste water infrastructure and interbasin water transfers through regional water supply and wastewater systems.

Widespread challenges of urban flooding in the early 19<sup>th</sup> century motivated the need to quantify urban runoff [90] and estimate the change in runoff for drainage design [91, 92]. Increased impervious area and more efficient drainage infrastructure have also been implicated in reducing recharge and hence baseflow. Leaking infrastructure, interbasin transfers, and both hydrologic and anthropogenic influences (as distinguished by Brandes et al. [93]) can yield varying effects on drainage, recharge, evapotranspiration (ET), and discharge, resulting in equivocal slowflow responses and significant variation in the dominant processes influencing slowflow.

Early engineering approaches to managing stormwater focused on flooding effects and the design of urban drainage infrastructure. The infrastructure focus on drainage is consistent with early engineering approaches to controlling flooding as a problem of inadequate channel conveyance [94]. Modern water resource engineering incorporated urban hydrologic effects in the estimation of watershed scale flood frequency [95]. Land transformation effects on urban stream channels were recognized by USGS in the middle of the 20<sup>th</sup> century and first synthesized by Leopold et al. [89]. Increased discharge and channel velocities associated with urbanization

magnify channel erosion degrading aquatic habitat, bank stability and exacerbating scour and undercutting of water infrastructure located in floodplains [96-100].

Urbanization is commonly expected to alter quickflow, with increases in the runoff ratio (the ratio of discharge to precipitation) associated with increases in peak discharge and volume of runoff [46, 101-103]. Continuity of the water balance would be expected to result in complementary reductions in recharge expressed as lower baseflow/slowflow. The net effect of water and wastewater infrastructure can moderate these tendencies and may either increase or decrease recharge – through leaky infrastructure, wastewater discharges, interbasin transfers for both municipal water supply and regional wastewater treatment, and deep groundwater pumping. Leaking infrastructure in older cities can dramatically increase effective annual recharge, raising regional water tables and increasing baseflow [8]. Low to moderate density development with significant disconnected impervious areas can increase *concentrated* recharge, shifting distributed infiltration from shallow soil water supporting root zone evapotranspiration to concentrated recharge enhancing baseflow through groundwater recharge [93].

Leopold [89] also anticipated that increasing runoff would be expected to alter the water balance by reducing recharge supporting baseflow, motivating the investigation of urban hydrologic effects on slowflow response [104-107]. Closer scrutiny and comparisons among urban watersheds suggested that baseflow responses are more subtle and variable than those of quickflow. [2, 3, 104, 108, 109].

Slowflow sustained by groundwater drainage integrates hydrologic forcings and cumulative changes to the watershed. The integrating nature of slowflow makes it relatively insensitive to isolated extreme storms (in contrast to quickflow). As an integrated signal, slowflow confounds multiple forcings from infrastructure, interbasin transfers etc. We therefore expect a multivariate characterization of baseflow response may help disaggregate the convolved forcings inherent in a gauge-derived slowflow signal. Multiple baseflow metrics offer the potential to help distinguish distinct responses embodying changes among the dominant processes contributing to slowflow response. The following section tests and evaluates a multimetric approach to interpreting baseflow response on the watersheds of the Baltimore Ecosystem Study.

### ***3.2 Baltimore Ecosystem Study: Urban Hydrology along a Rural to Urban Gradient***

The Baltimore Ecosystem Study (BES) is one of 26 Long Term Ecological Research (LTER) sites supported by the National Science Foundation and one of only two urban sites in the LTER network. BES supports diverse interdisciplinary research on the form and function of urban landscapes, grounded in long-term monitoring and data collection to capture and understand changes in the fluxes and flows along a rural to urban gradient spanning the subwatersheds in the Gwynns Falls watershed, shown in Figure 3. The BES monitoring design is anchored by a network of USGS streamflow gauges providing consistent hydrologic information along this gradient, with individual sub-basins dominated by forest and agricultural landuses with no significant impervious area, through ultra-urban landscapes with greater than 97% developed area. The landuse, landcover, and landuse history of the BES study domain spans subwatershed endpoints capturing modern 20<sup>th</sup> century land development.

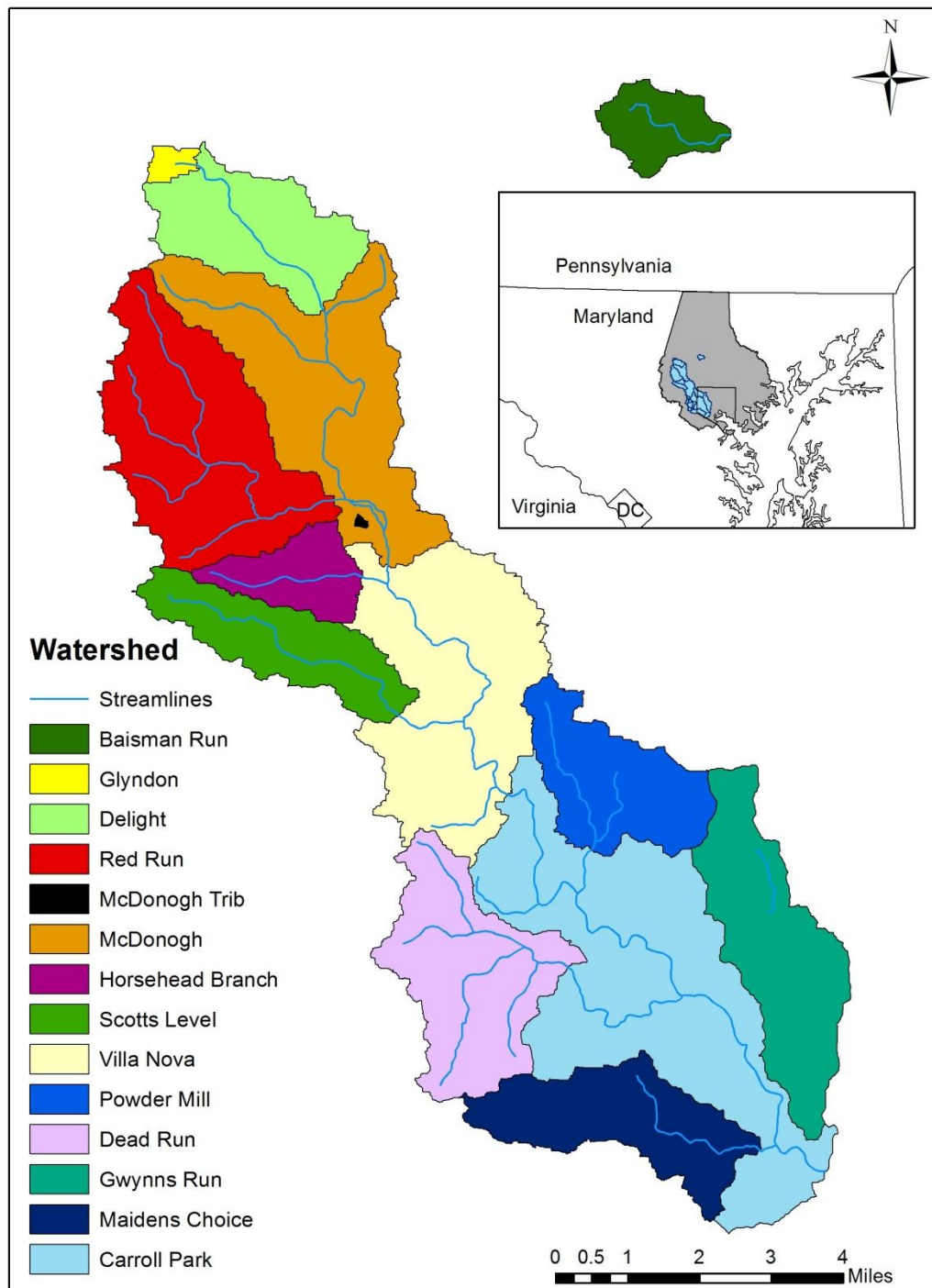


Figure 3 BES watersheds



The range of soils, landuses etc. represented in the BES watersheds is described by Groffman et al. [110] and summarized in Table 1

**Table 1 BES Watershed Characteristics**

Gauge Name	Land Use	Area (sq. mi.)	Developed 1 %	Developed 2 %	Forested %	Agricultural %	Impervious %
GF Carroll park	Mixed	65.9	56.1	73.0	20.7	5.9	26.7
GF Villa Nova	Mixed	32.5	42.7	61.1	27.2	10.9	19.1
GF Glyndon	Suburban	0.32	42.9	72.5	21.5	5.9	17.7
Scotts Level	Suburban	3.23	57.9	79.0	16.0	4.9	21.8
Baisman Run	Forested	1.47	1.7	23.1	73.8	3.1	1.0
Pond Branch	Forested	0.12	0.0	0.0	99.5	0.5	0.0
McDonogh	Agricultural	0.03	0.0	0.0	9.8	90.2	0.0
Powder Mill	Urban	3.64	76.2	88.2	11.5	0.3	35.6
Moore's Run	Urban	3.52	81.8	97.0	2.9	0.1	32.4
Dead Run	Urban	5.52	75.7	93.8	5.5	0.4	39.0
GF Delight	Suburban	4.23	45.1	76.0	21.4	2.5	16.7

- Impervious Percent is taken from the 2006 National Landcover Data(NLCD) Impervious Raster
- Land Use Data taken from NLCD 2006 Land Use Raster
- "Developed 1" is the summation of NLCD classes (Developed Low, Medium, and High Intensity).
- "Developed 2" is the summation of NLCD classes (Developed Open Space, Developed Low, Medium, and High Intensity).
- "Forested" is the summation of NLCD classes (Deciduous, Evergreen, and Mixed Forests).
- "Agricultural" is the summation of NLCD classes (Shrub/Scrub, Grassland, Pasture/Hay, and Row Crops).

Across the rural-urban gradient spanned by the BES watersheds, distinct eras of development are represented in subwatersheds dominated by the dense urban core, older urban residential areas, older suburbs and newer suburban sprawl [110]. Changes in suburban landuse accumulate through continual development and are imprinted on the landscape. Groffman et al. [110] characterized this gradient for the BES watersheds as ranging from the urban core, well established at the beginning of the 20<sup>th</sup> century, developing into older urban residential development through the 1930s; followed by postwar suburban development and newer suburban sprawl and infill in the 1970s and 1990s. Foresman [111] related these patterns to changes in the drivers of 20<sup>th</sup> century urbanization described as:

- 1900-1925 – industrial urbanization
- 1925-1950 - automotive urbanization
- 1950-1975 highway urbanization
- 1975-1990 modern urban sprawl.

In many ways the Gwynns Falls watershed and the associated watersheds of the Baltimore Ecosystem Study (BES) [110] provide a microcosm of the history, dynamics and evolution of 20<sup>th</sup> century urbanization, aggregating scale-dependent landuse and infrastructure

effects across watersheds. Although the geographic center of development has historically migrated among the BES watersheds during the 20<sup>th</sup> century, the cumulative effect of changing growth patterns has nevertheless resulted in a rather steady growth rate within the Gwynns Falls watershed as a whole.

Our initial research design anticipated capturing these spatio-temporal dynamics using LANDSAT images acquired and analyzed by Hanlon et al. [1] for much of central and southern Maryland. However the LANDSAT images licensed to us do not span all of the active eras of development and, of course, LANDSAT imagery is only available since the early 1970s. For these reasons we built on Hanlon et al.'s [1] use of the Maryland Property View Database and relied more heavily on the parcel information consistently available in the State of Maryland, to characterize the spatio-temporal patterns of land transformation throughout the State.

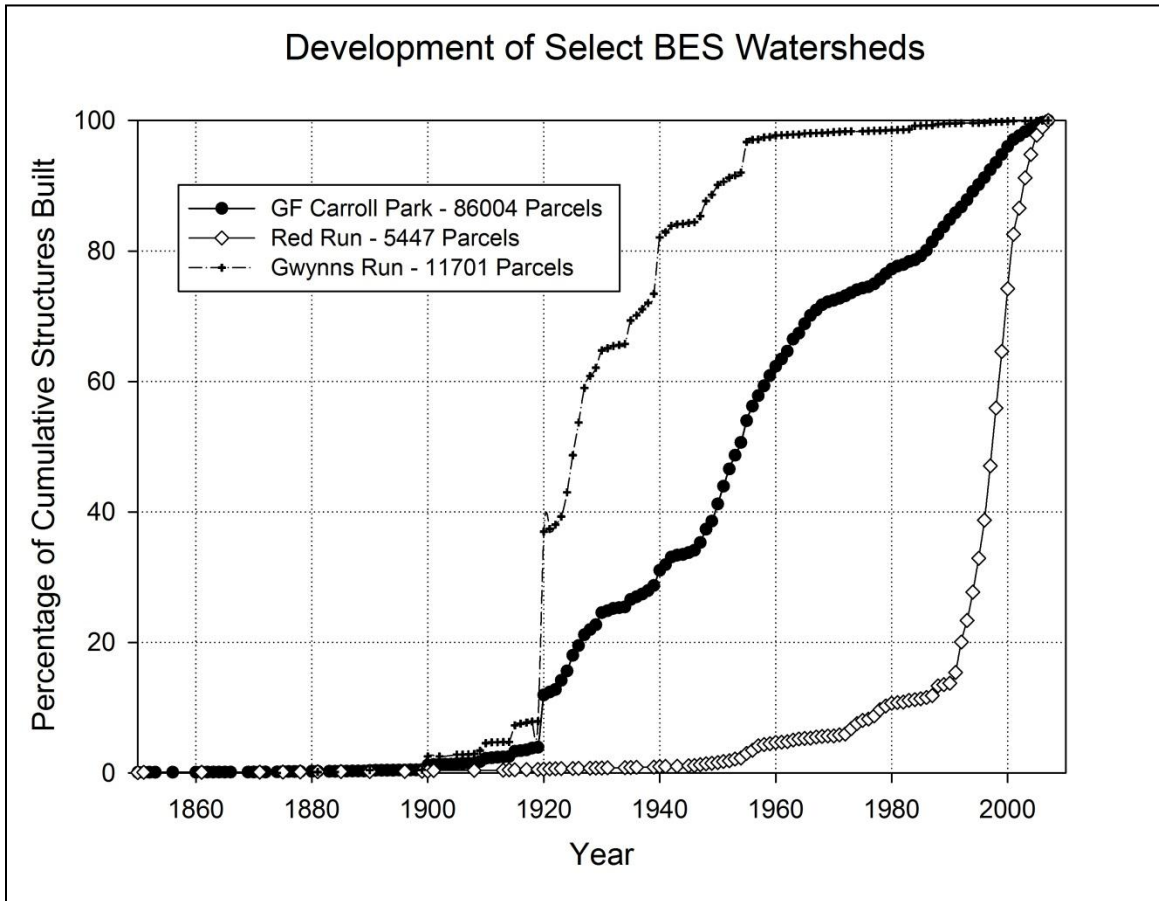
The Maryland Property View database provides locations and dates of construction for every parcel in Maryland. We used these data to reconstruct an estimate of the development history of each of our study watersheds in the State. These estimates are only approximate since they include information on neither the construction, redevelopment, nor subdivision *histories* of the individual parcels in the current parcel database. Nevertheless they offer a consistent quantitative measure of the spatiotemporal intensity of development – defined as location and date of construction of current built parcels.

Using the MD Property View parcel information we developed time series of built parcels for each of the individual and nested BES watersheds. While the overall rate of land transformation within the Gwynns Falls watershed has remained relatively constant over the last 80 years, the drivers and geographic center of development have varied through time and space. The dynamic development history has generated a current landscape imprinted with the distinct land transformation technologies (grading, stormwater management, drainage and transportation infrastructure) corresponding to the dominant practices, economics and regulatory requirements of the day. Aside from the look and feel of architectural styles and market preferences, the spatial and temporal migration of development activities leaves behind an infrastructure legacy – like an index fossil – marking the land development practices and controls for erosion and stormwater of the era.

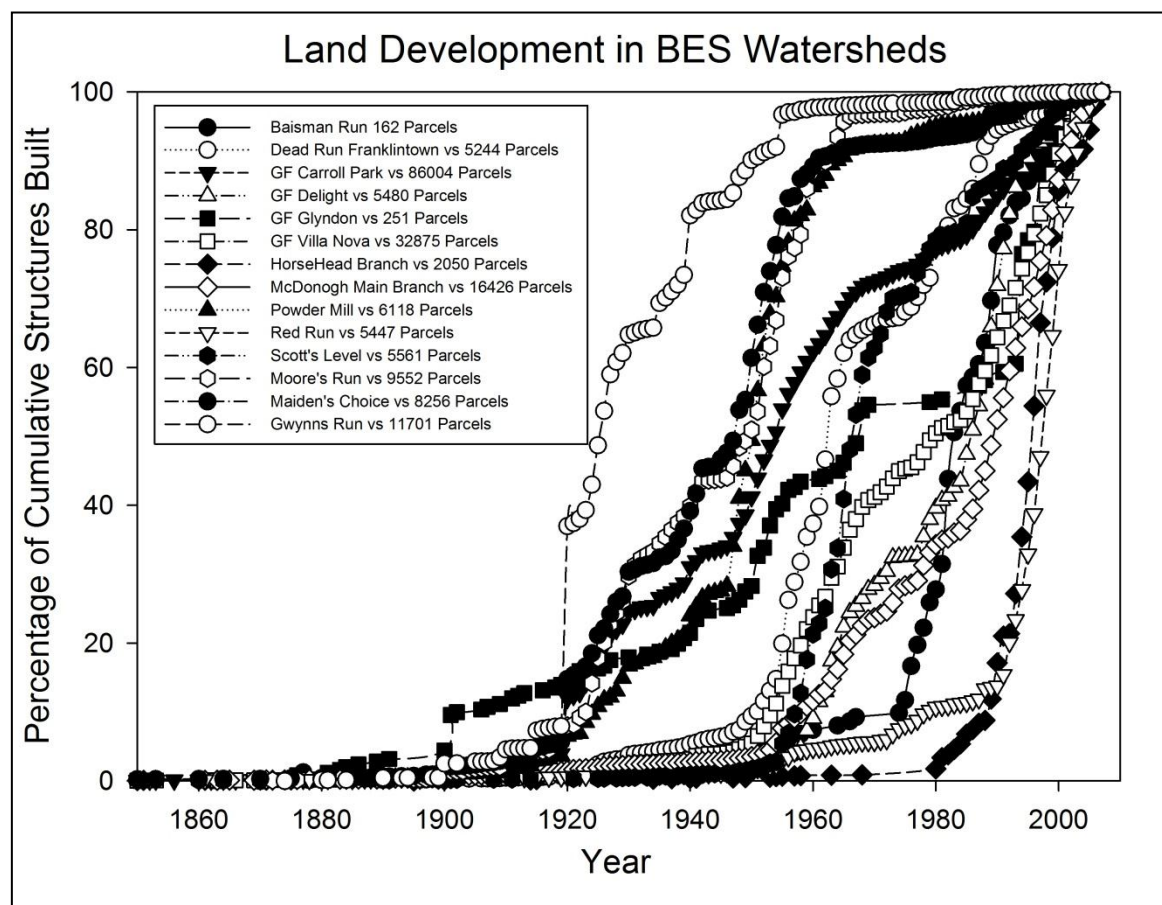
Early development (corresponding to Foresman's [111] age of industrial urbanization) took place in the lower watershed nearest to Baltimore Harbor in the Gwynns Run watershed (Groffman et al.'s [110] urban core). Expansion during the age of automotive urbanization spurred rapid development in the Moores Run and Maiden Choice catchments. Post-war suburbanization associated with highway urbanization and the construction of the Baltimore Beltway dominates the Powder Mill and Dead Run at Franklinton watersheds, with the most recent accelerated growth of Groffman et al.'s [110] new suburbs or Foresman's [111] modern urban sprawl in the 1990's, concentrated in Red Run and Horsehead Branch.

Figure 4 shows the time series of cumulative built parcels within the Gwynns Falls watershed derived from Maryland Property View data, along with similar data for both the Gwynns Run and Red Run catchments, representing the range and endpoints of 20<sup>th</sup> century

development histories in the watershed. The Cumulative built parcel time series for each of the BES watershed is shown in Figure 5.

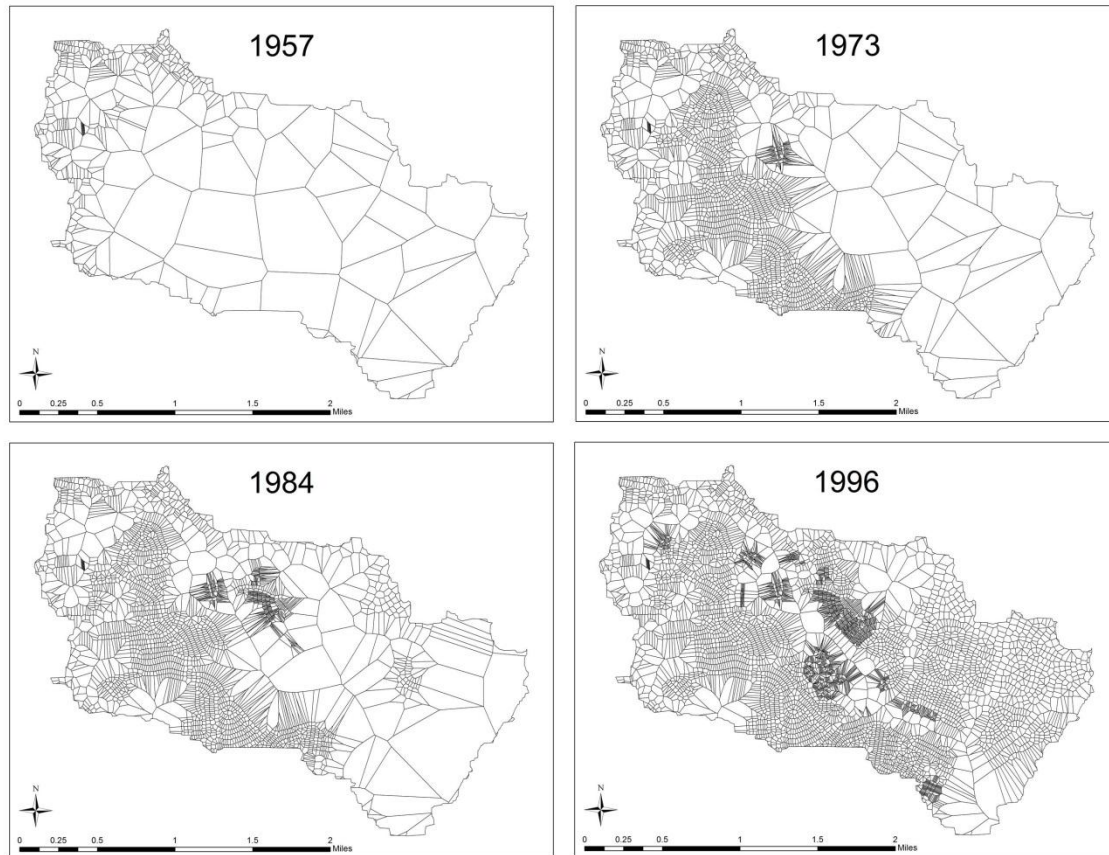


**Figure 4 Cumulative built parcels in the Gwynns Falls watershed**



**Figure 5 Summary of the timeline of development across BES watersheds. Y axis is the cumulative percentage of (year 2010) built parcels**

The temporal patterns of land transformation between watersheds can also be viewed at the smaller sub-basin scale through the spatial time series of development and subdivision within each of the watersheds. Using parcel centroids, the changing watershed-scale patterns of developed parcels reveals the spatial evolution of land transformation at the catchment scale, as individual development loci form a tessellation of the landscape. To help visualize the spatial intensity of the land transformation history of each watershed, we constructed Thiessen polygons around the built parcel centroids for critical years associated with change points in cumulative built parcels in Figure 5. An example of the dynamic spatial pattern derived from this landscape tessellation is shown in Figure 6 for the Gwynns Falls at Delight watershed.



**Figure 6 - Spatial intensity of development and build-out of Gwynns Falls at Delight**

Development also captures evolving land development practices, construction and infrastructure technologies, and stormwater regulatory requirements. Meierdierks et al. [112] described the more rigorous stormwater requirements in recent development, imprinted on the landscape through its development history. Meierdierks et al. [112] noted specifically that the Delight watershed developed during an earlier era of stormwater control focused on simple detention pond designs, creating a detention pond signature in the basin hydrology. In each of these ways the BES watersheds represent a microcosm of historical land transformation, and present an ideal case study for testing and evaluating the use of multimetric baseflow analysis.

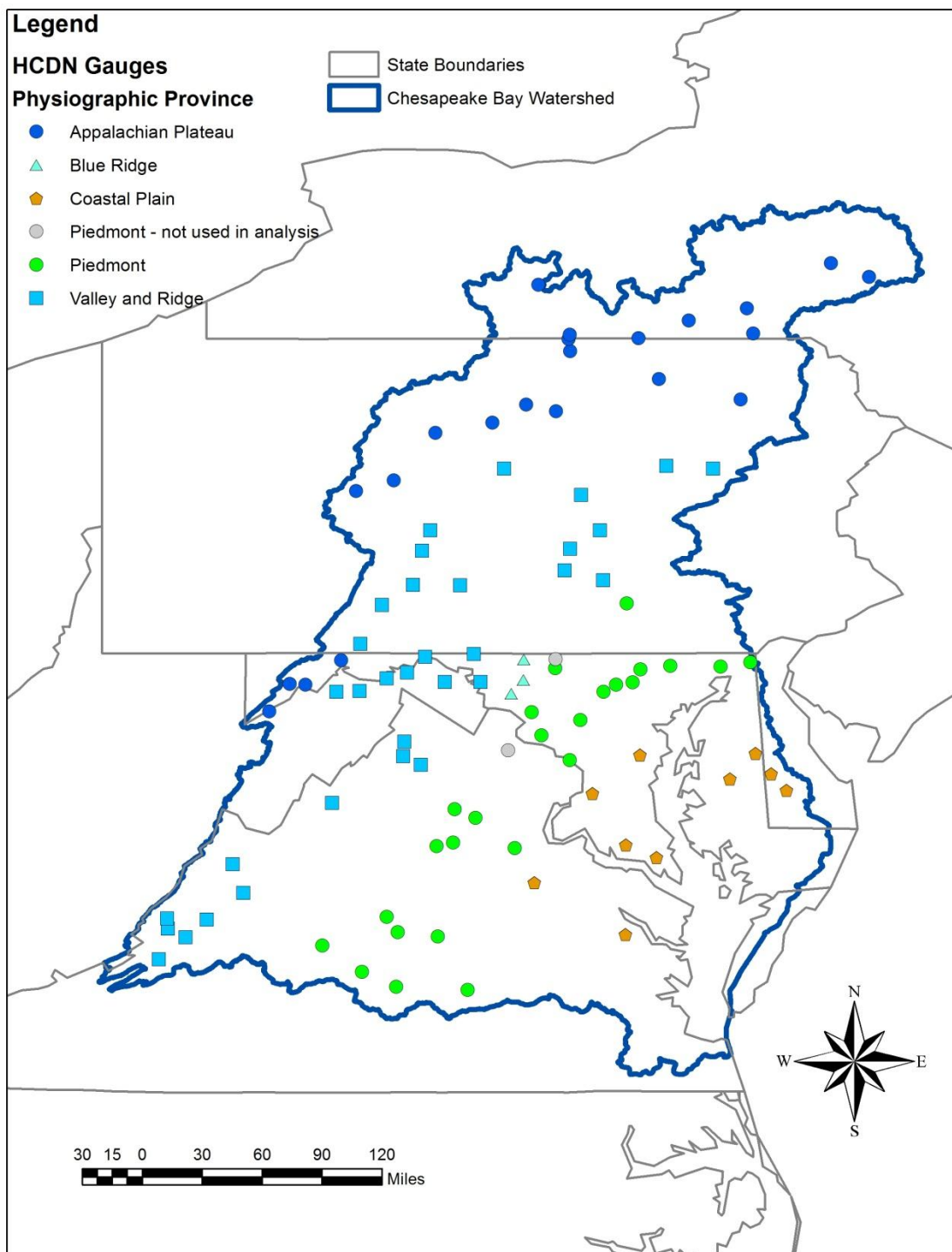
### 3.3 BES baseflow analysis

Baseflow metrics described in section 2 were computed from the gauge records of each of the BES watersheds. Metrics were also computed for all of the HCDN watersheds contained in the piedmont physiographic province of the Chesapeake Bay watershed, shown in Figure 7. The characteristics of the piedmont HCDN gauges serve as a hydrologic reference point for the mean and variability of piedmont baseflow characteristics in watersheds with limited human intervention. Descriptive statistics for the HCDN piedmont baseflow metrics are summarized in Table 2. The average piedmont watershed generates 15.2 ( $\pm 1.5$ ) inches of discharge and 9.09 ( $\pm 1.75$ ) inches of baseflow for a BFI of 0.594 ( $\pm 0.07$ ). The annual estimated recharge of 11.24 ( $\pm 2.05$ ) inches is significantly greater than the average baseflow due to our choice to report baseflow and BFI derived from 3 passes of the digital filter, which produces BF estimates consistently lower than HYSEP or PART estimates (see Appendix 3).

**Table 2 - Statistics on metrics for All HCDN Piedmont Gauges in the Chesapeake Bay Watershed**

	K	Kb	BFI	Q (in)	BF (in)	RORA Recharge (in)
<b>Mean</b>	76.2	0.9441	0.594	15.21	9.09	11.24
<b>Median</b>	80.7	0.9446	0.578	15.13	8.81	11.42
<b>Standard Deviation</b>	21.39	0.0119	0.076	1.50	1.75	2.05
<b>Minimum</b>	39.3	0.9140	0.425	12.82	6.21	7.64
<b>Maximum</b>	115.6	0.9640	0.729	18.59	12.70	15.07

The baseflow recession constants K (from RECESS) and Kb, annual average baseflow (BF) and baseflow index (BFI) from the digital filter, and annual average recharge from our automated implementation of the USGS recession displacement algorithm (RORA) were computed (Appendix 1 & 2) and compared to the average piedmont values for each of the BES watersheds in Table 2.



**Figure 7 HCDN stream gauges in the Chesapeake Bay Watershed. Green circles are HCDN Piedmont basins used in this analysis**

### 3.3.1 Comparing BES and HCDN Piedmont Baseflow metrics

Baseflow metrics for the BES watersheds were compared and contrasted with Chesapeake Bay Piedmont HCDN watersheds (hereafter referred to as the piedmont watersheds) by normalizing the values of each baseflow metric as a standardized deviation from the mean value of the 28 piedmont gauge statistics summarized in Table 2 and detailed in Appendix 3. For each BES watershed values of each baseflow metric,  $x_{ij}$  were normalized as a Z-score:

$z_{ij} = (x_{ij} - \bar{x}_i) / s_i$  by subtracting the piedmont mean, and dividing the difference by the piedmont standard deviation where  $x_{ij}$  is the value of the i-th metric in watershed j; and  $\bar{x}_i$  and  $s_i$  are, respectively, the mean and standard deviation of the piedmont values of the i-th metric. In this way transformed BES metrics similar to mean piedmont values will take values close to zero; baseflow metric values significantly above (or below) the piedmont mean take positive (or negative) values that can be interpreted as the difference – in standard deviations- from the mean for Chesapeake Bay piedmont watersheds least impacted by human activities.

The results summarized in table 3 highlight the patterns of variation for each baseflow metric among the BES watersheds, and reveal more nuanced subtle differences in baseflow response, evidenced by the different *combination* of characteristics realized in each watershed. For example, Moores Run and Dead Run at Franklinton have the lowest BFI among the BES watersheds with values almost 5 standard deviations below the piedmont mean. Yet the annual discharge for Dead Run is dramatically higher than both Moores Run and the piedmont mean. Similarly McDonogh and Powder Mill both display baseflow recession ( $K_b$ ) constants 5-7 standard deviations below the piedmont mean indicating baseflow recessions that decline sharply after storm events, yet the BFI for these watersheds differ significantly with anomalously low BFI in Powder Mill but above average BFI in McDonogh. The variation of coincident baseflow characteristics provides a more nuanced multivariate description of baseflow behavior among the BES watersheds. The differences among the BES watersheds are summarized in Table 3 and described below.

- The annual average discharge in Dead Run is more than 4 standard deviations above the piedmont mean, with annual baseflow more than two standard deviations below the piedmont mean. The resulting BFI is dramatically lower than the HCDN mean – consistent with the amplification of quickflow and decline of baseflow from urbanization.
- Low BFI values are also apparent for Powder Mill and Moore's Run, the other highly urbanized BES watersheds representing the urban core. Baseflow derived from these two gauge records is significantly less than the mean Piedmont baseflow, with annual discharge greater than the Piedmont average. Although the annual average discharge in Moores run is only modestly higher than mean piedmont discharge, the dramatically lower baseflow in Moores Run drives the low BFI value.
- The partially urbanized Glyndon and Scott's Level watersheds also have below average BFI. The annual baseflow is below the piedmont mean in both watersheds, but without the high discharge "expected" in the most urban watersheds.



- BFI values from the three undeveloped watersheds, Baisman Run, Pond Branch, and McDonogh Tributary are all significantly greater than the piedmont average, driven by above average baseflow values for Baisman Run and Pond Branch but below average annual discharge from McDonogh, again illustrating how differences in dominant processes can yield similar values of a single baseflow metric.
- Kb values are significantly less than mean piedmont values for Dead Run and Powder Mill, but only modestly lower for Moore's Run. Although the highly urbanized Moore's Run watershed has been identified as an urban endpoint with an exceptionally flashy quickflow response [112], and annual average baseflow dramatically less than the piedmont average, the recession constant indicates the rate at which sustained baseflow recedes is comparable to minimally impacted piedmont watersheds, even though the magnitude of baseflow is far below the regional average. This contrast highlights the difference between the hydrologic and hydraulic interpretation of baseflow embodied in these metrics.
- Strikingly low Kb values for Glyndon and McDonogh Tributary stand out because these watersheds are *not* heavily urbanized. These are the smallest watersheds in the BES network with flow rates that rarely exceed 1 cfs during non-storm events, and frequently drop to 0 under dry conditions.
- No BES watersheds show Kb values significantly greater than the Piedmont mean.

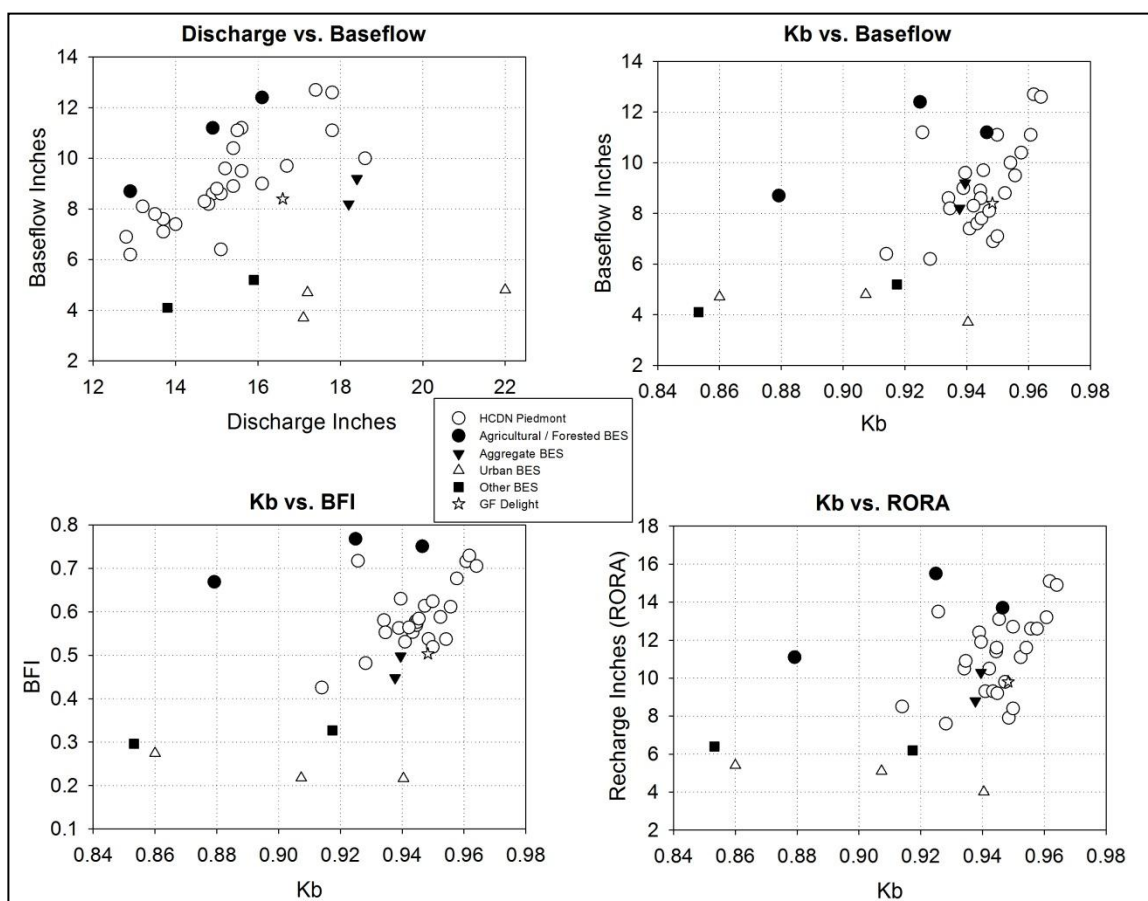
GAUGE NAME	Z Score computed from Mean				
	Kb	BFI	Q (in.)	BF (in.)	RORA (in.)
GF Carroll park	-0.54	-1.92	2.01	-0.53	-1.17
GF Villa Nova, recent	-0.38	-1.26	2.14	0.05	-0.48
GF Glyndon	-7.64	-3.92	-0.94	-2.86	-2.38
Scotts Level	-2.24	-3.51	0.49	-2.21	-2.47
Baisman Run	0.20	2.07	-0.18	1.22	1.22
Pond Branch	-1.61	2.28	0.61	1.88	2.06
McDonogh	-5.45	0.99	-1.51	-0.24	-0.05
Powder Mill	-7.06	-4.21	1.34	-2.50	-2.86
Moore's Run	-0.31	-4.97	1.27	-3.08	-3.53
Dead Run Franklinton, recent	-3.09	-4.97	4.52	-2.47	-2.99
GF Delight	0.35	-1.20	0.95	-0.41	-0.70

Table 3 - "Z scores" of BES watersheds relative to the HCDN Piedmont Statistics

### **BES Multimetric Slowflow Endpoints**

The contrasting combinations of baseflow metrics summarized in Tables 2 and 3 support a multimetric characterization of slowflow response in the BES watersheds. We interpret the additional information in this multivariate characterization to generate testable hypotheses, further diagnosing the slow flow fingerprint of urbanization. For example,  $K_b$  is uniformly lower in developed BES watersheds compared to HCDN watersheds indicating less sustained baseflow. This baseflow fingerprint is consistent with *both* lower recharge (impairing the capacity to sustain long recessions) and more rapid recession rates resulting from changes in subsurface drainage (that could result from infiltration and inflow into leaky sewer infrastructure). Joint comparison of  $K_b$  and recharge, such as our RORA estimate of annual recharge, may be able to distinguish dominant processes. Such a result can suggest further analysis, e.g. using added information such as the density and condition of the water infrastructure system, or stable isotope signatures of old and new water [113, 114] to test hypotheses about the significance of leaky infrastructure or interbasin transfers through water and wastewater systems.

Figure 8 compares bivariate patterns of baseflow metrics for BES and piedmont watersheds. Across the multivariate space of baseflow metrics, the variation within the piedmont watersheds is generally bounded from below by the most highly urbanized BES watersheds in the Gwynns Falls, and bounded from above by the rural (agricultural and forested) endpoint watersheds of the Baltimore Ecosystem Study. This pattern reinforces Meierdierks et al. [112] characterization of rural to urban endpoints of quickflow response across the BES watersheds. Interestingly, the Villanova and Carroll Park watersheds consistently provide intermediate baseflow characteristics along this gradient. Their multimetric baseflow fingerprint represents a filtered composite response, blending the distinct baseflow signals of their individual upstream subwatersheds. The gradient of composite baseflow signals along the BES rural to urban gradient suggests a conceptual endpoint mixing model for baseflow response, analogous to endpoint mixing models of chemical signatures of streamflow ([115]) or the quickflow endpoints suggested by Meierdierks et al. [112].



**Figure 8 Multimetric Fingerprints of BES and Piedmont HCDN Baseflow Characteristics**

Most notably, the baseflow characteristics of the Gwynns Falls at Delight consistently present a multimetric fingerprint within the cloud of piedmont HCDN watersheds. The Delight watershed is particularly notable since it was identified by Meierdierks et al. [112] as the BES watershed in which the era of maximum development resulted in the imprint of stormwater detention ponds (that affect the slowflow signal) throughout the landscape. These preliminary results suggest the cumulative watershed scale effects of extended detention stormwater strategies do mitigate the *flashiness* of urban runoff (yielding a baseflow fingerprint resembling average piedmont conditions). Of course the increased runoff volume being released through uncoordinated regional extended detention ponds can cumulatively combine to exacerbate peak discharge, channel erosion, and downstream flooding at the watershed scale [116]. The baseflow metrics capture the slow release of stormwater which resembles the slowflow response of HCDN watersheds. This also suggests the limitations of these aggregate slowflow metrics derived from gauged streamflow to discern, e.g. ecologically significant hydrologic changes, or changes in hyporheic process that also accompany land transformation.

Compared to piedmont HCDN basins, BFI is uniformly lower in developed BES watersheds, (though significantly higher, with above average baseflow, in the forested Pond Branch and mixed suburban Baisman Run watersheds). Above average quickflow with average slowflow results in a net decrease in BFI e.g. at Villanova. Lower BF accompanying higher quickflow results in even lower BFI as “expected” in developed watersheds such as Powder Mill and Dead Run at Franklinton. The components of BFI reveal differences in the dominant processes that can, nonetheless, yield similar BFI responses such as the average quickflow with unusually low slowflow in Scotts Level. These subtle and nuanced associations motivate the use of multiple baseflow metrics to discern different dominant processes driving the distinct baseflow fingerprints of land transformation.

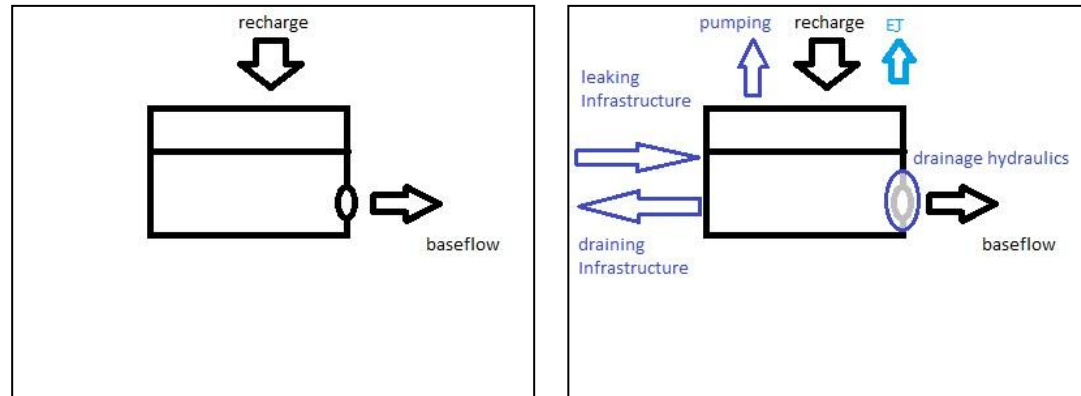
**Table 4 BES Baseflow Metrics. Rows are grouped to match symbology in Figure 8**

	Gauge	K	Kb	BFI	Q (in)	BF (in)	RORA (in)	Area (sq. mi.)	UVM Impervious %	NLCD Impervious %
Aggregate BES	GF Carroll Park	102	0.9377	0.448	18.2	8.2	8.8	65.9	34.8	26.7
	GF Villa Nova, recent	87	0.9395	0.498	18.4	9.2	10.3	32.5	28.6	19.1
Other BES	GF Glyndon	35	0.8532	0.296	13.8	4.1	6.4	0.32	27.5	17.7
	Scotts Level	38	0.9174	0.327	15.9	5.2	6.2	3.23	33.7	21.8
Agricultural / Forested BES	Baisman Run	93	0.9465	0.751	14.9	11.2	13.7	1.47	3.7	1
	Pond Branch	75	0.9249	0.768	16.1	12.4	15.5	0.12	0	0
	McDonogh	51	0.8792	0.669	12.9	8.7	11.1	0.03	0	0
Urban BES	Powder Mill	38	0.8600	0.274	17.2	4.7	5.4	3.64	43.4	35.6
	Moores Run	42	0.9404	0.216	17.1	3.7	4.0	3.52	37.8	32.5
	Dead Run Franklinton, recent	88	0.9073	0.217	22.0	4.8	5.1	5.52	52.4	39
	GF Delight	66	0.9483	0.503	16.6	8.4	9.8	4.23	28	16.7

### 3.4 Multimetric Fingerprints of Urban Hydrology

#### Conceptual Model of Urban Slowflow Effects

Figure 9a suggests the traditional conceptual model of baseflow as a “leaky bucket” – that is, a linear reservoir from which baseflow is generated as drainage from a linear reservoir.



**Figure 9 Conceptual models of Baseflow (a) a simple leaky bucket (b) multiple dominant processes**

Traditional conceptualizations of baseflow discharge,  $q_b$ , envision baseflow as drainage from a uniform aquifer  $q_b = aS^b$  where  $S$  is the aquifer storage. More nuanced conceptual models recognize both hydrologic effects on the aquifer water balance as well as hydraulic effects altering the drainage characteristics of the aquifer system. Hydrologic effects on baseflow include reduced evapotranspiration (ET) as impervious surfaces replace vegetated landcover, pumping and groundwater withdrawals that reduce groundwater storage, impairing baseflow; and recharge from leaking infrastructure, that may be derived from interbasin transfers of municipal water supply originating outside the watershed. Baseflow hydrology can also be altered independently from changes in aquifer storage by wastewater discharges of imported water that appear as slowflow, bypassing the groundwater system. As well, groundwater discharges from deep well pumping can transfer groundwater that originated in distant recharge areas outside the watershed boundary to the surface water system, effectively altering the measured fluxes of the water balance as a less direct interbasin transfer.

In addition to these hydrologic effects, infiltration and inflow to unpressurized stormwater infrastructure can accelerate groundwater discharge, altering the *effective* watershed drainage response. Significant groundwater depletion can result in subsidence and aquifer compaction, leading to permanent reductions in aquifer porosity and conductivity, and irreversible changes in the drainage characteristics of the compacted aquifer. Subsidence following over-pumping would also be expected to provide a change in the recession constant  $K_b$ .

## Metrics of the leaky bucket

We consider each of these effects and the range of qualitative responses expected in each of the baseflow metrics considered here.

1. Runoff – increased runoff –or quickflow- is a dominant feature of urbanizing basins. Although increased impervious area and stormwater drainage convey more rainfall to the surface water system, the runoff signature of urbanization in gauged streamflow can be obscured by regional stormwater and drainage infrastructure that effects an interbasin transfer of surface runoff, bypassing the watershed outlet. The relatively low gauged runoff from the highly impervious Moores Run watershed may be an example of surface water diversion by urban drainage infrastructure.
2. Recharge – Increased impervious area and drainage conveyance can be expected to decrease groundwater recharge in a closed water budget. Distributed water infrastructure can contribute to recharge through leakage of so-called “unaccounted water” in pressurized water supply systems [8]. As an example, the historical rates of unaccounted water from the Washington DC water supply system represented an annual average contribution to the District’s water balance comparable to natural rates of recharge for mid-Atlantic coastal plain watersheds. Moreover, regional municipal water supplies commonly represent interbasin transfers from source waters outside the watershed boundary and can fundamentally alter the water budget for urban catchments.

Water supply in the Gwynns Falls watershed comes from the Baltimore City system that draws on the Gunpowder, Patapsco and even the Susquehanna River Basin, altering the basic water balance for the BES catchments. For this reason the recharge signature of urbanization can differ significantly between watersheds with older leaking municipal water systems, and newer systems with minimal losses, or exurban self-supplied homes dependent on groundwater pumping.

3. Evapotranspiration – Like recharge, the conceptual model for urban hydrologic effects, projects decreased evapotranspiration, as vegetation is replaced by impervious surfaces.
4. Concentrated Recharge – The direct effects of impervious cover and storm drainage are expected to decrease recharge. The widespread presence of so-called disconnected impervious cover (without a direct hydraulic drainage path to receiving waters) can result in local ponding and concentrated recharge. Runoff that might otherwise dissipate and infiltrate to shallow soil water (where it is available for evapotranspiration from the root zone) may be concentrated and ponded, resulting in deeper percolation that incrementally increases recharge.
5. Pumping - Where shallow groundwater extraction is significant, the exploitation of groundwater can appear as a reduced recharge signal in gauged streamflow. Yet groundwater pumping from deep aquifers (with primary recharge areas outside the catchment) may effect a net interbasin import of water beyond precipitation inputs,

altering the basin water balance and generating a baseflow signature interpreted as increased recharge.

6. Leaking infrastructure: *recharge* – can increase baseflow with the signature of increased recharge
7. Leaking infrastructure: *drainage* - Leaking sewer infrastructure can also enhance the drainage of the shallow groundwater system, through infiltration and inflow to unpressurized sewer pipes. The “dewatering” of shallow groundwater may be manifested in so-called “dry weather flow” from storm sewers, which carry low flows – with the response signature of slowflow. As free water from shallow aquifers drains into the storm sewer “macropore” and returns to the surface water system, the signature of drainage infrastructure may be expressed in the recession constant  $K_b$
8. Subsidence and Compaction – Overexploitation of groundwater resources can result in an irreversible compaction of aquifers, associated with surface subsidence, lower well yields, and irreversible declines in groundwater drainage. Such phenomena might similarly be expected to yield a hydraulic signature of slowflow response – distinct and separate from the hydrologic signature of the BFI.
9. Wastewater discharges – Steady discharges from wastewater treatment plants can modify the slowflow response observed in gauged streamflow, increasing baseflow, BFI, and  $K_b$  as the discharge of treated wastewater sustains extended baseflow recession periods. Treated discharges from regional wastewater collection and treatment systems commonly enhance gauged streamflow as an interbasin transfer, increasing the hydrologic inputs to catchment water budgets beyond precipitation. These supplemental inputs may be disproportionately expressed in slowflow without making a hydrologic contribution to groundwater recharge.

## Slowflow Fingerprints

The individual influences of processes that may dominate or contribute to slow flow response are embedded in the baseflow metrics we consider. Distinct combinations of changes or anomalies from regional reference values suggests an initial template for fingerprinting urban slowflow, presented in Table 5

**Table 5 Slowflow Fingerprints**

	Q	BF	BFI	Recharge	Kb
Imp. Runoff	+	-	-	-	~/-
Conc. Rech	~	+	+	+	~
Deep pumping	+	~/+	~/+	~/+	~/+
Infrastructure Recharge	~/+	+	+	+	+
Infrastructure Drainage	~/+ <sup>5</sup>	-	-	-	-
Compaction	+	-	-	-	-
Wastewater Discharge <sup>6</sup>	+	+	-/+	~/+	+

Dominant expected effect: increase (+), decrease(-), increase or decrease (+/-), insignificant (~)

This suggested tableau of possible baseflow effects represents a multimetric fingerprint of dominant processes in baseflow endpoints. Mixture effects may obscure these subtle, though distinct, endpoints just as the mixture of baseflow responses among the BES watersheds obscured the processes affecting composite slowflow for the Gwynns Falls at Villanova and Carroll Park.

### Summary-

Multimetric fingerprints of the BES watersheds capture a rural to urban landuse gradient, compounded by water infrastructure effects, and the convolution of mixed landuses at aggregate scales. Across this gradient the slowflow responses of the HCDN piedmont watersheds are bounded by multimetric signatures of forested, agricultural and ultra-urban hydrologic responses. At the multicatchment scale, basin responses aggregate downstream; aggregate watersheds with composite landuse responses appear more similar to the Chesapeake Bay Piedmont watersheds in the USGS HCDN network. Of particular interest is the Gwynns Falls at Delight watershed identified by Meierdiercks et al. [112] as a watershed with a stormwater detention signature. The effect of late 20<sup>th</sup> century stormwater infrastructure appears to alter the baseflow fingerprint – in BFI-Kb space - to resemble HCDN piedmont watersheds. This is consistent with the emphasis on peak shaving and extended detention goals of the stormwater technology of the era. Despite a fingerprint similar to HCDN gauges bounded by urban and rural endpoints, Delight remains a densely developed watershed. Delight's multimetric similarity to HCDN gauges should not be automatically interpreted as equivalence to minimally influenced watersheds – highlighting

<sup>5</sup> We expect the direct effects of infrastructure drainage on discharge to be insignificant. However infrastructure drainage of groundwater assumes the presence of unpressurized stormwater infrastructure for surface drainage that increases runoff, and may therefore be associated with increased discharge.

<sup>6</sup> Wastewater discharges would not be expected to recharge groundwater, but the steady flows of wastewater discharges at lowflow could produce a recharge signature in gauge derived (e.g. RORA) estimates of recharge.



limitations of the hydrologic responses (e.g. ecologically significant flow patterns) discernible using the scale and metrics employed in this analysis.

Endpoints emerge from dominant processes. Composite watersheds driven by mixtures of processes will require additional information to decompose distinct signatures of urban development. To incorporate temporal information into the identification of changing baseflow, the following section develops methods for robust multimetric trend analysis of baseflow metric time series.

#### 4. Trend Analysis: Baseflow Fingerprints of Sustainable Water Resources

Section 3 developed multimetric signatures of human influence in slowflow characteristics of gauged streamflow. The heterogeneity of development in the watersheds of the Baltimore Ecosystem Study illustrated distinct baseflow responses across a multivariate slowflow fingerprint of urban development. Beyond the spatial heterogeneity of land transformation, the baseflow signature of sustainable water resources is present in the historical changes in baseflow that have accompanied land transformation. These changes are embodied in the historical streamflow records from which our baseflow metrics have been computed. Beyond the variation in these metrics between watersheds, this section considers the analysis of trends in baseflow metric time series, and the association between land transformation, fragmentation of working lands, and the changes in baseflow characteristics accompanying land transformation.

*Baseflow Trend Analysis*- Trend analysis of multiple baseflow metrics further elucidates the baseflow signatures of human hydrologic alteration. In this section we develop and implement robust trend analysis using consistent non-parametric methods. Trend analysis is performed on *all feasible sub-periods* within the period of record of *every gauged watershed in Maryland* for which sufficient data are available. Multi-metric trend analysis is used to distinguish significant historical trends dominated by anomalous extreme events (such as the drought of the 1960s) from long-term persistent secular shifts in baseflow characteristics. We also use a simple regional hydrometeorological water balance model to control for the inherent regional hydrometeorological forcings and persistence embedded in every streamflow record. In this way we can distinguish patterns of slowflow trends that are not explained by the natural regional hydrometeorological forcings, and are therefore inferred to be associated with other drivers – such as land transformation and human intervention in the land surface hydrology system. Together, these analyses provide the consistent tools with which continuous high quality stream flow records can be used to discern the baseflow signature of sustainable water resources.

#### *Changes in Hydrologic Response*

Land transformation is a dynamic cumulative process. As shown in Section 3, human alteration of the landscape and its coupled hydrologic system evolves through time, imprinting the cumulative history of landuse, land transformation, subdivision, and co-evolving infrastructure systems in developed landscapes. These dynamic changes alter the water budget and the associated water and energy fluxes, and modify the dominant processes influencing observed streamflow over time [101, 109, 117] resulting in non-stationary streamflow records in developed watersheds [118-120].

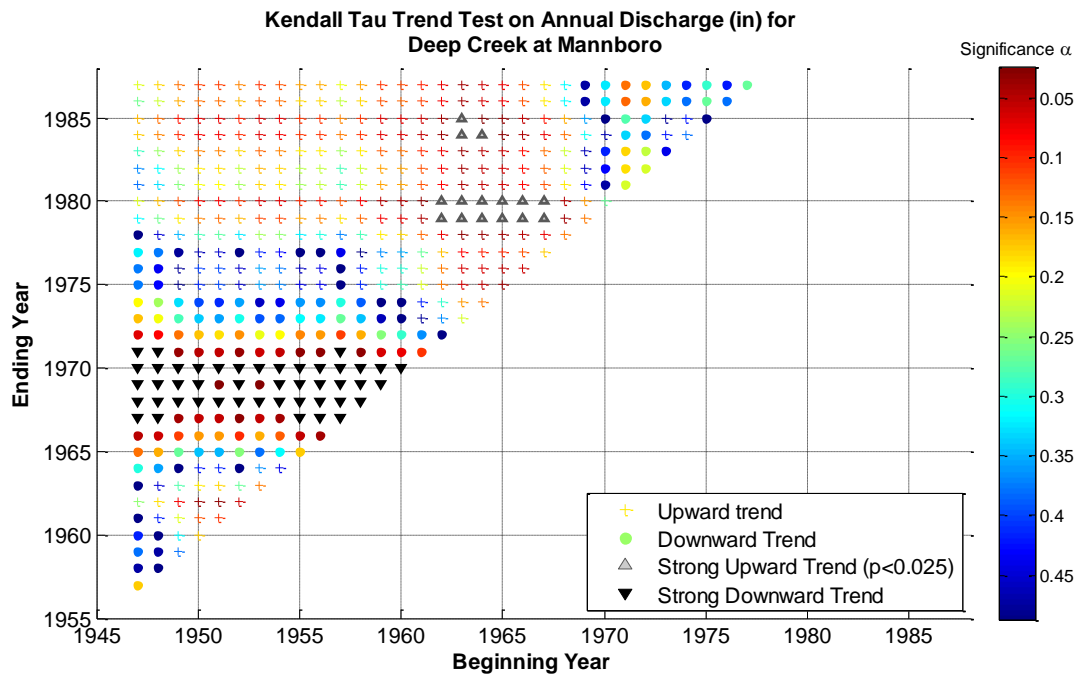
The coupling of land surface hydrology systems with human social systems that modify the landscape motivates the investigation of trends in land transformation and streamflow characteristics [93, 98, 121-124]. Extensive analysis of trend detection methods in geophysical time series has identified and documented the challenges of robust trend detection in hydrologic time series. A robust family of methods derived from the non-parametric Kendall-tau statistic has evolved, and is widely used for trend analysis of hydrologic and water quality time series [125, 126]. The Kendal-tau (KT) non-parametric test of trend is robust against common violations of the assumptions behind the standard linear model. The KT test has also been

extended to trend detection in time series with seasonal effects – the seasonal Kendall tau – and to a non-parametric Kendall slope estimator for robust estimation of the magnitude of monotonic trends. We use a variation of the Kendall tau statistics to identify the pattern of trends in baseflow metrics of gauged streamflow in Maryland.

Traditional trend detection would perform a single trend test for the period of record of the time series of interest. The inherent variability of hydrologic times series, combined with the vagaries of continuous hydrologic data records, can make trend inferences sensitive to the somewhat arbitrary starting and ending dates of available time series. Weak dependence and transient periods of hydrometeorological extremes (such as the persistent drought of the 1960s or extreme flooding associated with Hurricane Agnes) can exert an undue influence on inferences regarding the significance of trends, simply due to the vagaries of the record length.

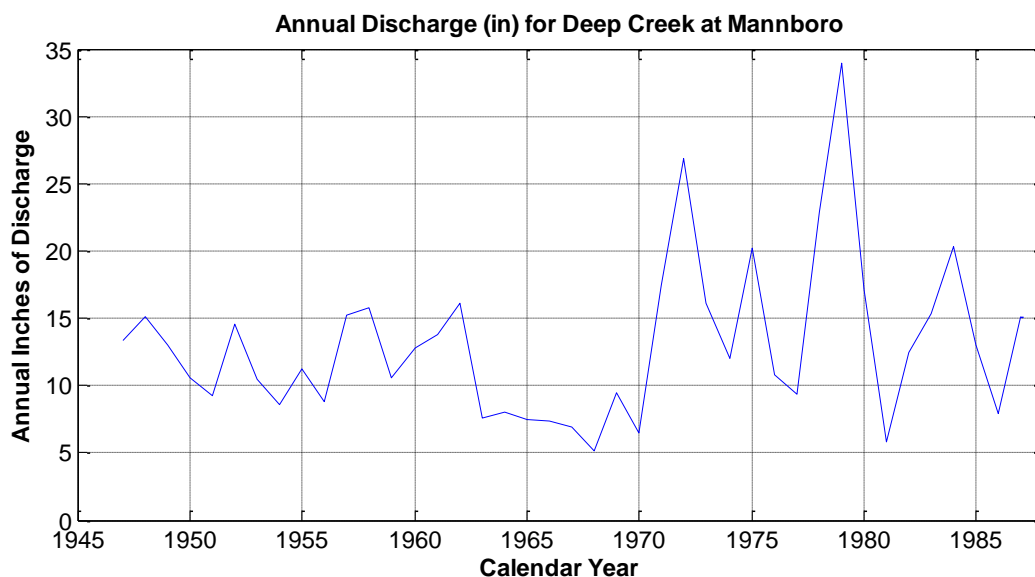
We adapt methods of McCabe and Woolock [127], and Zhang et al. [128] to evaluate trends in baseflow metrics over historical conditions of significant landuse and infrastructure change. Rather than performing a single test for monotonic trend over the entire period of record for each stream gauge, we use the non-parametric Kendall tau statistic to test for monotonic trend for every feasible subperiod of the available streamflow record of each stream gauge. For a stream gauge record with  $N$  years of data, if we require a minimum record length of  $k$  years to detect a significant trend, then there are  $(N^2 - N) / 2 - k(N - k) - k(k - 1) / 2$  distinct subperiods for which we can perform a KT test of trend. If we require at least 10 years of annual values for a significant KT-trend test, a stream gauge with 50 years of record would result in 780 unique (though not independent) subperiods for which we perform a KT test of monotonic trend, including the entire period of record. The number of statistically significant trends, as well as their distribution through the period of record, provides added insight into the nonstationarity of the streamflow record and testable hypotheses regarding the underlying causal mechanisms of the observed trends.

Following McCabe and Woolock [127] and Zhang et al. [128] the statistical significance of the KT test for each subperiod can be displayed in a plot such as Figure 10 with axes corresponding to the starting date and ending date of each subperiod of the available record; each point corresponds to one particular subperiod. Since the ending date must obviously follow the starting date, the graph is an upper triangular matrix with the lower diagonal offset by  $k$  years (the minimum record length for which the trend can be tested for significance).



**Figure 10 Kendal Tau surface for Annual discharge of Deep Creek at Mannboro**

We refer to this diagram as a kendall tau surface, connoting the surface of statistical significance that can be associated with the individual trend tests over all subperiods. The nonparametric KT test admits tests for both increasing and decreasing monotonic trends, and the direction of the trend for every subperiod is designated by a plus sign (+) for increasing trends, and a closed circle (•) for decreasing trends. The two-sided test is considered significant at the  $\alpha$  % significance level if the probability of the observed test statistic in either tail (increasing or decreasing trend) is  $\leq \alpha / 2$ . Subperiods with trends that are significant at the  $p=0.025$  level are designated with an open triangle, with an upward grey triangle designating a significant increasing trend, and a downward black triangle designating a decreasing trend. The significance of the trend for subperiods that are not significant at the  $p = 0.025$  level is represented by the color of the trend symbol, with cooler blue colors indicating lower significance and warmer/hotter red colors conveying increasing significance up to the  $p=0.025$  level.



**Figure 11 Annual discharge Deep Creek at Mannboro**

Figures 10 and 11 show the Kendall tau surface and time series of annual discharge in inches of runoff, for the HCDN stream gauge on Deep Creek at Mannboro USGS stream gauge 02041000. The KT test of monotonic trend does not show a statistically significant trend for the period of record – as we would expect for an HCDN stream gauge. The annual discharge series does show a clear period of low flows associated with the drought of the 1960s, as well as a dramatic increase in the overall magnitude and variability of runoff after 1970 – a step increase in hydrologic intensity that is observed throughout the streamflow records of the Chesapeake Bay and the eastern United States [127]. The annual discharge record also captures the record flows of Hurricane Agnes in 1972. Despite these clear patterns and the weak dependence of persistent hydroclimatic forcings inherent in this time series, the KT test for monotonic trend is not statistically significant at the  $\alpha = 5\%$  level.

Although the period of record does not show a statistically significant trend, the Kendall tau surface reveals highly significant trends in streamflow among subperiods of the record. Figure 10 shows that any subperiod of record starting between 1945 and 1960 and ending between 1968 and 1971 shows a significant downward monotonic trend. These downward trends clearly reflect and are anchored by the extremely low flows of the 1960's drought. Moreover the contiguous clustered pattern of these significant downward trends is a striking feature and highlights the integrating information embodied in the Kendall tau surface.

A complementary, somewhat less extensive, but equally significant increasing trend is seen for subperiods starting between approximately 1962 and 1967, and ending about 1980. These increasing trends which are also statistically significant ( $p = 0.025$ ) are the complementary image of the 1960s drought. For subperiods of the record starting in the drought and extending through the highest annual flow years through 1980 these statistically significant increasing trends are also anchored by the extreme low annual flows of the 60s drought. It is interesting to note that, despite the step increase in discharge and variability of streamflow starting in 1970, the

low annual discharge values within this new hydrologic regime diminish the statistical significance of the anchoring effect of the 1960s drought as subperiods extending into the latter portion of the period of record are considered.

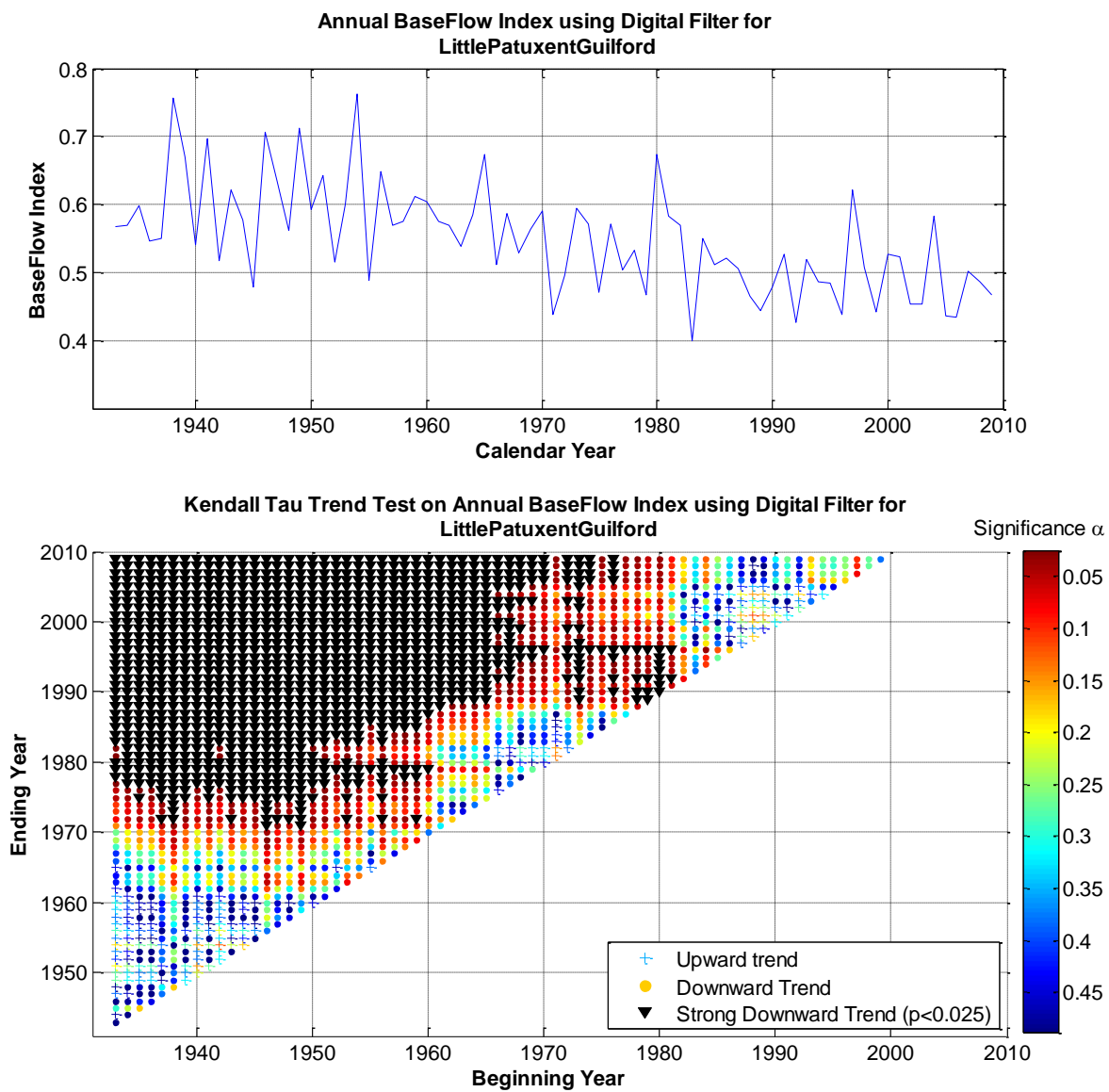
Kendall tau surfaces were developed for each of the baseflow metrics for the entire period of record of every stream gauge in Maryland for which sufficient data are available. The Kendall tau surfaces provide the foundation for analytical templates of slowflow metrics developed to diagnose the baseflow signatures of sustainable water resources.

#### Example 1: Patuxent River at Guilford.

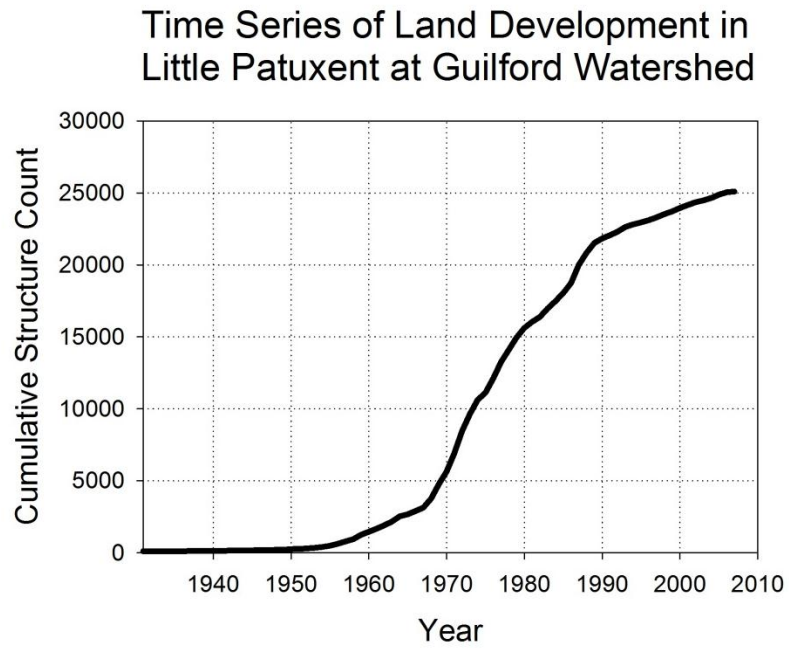
Beighley and Moglen's [101] analysis of streamflow trends in urbanizing watersheds of Central Maryland identified highly significant changes in quickflow response for the Patuxent River at Guilford. Using aerial photography and Maryland Property View parcel data to reconstruct the time series of landscape subdivision and development, they showed the dramatic increases in quickflow response corresponded to the period of most rapid post-war landscape development. We apply our slowflow trend analysis techniques to this watershed to elucidate the slowflow signature accompanying the quickflow trends they identified.

Figure 12 shows the BFI Kendall tau surface for the period of record. This dramatic pattern clearly identifies a rapid pervasive change in the baseflow regime, captured in the watershed's gauged streamflow record. Any subperiods starting prior to about 1960-1968, and ending after approximately 1975 show a strong statistically significant downward trend in the proportion of annual discharge coming from baseflow – the baseflow index. Note as well that any subperiods starting prior to about 1960 and ending before 1970 did not display a statistically significant trend. Similarly any subperiod beginning after about 1980 showed no significant trends. The pattern of the Kendall tau surface suggests relatively stationary behavior of BFI in the early and late portions of the period of record with a strong dramatic decrease in BFI beginning in about 1975.

Analogous to Beighley and Moglen's [101] approach, we reconstructed the cumulative time series of built parcels within the Patuxent at Guilford watershed, shown in Figure 13 from which the striking change in BFI is seen to correspond closely with the most rapid period of suburban development within the watershed. Figure 12 also shows the time series of BFI for the Patuxent at Guilford. The pattern revealed in the Kendall tau surface is evident here, as two relatively stationary but distinctly different BFI regimes, connected by a rapid persistent declining trend in BFI (coinciding with the hydrometeorological effects of the 1960s drought) from about 1960-1980.



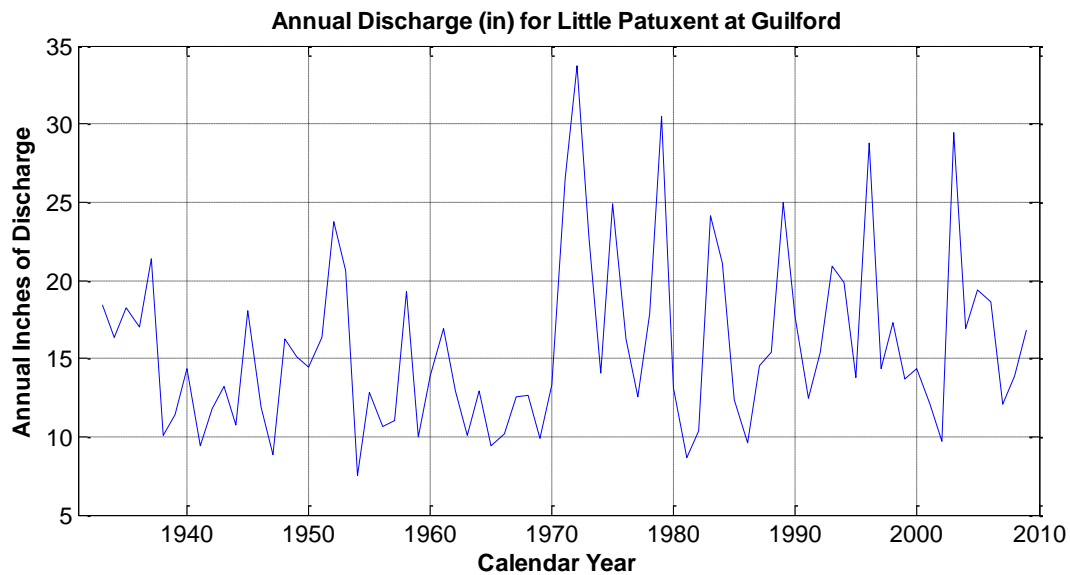
**Figure 12 Patuxent River at Guilford BFI time Series and Kendall Tau Surface**



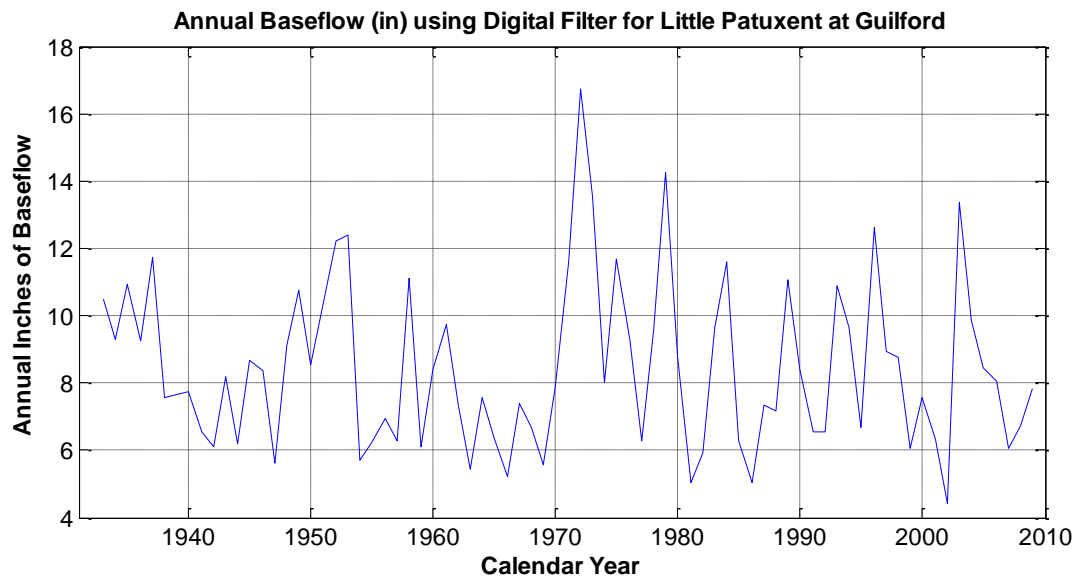
**Figure 13 Patuxent River at Guilford Cumulative Built Parcel Time Series**



To elucidate the baseflow effect of development in the Patuxent, we interpret trends in baseflow metrics using the conceptual model described in Section 3, to understand the time series of baseflow and discharge producing this shift in BFI regime. Figures 14 and 15 show the time series of annual discharge and annual baseflow for the Patuxent at Guilford. Both figures clearly show the large-scale hydroclimatic shift in both the magnitude and variability of runoff observed in MidAtlantic streamflow after 1970 [127]. Perhaps more striking is the absence of clear trends in either baseflow or streamflow that would explain the dramatic decline in BFI. The Kendall tau surfaces for both annual discharge and annual baseflow shown in Figures 16 and 17 offer a disaggregated multimetric perspective that can help diagnose the downward trend in BFI.



**Figure 14 Patuxent at Guilford Annual Discharge**



**Figure 15 Patuxent at Guilford Annual Baseflow**

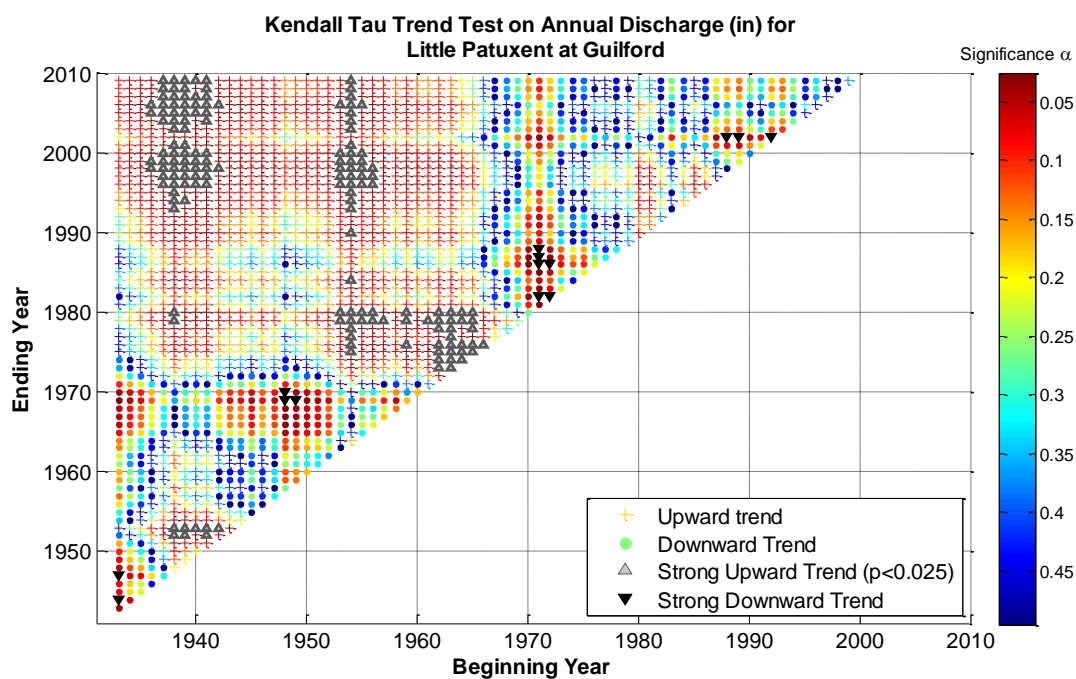


Figure 16 Patuxent at Guilford KT Discharge

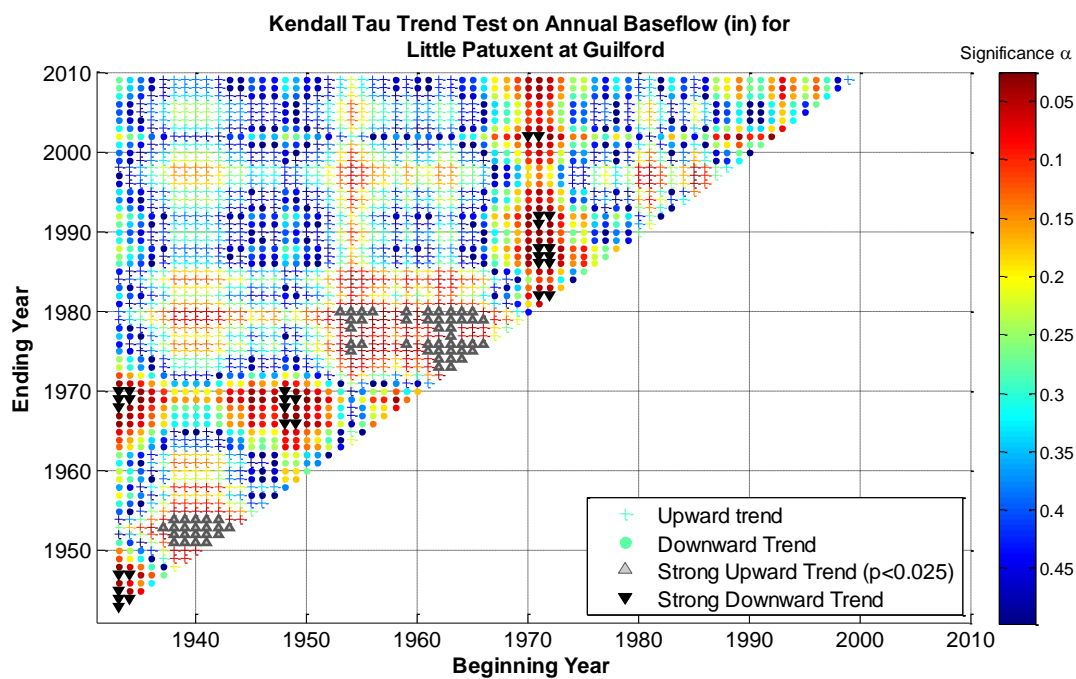
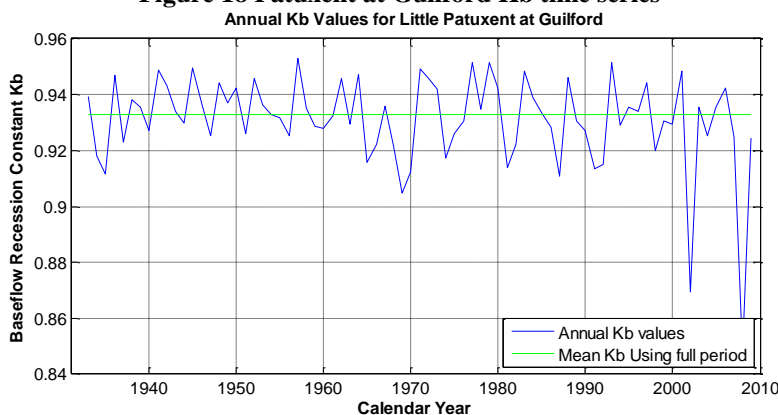


Figure 17 Patuxent at Guilford KT Baseflow

Neither baseflow nor discharge shows a statistically significant trend, but a closer examination of the Kendall tau surfaces is revealing. While not statistically significant, both Kendall tau surfaces show *increasing* trends over the critical subperiods during which BFI is decreasing. The more subtle pattern that can be disaggregated from the components of BFI show that baseflow and discharge are indeed both increasing throughout the period of maximum development –as the BFI is decreasing. This apparent paradox is resolved by recognizing that the increase in discharge is significantly greater than the increase in baseflow. As a consequence, baseflow represents a declining fraction of annual discharge, even as both fluxes are increasing. It is also notable that neither time series shows a statistically significant trend, but their ratio (BFI) shows a highly significant trend over this critical period. The dramatic increase in discharge without a complementary decrease in baseflow or recharge suggests additional sources of baseflow and recharge, and would be consistent with infrastructure effects that may alter the water budget through interbasin transfers. Municipal water supply in the Patuxent watershed comes from the Washington Suburban Sanitary Commission which treats raw water sources from the Potomac River and the Patuxent Reservoirs in the headwaters of the basin delivering treated disinfected drinking water (which becomes wastewater) as a net interbasin import to the watershed of the Patuxent at Guilford. The trends of Q, BF and BFI are consistent with baseflow fingerprints of additional hydrologic inputs such as leaking infrastructure recharge and/or wastewater discharges as described in section 3.

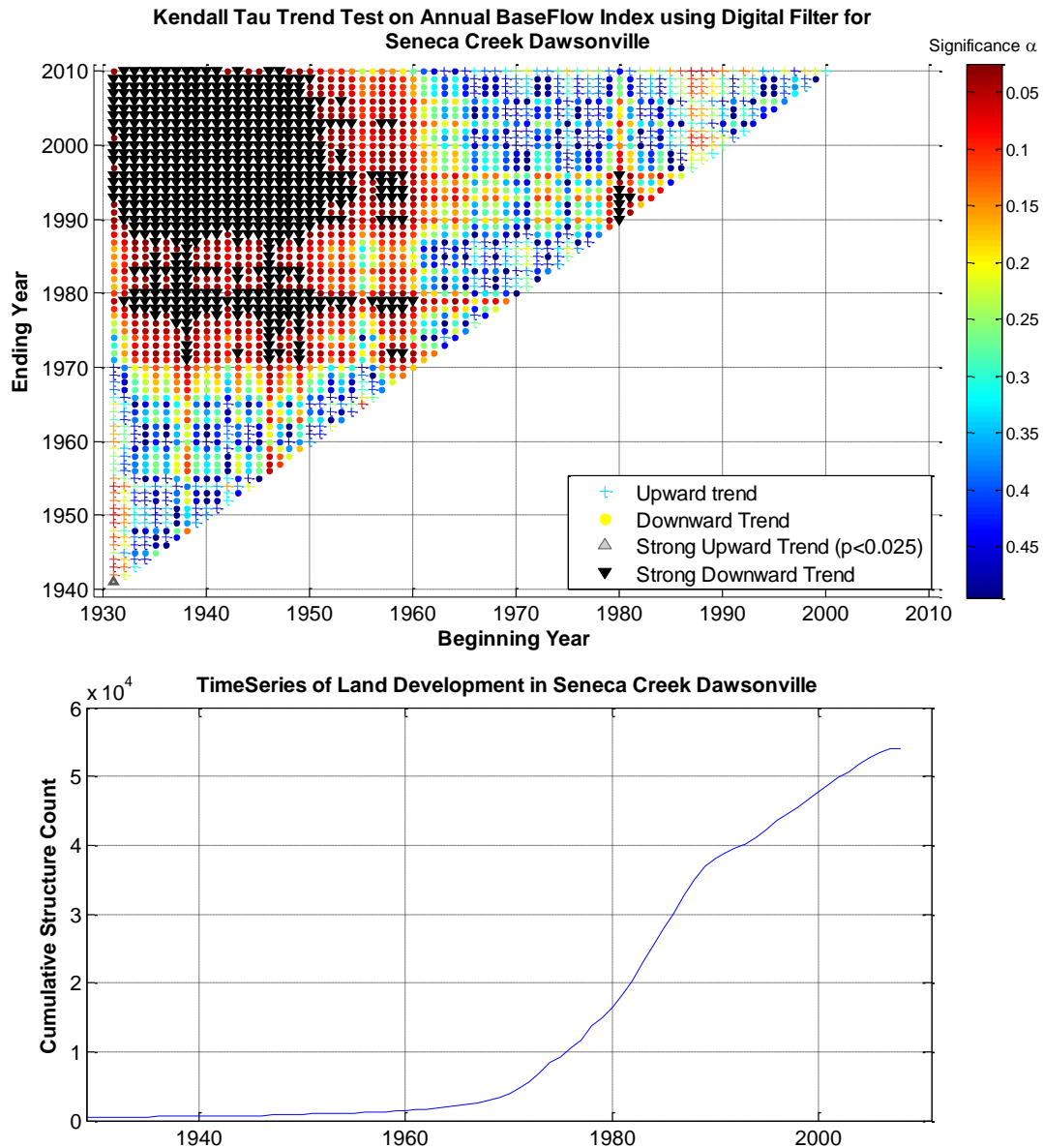
Patuxent baseflow drainage:  $K_b$  – In sharp contrast to the dramatic regime shift in BFI, the trend in baseflow recession,  $K_b$ , for the Patuxent at Guilford shows no significant change. Taken together the trends in BFI and  $K_b$  indicate a dramatic shift in baseflow hydrology without a significant change in baseflow or aquifer hydraulics. One possible effect of suburban development is accelerated drainage of groundwater through infiltration and inflow to sewer infrastructure. Such a change could alter both the hydrology of baseflow (by lowering groundwater storage) and the hydraulic signature captured by  $K_b$  (by accelerating recession rate for all baseflow dominated events). The stationarity of  $K_b$  (Figure 18) over the period of maximum development suggests that the development of sewer infrastructure accompanying the period of most rapid growth in the 1970s had no significant detectable effect on the *drainage* characteristics of the baseflow reservoir – as quantified by the recession constant  $K_b$ - even as more efficient stormwater drainage dramatically increased discharge and the runoff ratio - as observed in Beighley and Moglen [101].

**Figure 18 Patuxent at Guilford  $K_b$  time series**



### Example 2: Baseflow Signatures of Suburban development – Seneca Creek

Figure 19 shows the annual BFI kendall tau surface and time series of cumulative built parcels for Seneca Creek at Dawsonville, USGS gauge number 01645000.

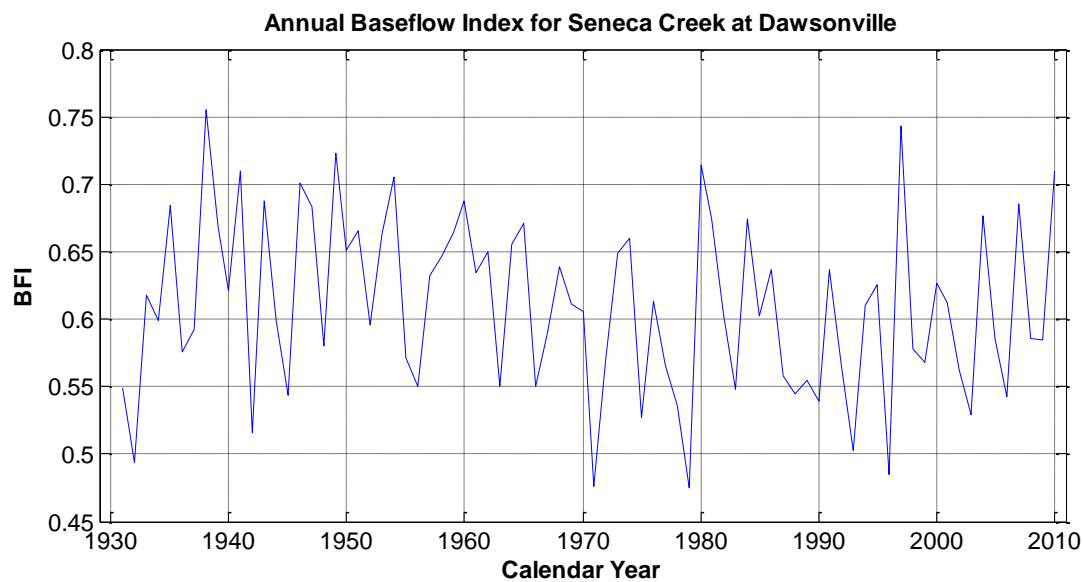


**Figure 19 Seneca Creek at Dawsonville BFI KT Surface and Cumulative Built Parcels. Legend shows non exceedance probability of the Kendall Tau statistic, or  $1 - \alpha$**

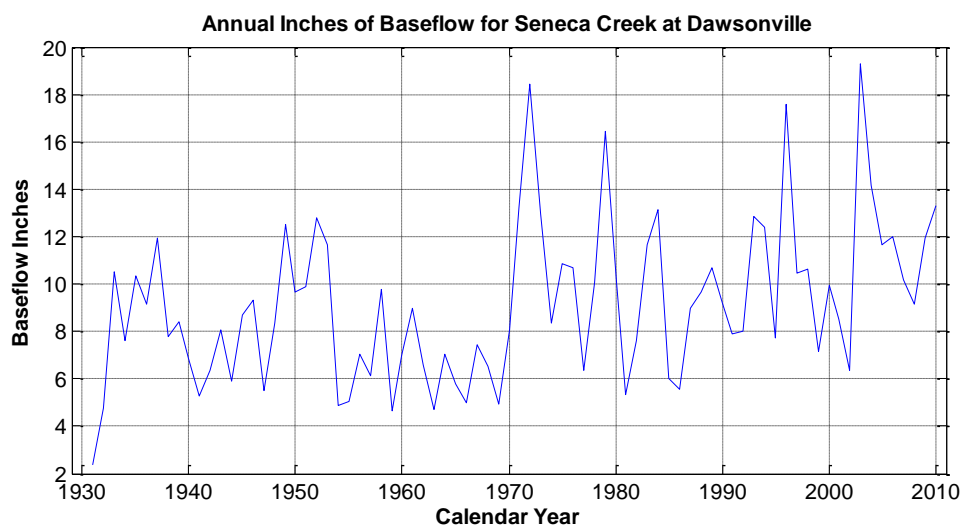
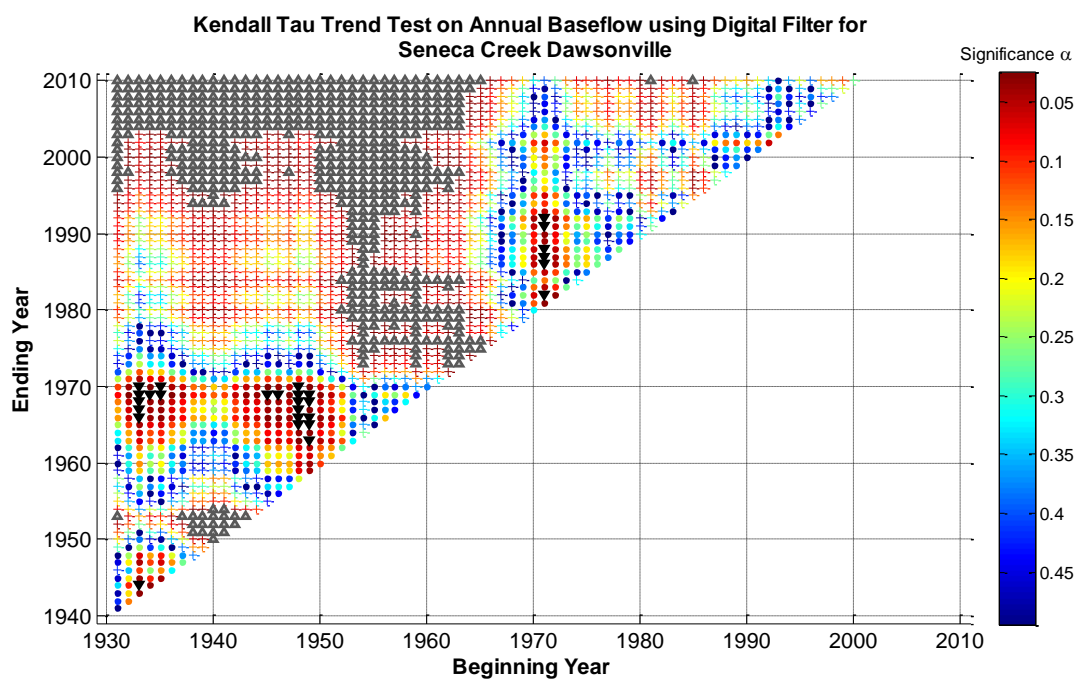
The BFI Kendall tau surface resembles that of the Patuxent at Guilford, with sub-periods of the gauged record from 1930-1970 and 1960-present without significant trends, but an intermediate

transitional sub-period in which sub-periods starting before 1955 and extending beyond about 1975 show a strong statistically significant decline in BFI ( $p = 0.025$ ).

The corresponding BFI time series is not nearly as clear and dramatic as the change in BFI regime seen in the Patuxent at Guilford. Time series and Kendall tau surfaces of annual baseflow and discharge in Figures 21 and 22 show clear increases in both the mean and the variability of streamflow and baseflow after 1970 – a pattern that is widely observed throughout MidAtlantic streamflow records [127].



**Figure 20 Seneca Creek at Dawsonville Annual BFI**



**Figure 21 Seneca Creek at Dawsonville Annual Baseflow**

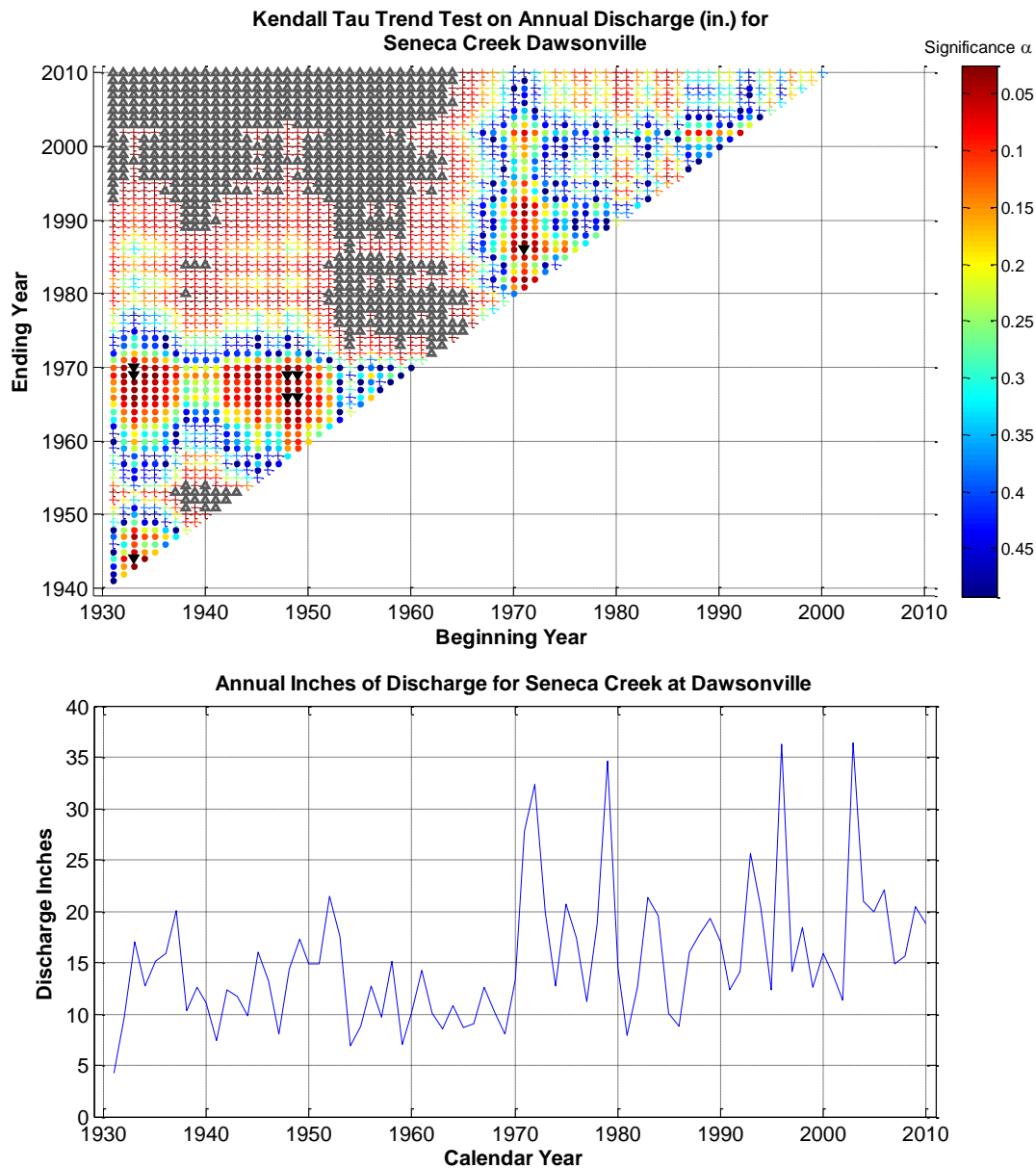


Figure 22 Seneca Creek at Dawsonville Annual Discharge

Remarkably, the statistically significant decline in BFI corresponds to statistically significant *increases* in both discharge and baseflow (as well as recharge estimated through recession displacement - see Appendix 4). Similar to the Little Patuxent at Guilford, the explanation for this apparent paradox is found in closer examination of the relative magnitudes of these increases. While streamflow and baseflow both increase, the increase in discharge is greater than the increase in baseflow. For this reason the proportion of annual discharge attributed to baseflow (the BFI) significantly decreases even as quickflow and slowflow are both significantly increasing.

Increases in discharge are consistent with the steady rapid development within the watershed, captured in the MD Property View time series of constructed parcels in Figure 19. Increases in baseflow are dominated by the overall hydrometeorological shift in about 1970, but are also incrementally affected by the construction of the Little Seneca regional water supply reservoir (which also maintains minimum instream flows). Slowflow is also incrementally affected by wastewater discharges within the watershed, which add steady return flows from municipal water supply that originates in the Patuxent and mainstem Potomac Rivers. This significant anthropogenic alteration of the flow regime has significant policy implications as well, since Seneca Creek at Dawsonville is one of the regional reference gauges used by MDE to guide the appropriation of groundwater resources in the State of Maryland.

### Example 3: Baseflow signatures of slowflow hydraulics – Georges Creek

In contrast to the baseflow fingerprints of urbanization described for the Patuxent at Guilford, Georges Creek at Franklinton shows no strong statistically significant trends in either baseflow, streamflow or recharge. A comparison of the Kendall Tau surfaces for both monthly baseflow and monthly soil moisture for climate division 126 in Figures 23 and 24 suggests that the dominant pattern of weakly dependent baseflow trends is largely explained by hydrometeorological variation. One dramatic exception to this pattern is the Kendall tau surface for the Georges Creek annual recession constant  $K_b$ , shown in Figure 25 and Appendix 4.

In contrast to streamflow, baseflow, recharge, and BFI, the recession constant  $K_b$  for Georges Creek shows a dramatic statistically significant step increase in about 1988. The time series of  $K_b$  in Figure 26 presents a relatively steady recession rate prior to about 1985, with an unusually low value of  $K_b$  associated with the drought of the 30s [129]. However after 1985 all but two of the annual values of  $K_b$  exceed the mean value for the period of record.

We note the extremely low recession constant estimated during the extreme drought to the 1930s is seen throughout the stream records we examined, signaling a change in the dominant aquifer hydraulics actively supporting baseflow under extreme drought. Under these conditions, with lowered depleted water tables, we expect the saturated media still supporting baseflow will be lower in the soil/stratigraphic profile. The exponential decline in transmissivity with depth considered by Rupp and Selker [129] would be expected to show this dramatic decline in hydraulic drainage as the shallow strata that normally provide the dominant source (and response characteristics) of baseflow dry out under extreme drought conditions.



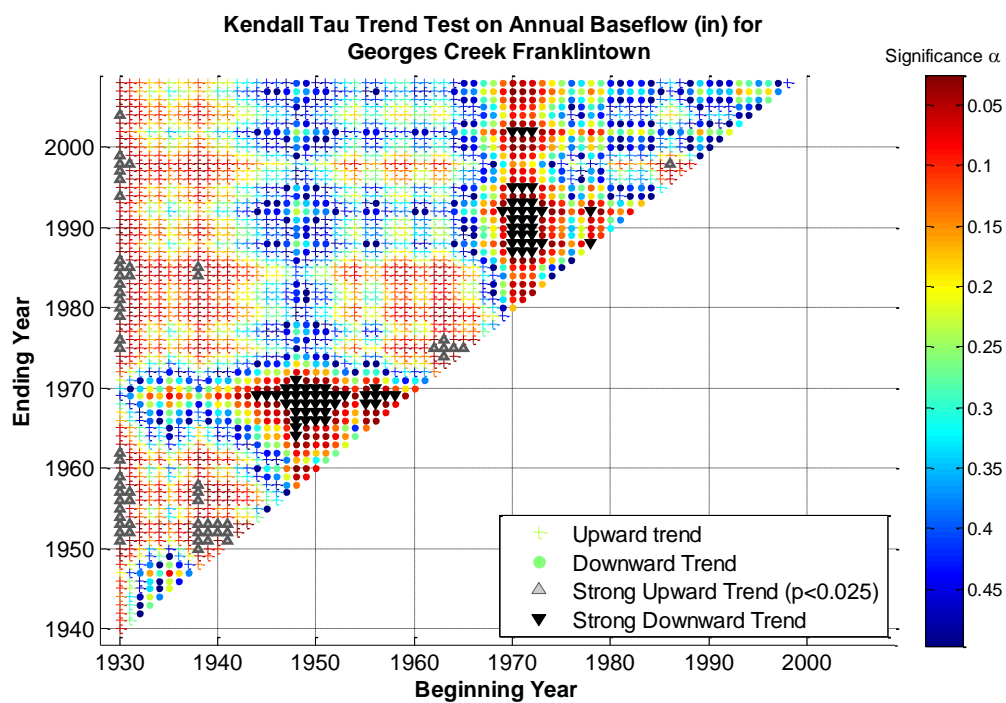


Figure 23 Georges Creek KT Surface for Baseflow

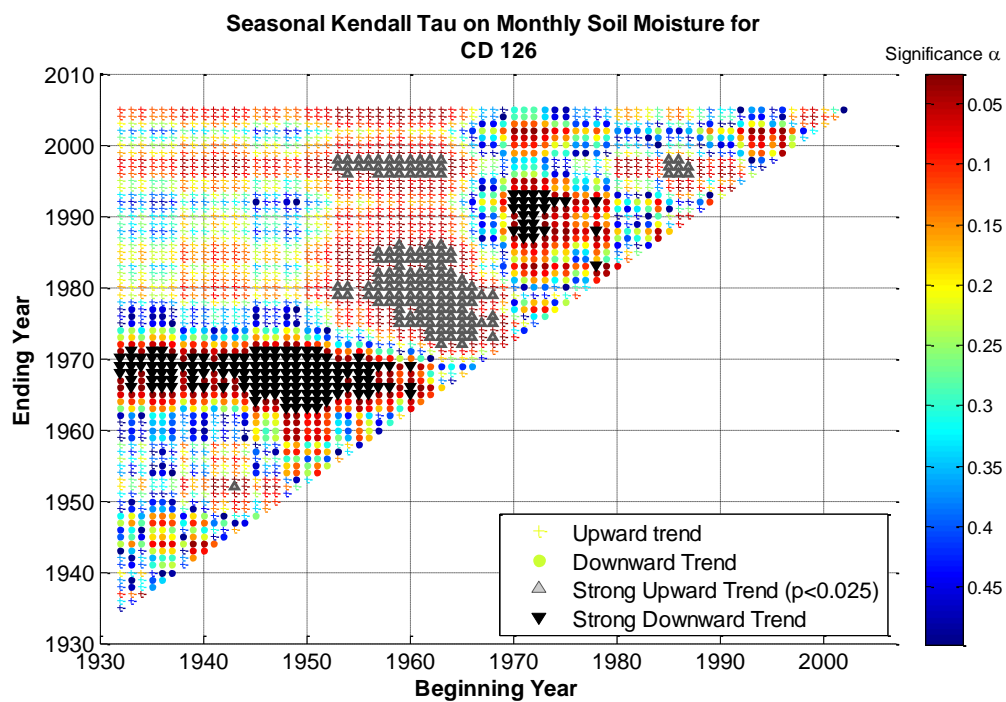


Figure 24 Georges Creek KT Surface for Climate Division 126

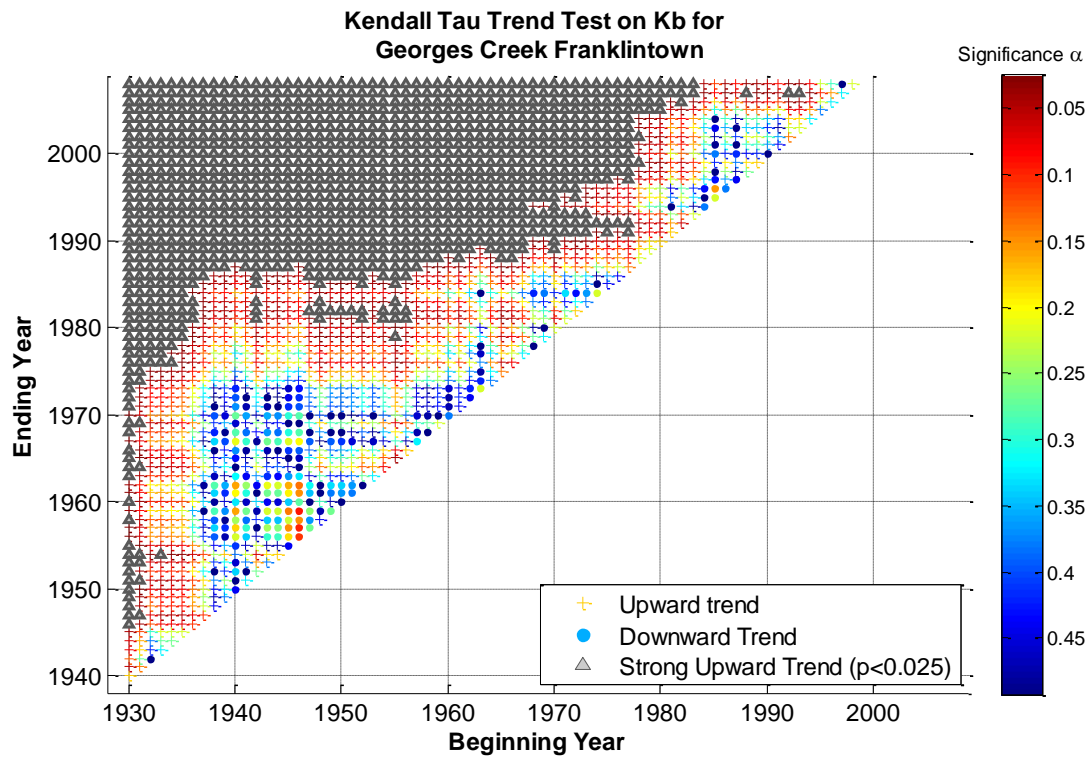


Figure 25 Georges Creek KT Surface of Kb

Timeseries of Kb for George's Creek at Franklinton

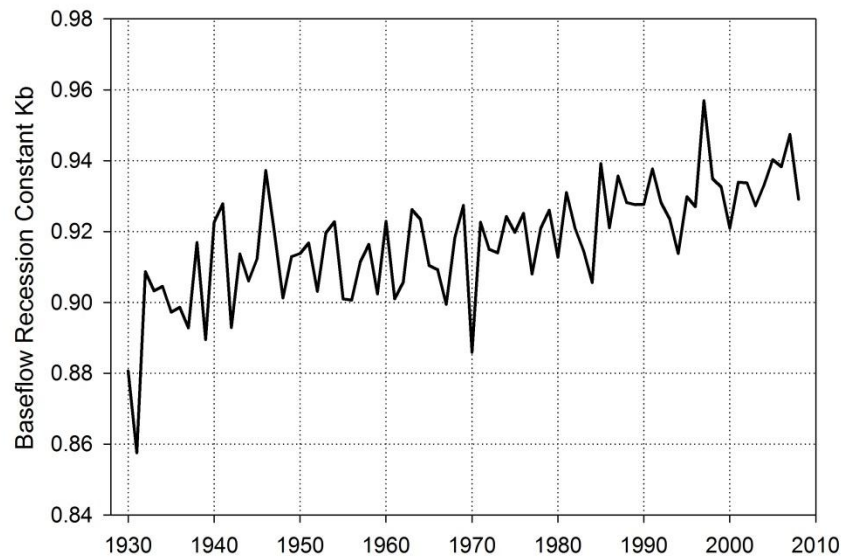
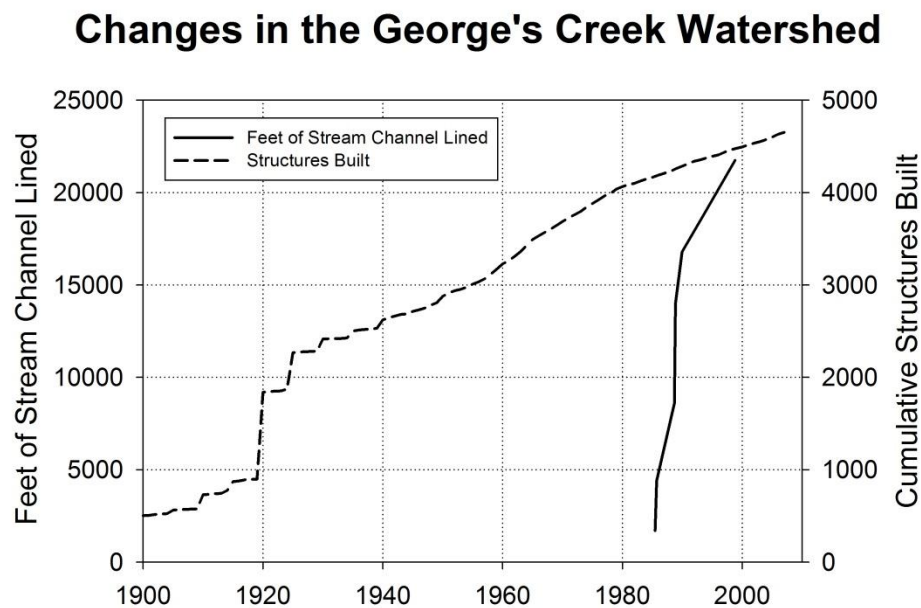


Figure 26 Georges Creek Time Series of Kb

The time series plot of cumulative built parcels suggests no apparent development-related association with this striking step trend. Georges Creek in western Maryland is not a locus for intense suburban development – or other significant active land transformation- but is in the heart of Maryland’s Appalachian coal region historically impacted by acid mine drainage. Further investigation revealed that the Maryland Bureau of Mines initiated a targeted effort in the mid- to late 1980s to grout and seal targeted sections of the Georges Creek streambed. These stream engineering projects sought to reduce the formation of acid mine drainage by eliminating channel seepage into underground abandoned mines. Over a five year period beginning in about 1988, MBOM lined over 25,000 linear feet of the Georges Creek streambed. This active management effort to reduce channel losses and underground seepage, coincides with the sharp observed increase in Kb – indicating a much slower rate of baseflow recession and higher, more sustained baseflow following the stream grouting.



**Figure 27 Georges Creek Cumulative Built Parcels and cumulative feet of grouted channel**

The highly significant trend in Kb in the absence of significant trends in any hydrologic indices of baseflow again highlights the value of combining a multimetric approach to diagnose the fingerprint of baseflow response. Non-parametric trend analysis, using the Kendall tau surface enables critical periods within the available gauge record to be targeted for further confirmatory investigation and analysis. Successfully distinguishing hydraulic baseflow alteration from

hydrologic changes further validates our multimetric approach, and enhances the confidence that a significant hydraulic alteration of baseflow response (such as might be expected if infiltration and inflow to sewer infrastructure was a dominant feature) would be more reliably detected and diagnosed using multiple baseflow metrics.

#### Controlling for Hydrometeorology

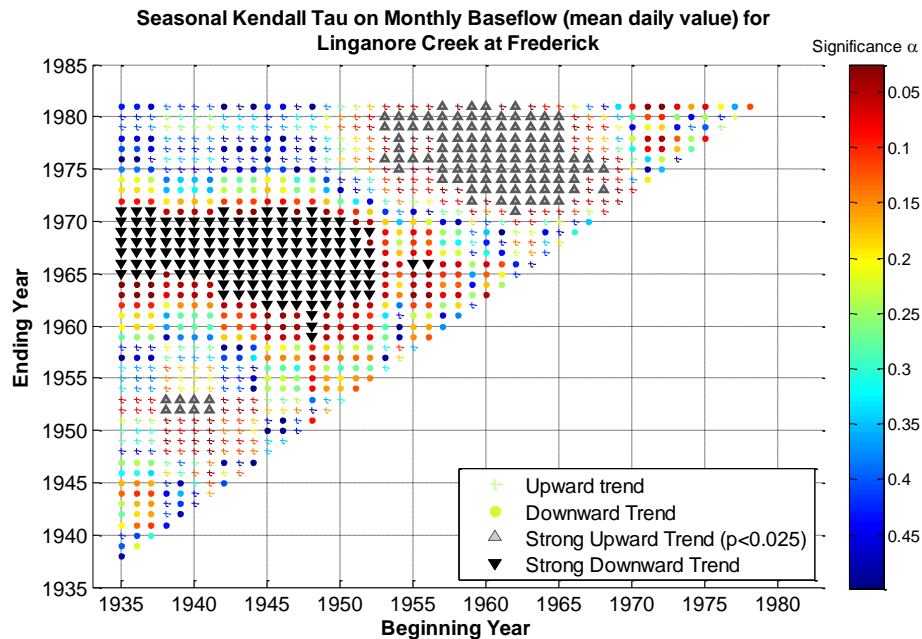
Of course all of the time series and trends considered here are inseparably coupled to the overarching regional hydrometeorological forcings that drive the hydrologic system. This strong driving signal can confound trend analysis and other approaches to detect human signatures of hydrologic alteration. To partially control for this ubiquitous forcing, we utilized timeseries of monthly conceptual soil moisture values as a reference signal for the integrated state of the regional hydrologic system.

As an example, Figures 28 & 29 show the seasonal kendal tau surface for both baseflow and monthly soil moisture (Maryland Climate division 125) for the USGS stream gauge for Linganore Creek at Frederick, one of the MDE reference gauges used for groundwater allocation. Both trend surfaces show a statistically significant declining trend ( $p = 0.025$ ) for periods of record that begin prior to 1955 and extend to approximately 1970, clearly delineating the short-term trend due to the drought of the 1960s. Both trend surfaces similarly show a statistically significant ( $p = 0.025$ ) increasing trend for periods beginning in about 1950 (for soil moisture) or 1960 (for baseflow) and ending in about 1980. As seen earlier and throughout the MidAtlantic stream gauge network, these increasing trends correspond to the particularly wet decade of the 1970s following the hydrologic drought of the 1960s. These same patterns are seen in the trend surfaces for recharge, discharge, and baseflow, as estimated with our automated implementation of the USGS PART algorithm; (in the complete slowflow templates for each gauge in Appendix 4). Collectively the multimetric signature of the basin shows little evidence of human land transformation beyond regional hydrometeorological variation. The dominant trends and variability are most closely associated with regional hydrometeorological variation.

To quantify the extent to which Linganore Creek baseflow may display trends above and beyond the inherent hydroclimatic forcing embodied in the regional soil moisture signal, we computed a heuristic measure of “climate-corrected” trend. Both Kendal tau surfaces display the statistical significance of the trend for each possible period of record, defined as the probability that a test statistic as large as that observed could occur by chance if the null hypothesis (no monotonic trend) were true. To compare the significance of a baseflow trend and a soil moisture trend, the inverse normal distribution was used to transform the significance of each trend test (a probability) into a standard normal deviate or Z-score. This value has the approximate interpretation of the distance (in standard deviations) of each test statistic from the null hypothesis of no monotonic trend, for each metric. The difference between these Z scores was then plotted on the same axes – corresponding to the starting and ending years of the kendal tau surface- as an index of the “excess trend”, normalized to the inherent regional hydrometeorological forcings captured by the divisional soil moisture reference signal.

An example of the difference in the seasonal Kendall tau Z-score surfaces for monthly baseflow for Linganore Creek and monthly divisional soil moisture is shown in Figure 29. For the vast majority of feasible subperiods of the gauge record, the difference in the baseflow trend

and the soil moisture trend is less than one standard deviation. We note that the Linganore Creek gauge record is influenced by reservoir releases from Lake Linganore reservoir after 1971. The absence of a significant signal corresponding to this influence indicates the effects of low flow releases from Lake Linganore is not large enough to produce a statistically significant basin-scale low flow trend, above and beyond beyond the region's natural hydroclimatic variability.



**Figure 28 Linganore Creek at Frederick KT Baseflow Surface**

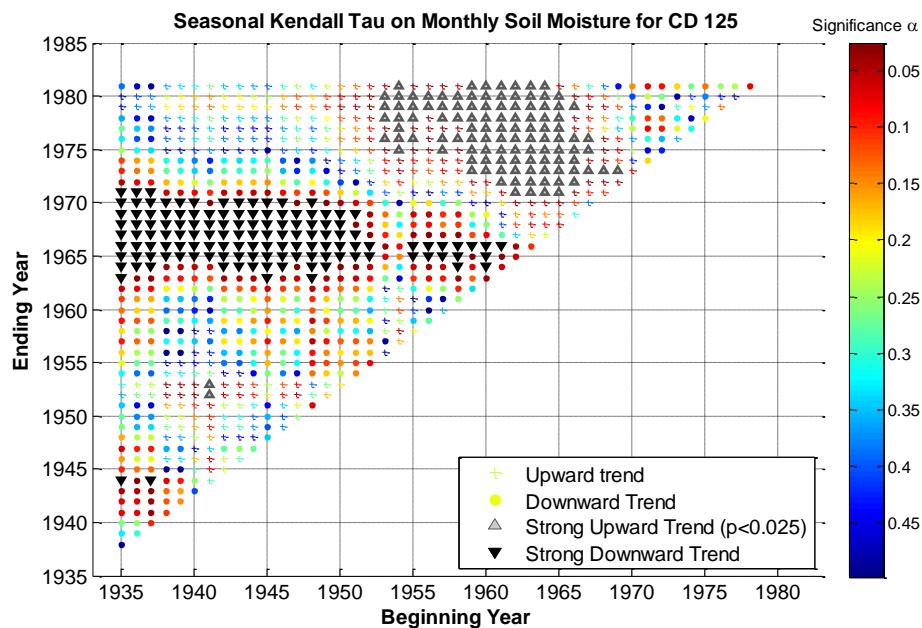


Figure 29 KT Surface for MD Climate Division 125

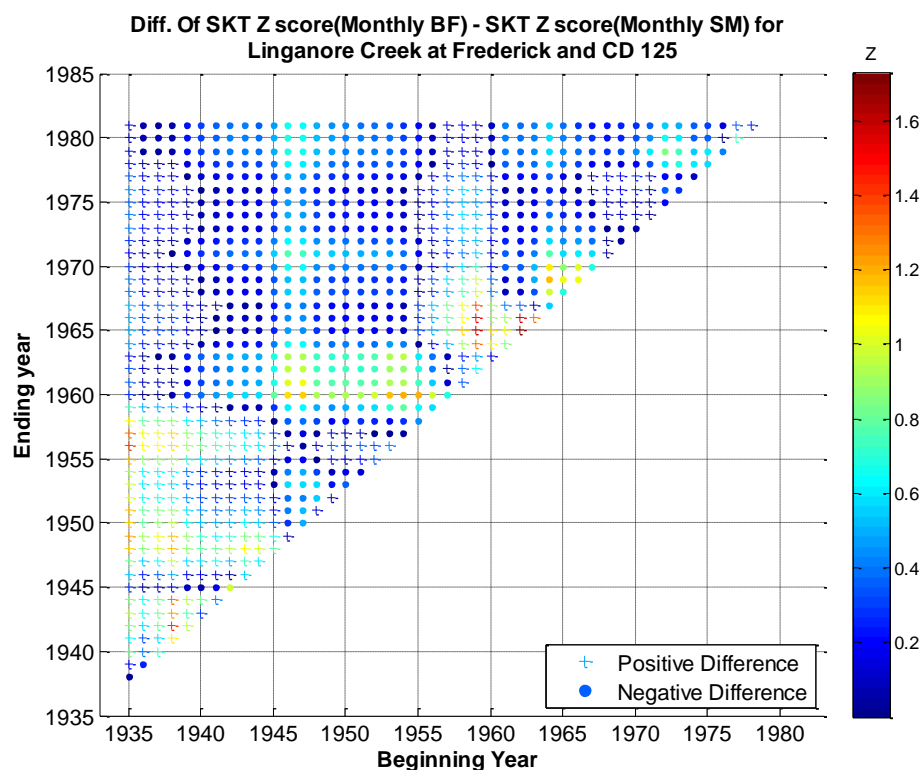


Figure 30 KT Surface of "excess" trend in Linganore Creek Baseflow &amp; CD 125

In contrast the seasonal kendal tau surfaces for baseflow (Figure 31) for Seneca Creek at Dawsonville and soil moisture for CD 125 (Figure 29) show significant differences. Most notably the Seneca Creek kendal tau surface for monthly baseflow (Figure 27) shows a very significant increase ( $p = 0.025$ ) in baseflow for periods starting between 1935 and 1965 and ending after about 1995. This strong consistent increase – corresponding to a period of development with increasing wastewater discharges in the watershed- is mimicked in estimated recharge, but is *not* strongly expressed in the hydrometeorological control signal from divisional soil moisture. The Z-score difference surface between monthly baseflow and monthly soil moisture trends (Figure 32) clearly shows a very significant increase in baseflow (1.5 to over 2 standard deviations of “excess trend”) consistent with a strong consistent trend above and beyond the inherent climate signal.



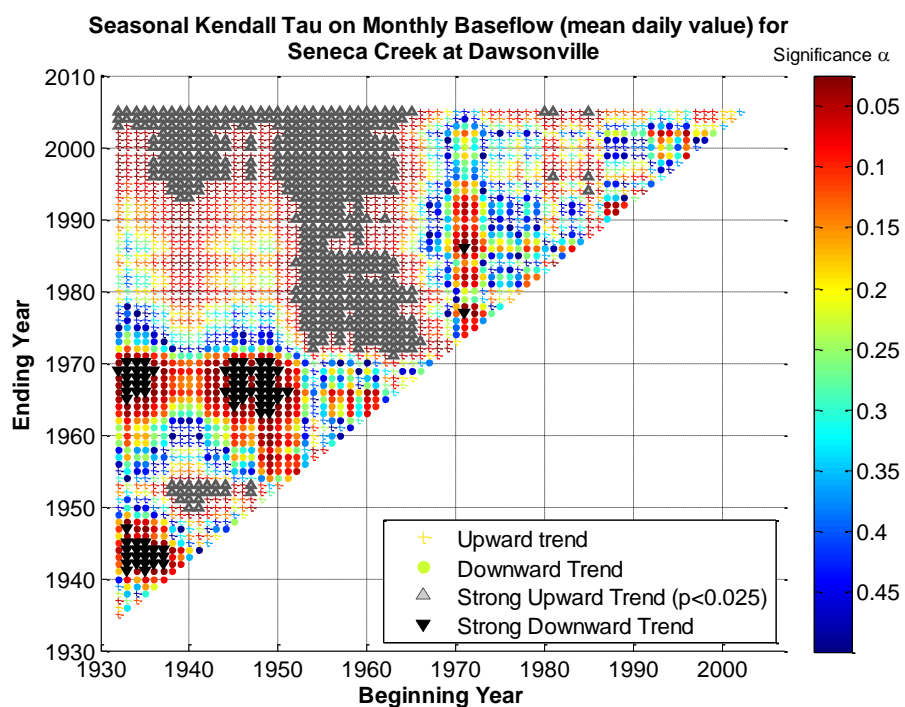


Figure 31 Seneca Creek at Dawsonville BF KT Surface

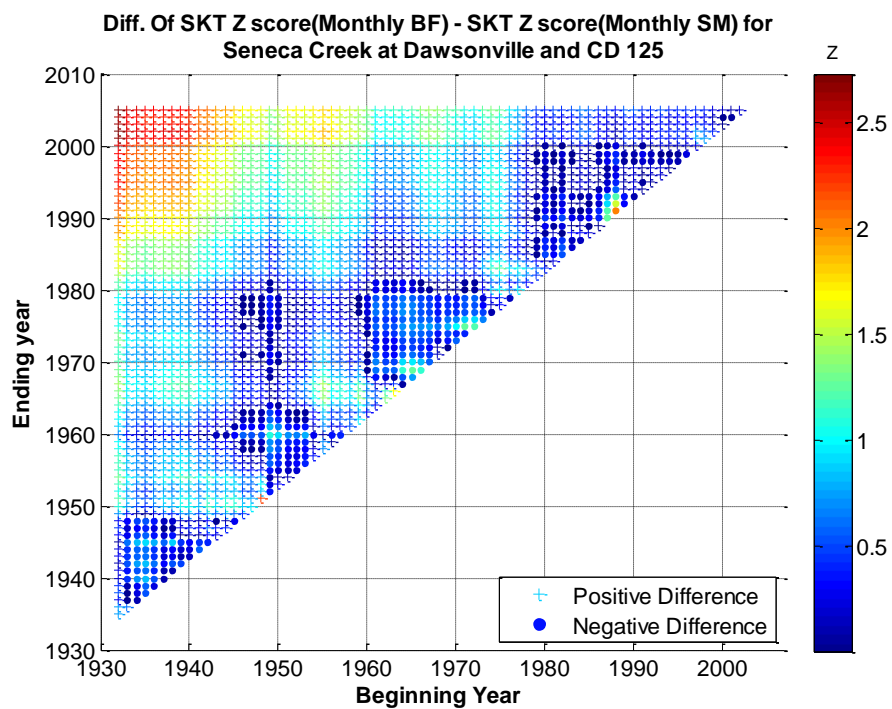


Figure 32 Seneca Creek at Dawsonville KT Surface of "excess" trend in baseflow referenced to CD 125

This difference surface is only a first attempt to construct a simple consistent dimensionless measure of climate-adjusted trend. Bootstrap methods capable of consistently controlling for weak dependence have been developed, and offer more rigorous approaches to identifying statistically significant trends, above and beyond the weak dependence of hydrometeorological forcings inherent in all streamflow metrics. While the full development testing and implementation of these methods was beyond the scope of the current project, this remains a promising avenue for further investigation to enhance the value of the techniques developed here.

As a simple consistent indicator of climate-adjusted trend, the normalized difference surfaces between monthly baseflow metrics and monthly soil moisture Kendall tau surfaces were also computed for all stream gauge records and are incorporated in the gauge templates presented in Appendix 4.

### Summary

- Trend analysis of baseflow metrics adds a temporal dimension to multivariate baseflow fingerprints. We used a robust nonparametric trend test to analyze time series of each of the baseflow metrics for every gauge in Maryland with sufficient data.
- Trend analysis of hydrologic time series can be sensitive to anomalies from short lived extremes as well as secular trends, influenced by the vagaries of the available period of record.
- To refine our interpretation of significant trends, we adapted methods of McCabe et al. [127] and Zhang [128], testing for trends of all possible subperiods in the gauged period of record, summarized in a Kendall tau surface for each baseflow metric.
- Multimetric trend patterns suggested causal mechanisms that could be evaluated with supplemental information including parcel-based indicators of landuse fragmentation and development rates, and evidence of infrastructure effects and drainage modification.
- The Patuxent River at Guilford was representative of watersheds dominated by older suburban development. We found declining trends in BFI coincided with peak development estimated from MDProperty View parcel data.
- Surprisingly, trends of declining BFI often corresponded to trends of *increasing* baseflow, recharge and streamflow. Using multimetric slowflow analysis, these paradoxical patterns were found to result from a relatively *greater* increase in streamflow (consistent with increased runoff production from urbanization) than baseflow. The synchronous increase of discharge, baseflow, and recharge strongly suggests additional water budget inputs such as interbasin transfers from infrastructure water systems.



- Trend effects due to climate extremes and hydrometeorological variability were also accounted for using a derived regional water balance that was independent of catchment landuse change. Where hydrologic patterns closely mimic water balance patterns, trends show little significance beyond climate forcing.
- Where the pattern of land transformation introduces significant trends above and beyond climate forcing, this hydrometeorological reference signal adds useful insight into the timing and magnitude of human intervention, above and beyond the inherent signature of climate forcing.

## 5. Discussion

### **Baseflow and Groundwater Appropriation in Maryland**

Slow flow characteristics of Maryland's gauged watersheds directly influence sustainable management of the State's water resources. Ground water appropriations in Maryland are permitted based on regional estimates of groundwater recharge based on baseflow estimates derived from gauged streamflow [88, 130]. Baseflow separation using the USGS PART algorithm (Appendix 1) is used to estimate the annual recharge with a 10-year recurrence interval, referred to as a 10-year drought recharge. The 10-year recharge depth is further reduced by a reserve volume derived from the watershed  $7Q_{10}$  discharge, to estimate an upper bound on the annual recharge that could be appropriated for groundwater withdrawal.

The current groundwater appropriation system clearly ties the availability of groundwater to slowflow characteristics of gauged streamflow considered in this work. Element 26 (The Water Resources Element) of the Maryland Department of Planning's series, "Managing Maryland's Growth" describes these computations, and reports the estimated baseflow-derived recharge for 33 reference gauges used for groundwater appropriation throughout the State. Land transformation impacts on streamflow directly affect both the hydrologic recharge of groundwater resources and the quantitative regulatory criteria used for appropriating groundwater in the State of Maryland. Maryland's 33 original groundwater appropriation reference gauges (now expanded to 37 reference gauges) are therefore also included in our analysis, with baseflow characteristics summarized in Appendix 3 and full multimetric slowflow templates included in Appendix 4.

### **Streamflow Records Analyzed**

Two hundred-twenty-three (223) stream gauge records – of varying length and quality – are available within the state of Maryland. The period of record for many of these gauges is too short to be used in our trend analysis, or have been inactive for decades. One hundred-seven (107) stream gauges in Maryland have periods of record spanning at least 25 years and could support meaningful trend analysis. Closer inspection revealed that many of these gauge records had significant data gaps, and were therefore unsuitable for continuous trend analysis. The analysis supporting this study therefore focused on a subset of 57 continuous gauge records. Eleven additional BES gauges with relatively short records were also included in the analysis in Section 3 (though not analyzed for trend), bringing the number of gauges analyzed to 68. Five gauges outside Maryland that are used as reference gauges for groundwater appropriation in Maryland are also included among the set of 57 gauges used for our analysis. These include Brandywine Creek and the Yellow Breeches in PA, the Cacapon and Blackwater River in WV, and Goose Creek in VA along with all of the Maryland reference gauges identified by the Maryland Department of Planning [130]. The full set of baseflow metrics derived for the core set of 57 gauges is presented in Appendices 3 and 4.

Of the 95 HCDN gauges in the Chesapeake Bay Watershed, 30 are associated with the State of Maryland and were included in our core set of 57 gauges, although the HCDN period of

record generally represents a subperiod of the full period of record analyzed in this work. Twenty-nine HCDN gauges are also located in the Piedmont physiographic province of Chesapeake Bay, of which 27 were used to define the HCDN Piedmont baseflow response in Section 3. Two HCDN piedmont gauges not included in that analysis were Goose Creek and the Monocacy at Bridgeport. Both were excluded from the Piedmont HCDN gauge statistics because a substantial portion of their contributing drainage area lies outside the piedmont.

Of the screened gauge records available for this study a set of 57 continuous daily flow records were selected and used to produce a consistent set of metrics assembled as a slowflow “template”. The slowflow template for each gauge includes time series and Kendall tau surfaces for the slow flow metrics used in this research (see Appendix 4). The locations of these gauges are shown in Figure 37 and constitute the core streamflow data used to investigate the slowflow signature of sustainable water resources in Maryland.

### Slowflow templates

For the 57 continuous streamflow records assembled as the core data set for this analysis, a consistent set of slow flow metrics were computed and assembled into two-page “slowflow templates”, reproduced in Appendix 4. The slowflow templates include Kendall tau surfaces for baseflow, BFI, RORA Recharge, Kb, and monthly divisional soil moisture, as well as the climate-adjusted baseflow trend indicator surface described in section 4. The template also includes time series plots of discharge, baseflow, BFI, soil moisture, and recharge as well as cumulative built parcels for each Maryland watershed. Since consistent parcel data was only available in Maryland, templates for watersheds that span interstate boundaries (e.g. Rock Creek at DC) do not include a built parcel time series. Collectively the information consistently assembled in these templates provides the suite of metrics used to investigate the slowflow fingerprints of sustainable water resources in Maryland.

### **Baseflow Signatures of Working Lands Fragmentation**

Our analysis set out to use Hanlon et al.’s [1] identification of areas with greatest exurban fragmentation to infer baseflow signatures from the fragmentation of Maryland’s working lands. The dominant areas of fragmentation they identified were not well associated with the boundaries of watersheds with high quality continuous streamflow records. The strength (and the weakness) of our analytical approach depends critically on the availability of high quality continuous streamflow records that capture the dominant signals of land transformation processes at work within each watershed. Our analysis therefore evolved to first identify the significant watershed-scale signals that could be detected in extant streamflow records, and use these signals to interpret the patterns of development and associated hydrologic change. As the analysis progressed, the variety of forcings revealed through our multimetric analysis illuminated the complexity of the problem and the strengths and inherent limitations imposed by the reliance on the availability of high quality continuous streamflow records.

Hanlon et al. [1] identified the areas of Frederick and Montgomery counties experiencing the greatest fragmentation of working lands between 1986 and 2001. We located these fragmentation patterns within the gauged watersheds analyzed to identify the signature of working land fragmentation in slowflow. A number of watersheds associated with significant

1986-2001 fragmentation, had streamflow records that were discontinued between ~1980-1995. For these watersheds, including the Anacostia at Colesville, Owens Creek, Watts Branch, Linganore Creek, Fishing Creek, and Hunting Creek, no streamflow data was available to evaluate the potential effects of the fragmentation footprints identified by Hanlon et al. [1]. Significant fragmentation of agricultural lands was identified in the Seneca Creek watershed. As discussed in detail in Sections 3 and 4, any slowflow fingerprint from the fragmentation of working lands in this watershed is dominated by the overwhelming urbanization-infrastructure signals described earlier. Little Bennett Creek and Catocin Creek captured a significant forest fragmentation footprint within part of their watersheds, but no significant slowflow signal was found in these gauge records. The Anacostia River at Hyattsville included a significant footprint of 1986-2001 agricultural fragmentation, but the overwhelming slowflow signal in this gauge record is dominated by older post-WWII suburban/infrastructure development.

Within the existing Maryland stream gauge network we found no watersheds in which Hanlon et al.'s [1] exurban fragmentation represented the *dominant* watershed-scale landuse change, and coincided with a stream gauge record suitable for the analyses performed here. For the streamflow records available in Maryland, a quantitative estimate of the specific hydrologic effect of exurban fragmentation could not be uniquely distinguished from the other dominant processes affecting observed streamflow. Our interpretation of these baseflow metrics suggests that, *within the scale and resolution available to us through existing continuous streamflow records*, the impact of exurban fragmentation has not yet reached the threshold at which it can be clearly distinguished using the combination of metrics prepared in this work.

### **Slowflow Templates: Overview of dominant patterns.**

Over the 57 slowflow templates in Appendix 4, a range of striking and consistent patterns emerged and are briefly summarized below.

Increasing trends in BFI- Five of the core gauge records, primarily on the mainstem of the Potomac River, displayed significant increasing BFI trends. The significant increase in the recession constant  $K_b$  associated with these trends indicates a more gradual recession and more sustained baseflow signal on the mainstem of the upper Potomac. These coincident changes in apparent baseflow recession characteristics are consistent with active management of minimum instream flows from Savage River Reservoir and (since 1981) by Jennings Randolph Reservoir (the largest impoundment in the Potomac River Basin) and significant regional wastewater discharges. The Potomac River at Steyer is located upstream of Jennings Randolph Reservoir on the North Branch of the Potomac. This watershed is severely impacted by acid mine drainage and active mining activity, and has been targeted by the State of Maryland for AMD mitigation projects. The step increase in baseflow and  $K_b$  in the late 80's in this watershed is associated with a combination of coal processing discharges and AMD mitigation activities similar to those described for Georges Creek in Section 4. For example, within the watershed of the North Branch at Steyer, Mettiki Coal LLC is permitted to discharge 80 MGD of treated water from mining operations.

Declining BFI trends – Eight basins were identified with significant decreases in BFI, in watersheds with significant older suburban development. Typical among these trends is the

pattern of increasing trends in both streamflow and baseflow. Like the *Patuxent at Guilford* and *Seneca Creek at Dawsonville*, this pattern suggests increases in quickflow expected from urban development, along with infrastructure effects consistent with interbasin transfers via regional municipal water supply or wastewater discharges that also increase slowflow. This recurring multimetric fingerprint of older suburban development in watersheds with centralized water infrastructure offers testable hypotheses that can be evaluated with additional data on the history and magnitude of NPDES discharge permits, the bounds and configuration of the water and wastewater infrastructure system, and a refined understanding of source waters for regional water supply systems.

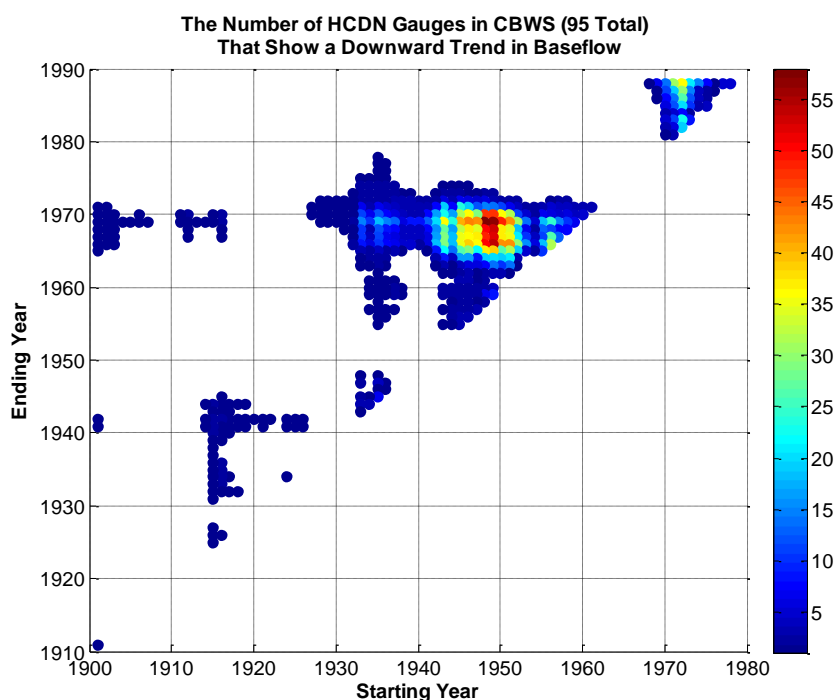
In Maryland's portion of the Baltimore-Washington metroplex, the dominant water suppliers are the Washington Suburban Sanitary Commission and Baltimore City. For the vast majority of their service areas the municipal source waters exploited by these suppliers represent an interbasin transfer. For this reason significant leakage or wastewater discharges change not only the discharge patterns, but also the basin water balance. Multimetric indicators of both recession rate ( $K_b$ ) and BFI provide useful discriminating indicators of this dominant pattern of suburban development. The recurring pattern of declining BFI with increasing  $Q$  and BF frames the signature of interbasin transfer effects through water infrastructure accompanying increased quickflow response from urban development and enhanced urban drainage. Perhaps one of the most striking examples of this pattern is found in Rock Creek at DC, with an abrupt change in flow regime in 1960 corresponding to the period of most rapid buildout of the Maryland-DC suburbs in the watershed. To this day the dramatic increase in Rock Creek quickflow (driving the decline in BFI) remains a source of urban flooding problems that periodically closes the Rock Creek Parkway.

Increasing  $K_b$  Trends Twelve watersheds displayed clear striking trends of increasing  $K_b$ . Increasing values of the recession constant indicate more sustained baseflow and a slower rate of baseflow recession. Supplemental discharges from wastewater treatment plants can strongly influence computed  $K_b$ , as steady wastewater discharges maintain low flows – even as groundwater drainage may be declining or impaired. This ambiguity is weakly confirmed by modest trends in RORA recharge estimates, suggesting subtle differences between  $K_b$  and RORA recharge may help distinguish hydraulic and hydrologic changes in slowflow when no recharge of the subsurface hydrologic system is occurring. This ambiguity has significant implications for the estimation of regulatory recharge and the MDE methods of appropriating groundwater in the State [88].

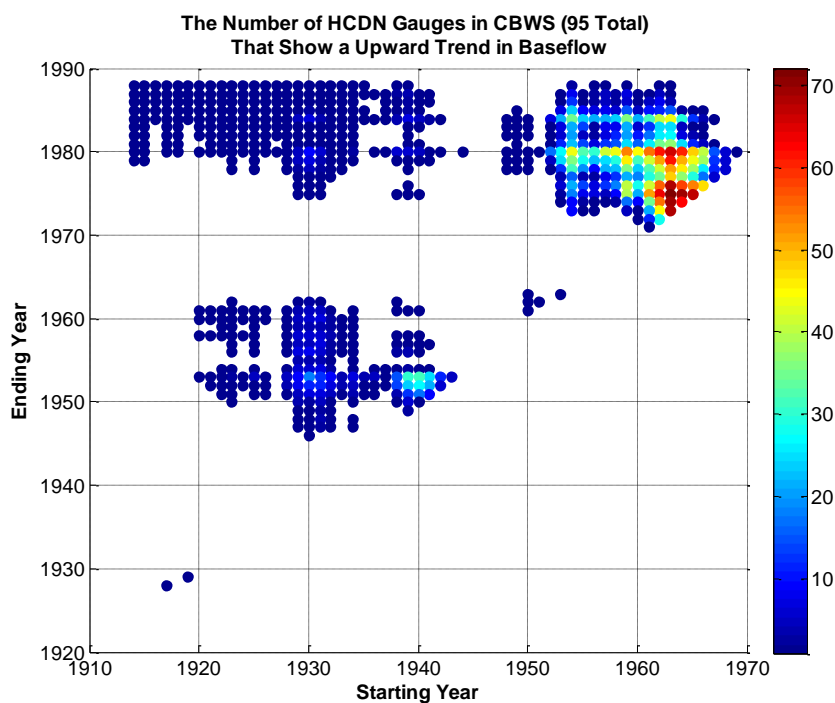
Distinguishing changes in hydraulic drainage and recharge from wastewater discharges (that may involve interbasin transfers) requires additional information beyond gauged streamflow records alone. As an example of the hypothesis-driven investigation of the cause of these slowflow signals, we searched for NPDES permitted discharges in the watersheds showing significant increasing trends in  $K_b$ . We found significant permitted NPDES discharges within most of the watersheds with a significant increasing  $K_b$  signal, including permitted discharges of over 6 mgd in Conococheague Creek; 15 mgd in Antietam Creek; 6 mgd in Monocacy River at Bridgeport; 26 mgd for the Monocacy River at Jug Bridge; 120 mgd for the Potomac River at Hancock; and nearly 1 mgd on Western Run.

Of all the Maryland gauge records analyzed, only Owens Creek showed a clear declining trend in Kb. The coherent period of decreasing trends in Kb appears to be most closely associated with – though starting before- the drought of the 1960s. The absence of significant trends in other metrics and a post-drought increase in Kb for the remainder of the truncated record, make the interpretation of this lone significant declining trend in Kb unclear, motivating a more detailed investigation of watershed diversion and infrastructure history. Most striking however is the absence of significant declining trends in Kb among all the records examined. One postulated effect of urban/suburban land transformation is a hydraulic response associated with infiltration and inflow to storm sewers that would be expected to produce a significant declining trend in Kb. At the watershed scales captured in Maryland's stream gauge network, we found no significant evidence of this hydraulic change in baseflow response associated with suburban land transformation.

Significant baseflow trends in the 95 HCDN gauges of the Chesapeake Bay watershed are summarized in Figures 33 and 34:



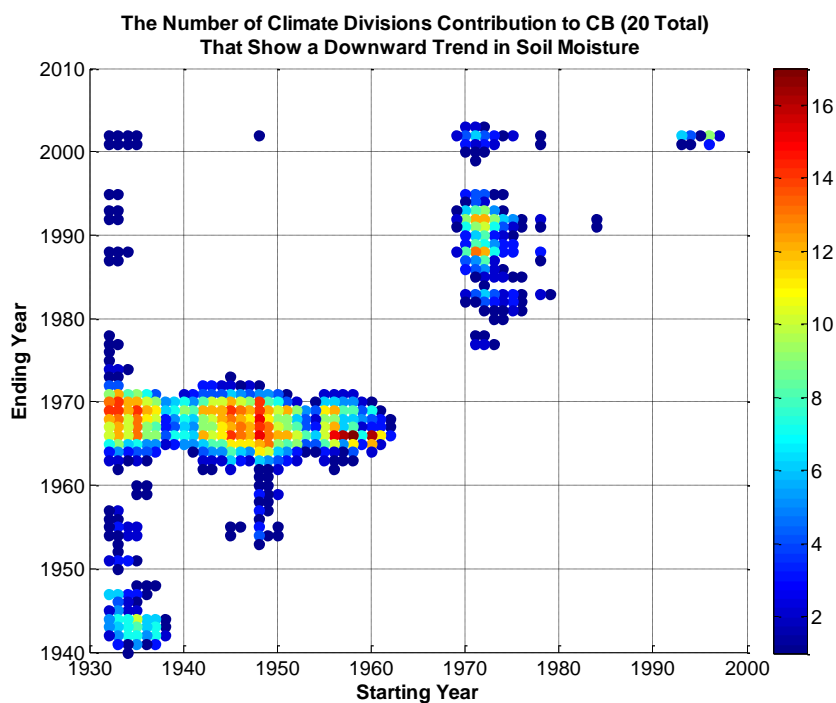
**Figure 33** Number of HCDN gauges with significant decreasing baseflow trends



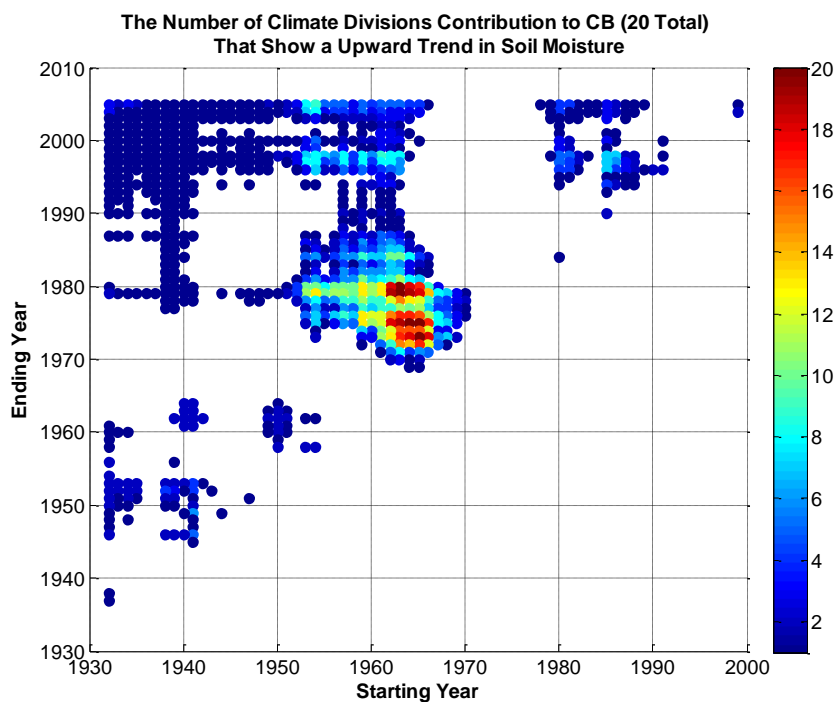
**Figure 34 Number of HCDN gauges with significant increasing baseflow trends**

The majority of the Bay's 95 HCDN gauges show a significant decreasing baseflow trend entering drought of the 60's and a complementary increasing trend emerging from the drought through the 1970s.

Essentially the same trends are seen in time series of regional soil moisture among the 20 climate divisions of the Chesapeake Bay Watershed in Figures 35-36. The majority of climate divisions show the same strong downward trend through the sixties and the re-wetting in the seventies.



**Figure 35 Chesapeake Bay Climate Divisions with decreasing trends in soil moisture**



**Figure 36 Chesapeake Bay Climate Divisions with increasing trends in soil moisture**



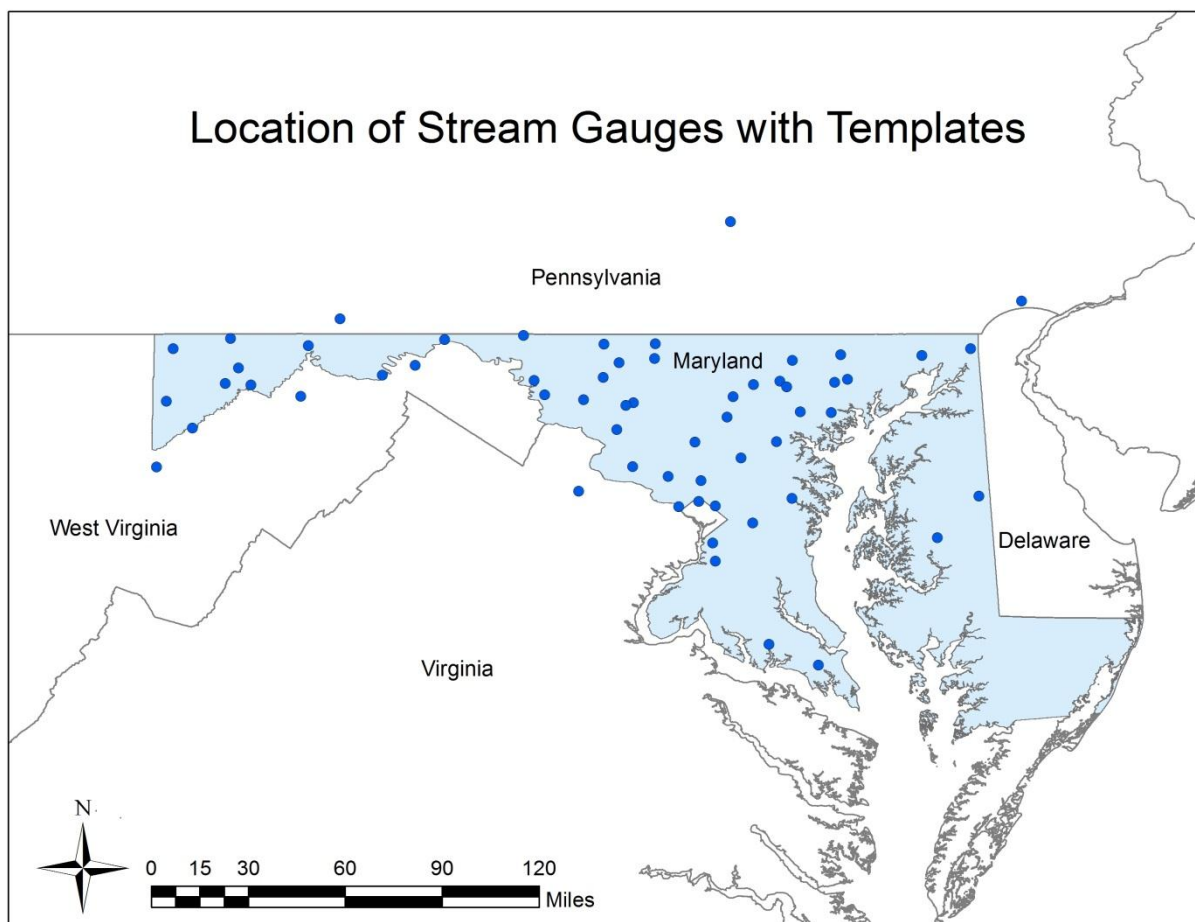
## Summary

Methods developed in this project offer enhanced insights into the interaction of human activities and sustainable water resources, and are directly transferable to other gauged watersheds of the Chesapeake Bay watershed. Where available, streamflow information can provide a rich tool to diagnose and quantify human impacts to the hydrologic system and the baseflow signatures of sustainable water resources.

Significant trends among baseflow metrics provide a refined fingerprint of changes to the dominant processes shaping watershed-scale hydrologic response. The detection of significant changes in the slowflow characteristics of Maryland's water resources signals change that propagates through the system affecting water resource planning for human and ecological goals. Detectable changes in the streamflow characteristics of the reference gauges used to permit groundwater appropriations [88, 130] have immediate and direct implications for regulatory decision making and reliable long-term planning for growth and natural resource management.

Seneca Creek at Dawsonville is one of the State's 37 groundwater reference gauges. Significant trends in the gauge record for Seneca Creek suggest historical baseflow may be an inadequate basis for allocating groundwater. To the extent that a gauged-derived recharge or baseflow signal is not groundwater recharge, the heuristic recharge estimate from gauged streamflow can exacerbate groundwater exploitation beyond the reserve limits used in current regulatory assessment.

The complex compound mechanisms affecting slowflow response, including interbasin transfers and leaky infrastructure, create a regulatory paradox for current groundwater appropriation practices. To the extent leaking infrastructure truly recharges ground water, the State faces the dilemma of whether or not to explicitly appropriate this unintended interbasin transfer as an exploitable component of regional groundwater system. Where baseflow signals reflect wastewater return flows that bypass the subsurface hydrologic system, groundwater appropriations based on the slowflow characteristics of gauged streamflow may over-appropriate the resource and fail to adequately protect the groundwater resource from depletion. The limitations and potential risks from appropriating groundwater based only on the characteristics of observed streamflow highlight the value of a more process-based understanding of Maryland's coupled surface water- groundwater resource.



**Figure 37** Location of core stream gauges used for trend analysis

## 6. Conclusions

### Overview

Increasing trends in suburban and exurban development are fragmenting Maryland's agricultural and forested lands, amplifying the cumulative stresses on the State's water resources. This project developed methods to evaluate the effects of landscape fragmentation on the sustainability of Maryland's water resources through regional analysis of low flow characteristics of gauged stream flow.

*Baseflow Metrics* Multimetric baseflow indices were developed and applied to USGS streamflow records to derive consistent quantitative measures of baseflow characteristics. Baseflow characteristics from developed watersheds and watersheds with minimal human influence (the USGS Hydroclimatic Data Network<sup>7</sup> or HCDN) demonstrated a multimetric fingerprint of human hydrologic alteration. Along a rural to urban gradient, multimetric baseflow analysis of Piedmont streams in Central MD revealed clear endpoints, identifiable as rural forest and agricultural watersheds, and urban watersheds. These endpoints bounded the response of intermediate mixed and developing watersheds, as well as the HCDN gauges in the Piedmont of Chesapeake Bay.

Multimetric fingerprinting also distinguished hydrologic changes – (changes in runoff and recharge) from hydraulic changes (changes in the hydraulic *response* of aquifer drainage). Characteristics of quickflow and slowflow derived from USGS streamflow records revealed clear signatures of hydrologic alteration along the rural to urban landuse gradient in the watersheds of the Baltimore Ecosystem Study<sup>8</sup> (an NSF Urban Long Term Ecological Research site in the Baltimore Metropolitan area).

- Taken together, **multiple baseflow indices provide a more refined characterization of changes in the dominant hydrologic processes resulting from urban/suburban land transformation than single metrics such as the baseflow index or estimated recharge.**

*Baseflow Trend Analysis*- Trend analysis of multiple baseflow metrics further elucidated the baseflow signatures of human hydrologic alteration. We developed and implemented robust trend analysis using consistent non-parametric tests for all feasible sub-periods within the period of record of every gauged watershed in Maryland for which sufficient data are available. These multi-metric trend analyses enabled us to distinguish significant trends that were dominated by anomalous extreme events (such as the drought of the 1960s) from long-term persistent secular shifts in baseflow characteristics, controlling for hydrometeorological variability.

- For Maryland's urban/suburban watersheds, we consistently found **highly significant decreasing trends in the fraction of annual streamflow attributed to baseflow (i.e. the**

<sup>7</sup> HCDN: <http://water.usgs.gov/GIS/metadata/usgswrd/XML/hcdn.xml>

<sup>8</sup> BES: <http://beslter.org/>

**baseflow index or BFI) closely associated with the period of maximum historical urban/suburban development.**

Declining baseflow is consistent with traditional expectations that suburban land conversion increases runoff and decreases infiltration, recharge, and hence baseflow. Remarkably, many of Maryland's suburban watersheds with declining BFI trends also showed consistent *increasing* trends in baseflow, recharge and surface runoff. This apparent paradox resulted from baseflow trends that increased *less than* the increase in discharge, yielding a smaller fraction of annual discharge derived from baseflow and thus a lower BFI. The combination of declining BFI and increasing discharge and baseflow trends suggests the signature of interbasin transfers in altering the urban water budget through leaky infrastructure and return flows. We found consistent *differences* in baseflow characteristics identified through hydrologic baseflow metrics (BFI, recharge etc.) and hydraulic metrics (baseflow recession constant,  $K_b$ ), strongly validating a multimetric approach to diagnose baseflow changes. One postulated effect of urban/suburban land transformation is a hydraulic response associated with infiltration and inflow to storm sewers.

- **At the watershed scale captured in Maryland's stream gauge network, *we found no significant evidence of hydraulic changes in baseflow response due to suburban land transformation.***

### Findings

Observed baseflow response to land transformation is more complex than traditional conceptual models, with confounding signals from interbasin transfers (of both drinking water and wastewater); changes in effective drainage (from infiltration and inflow to sewer systems); and hydroclimatic variation.

- Where high quality long-term streamflow records are available, multimetric baseflow analysis (combining non-parametric trend analysis and controls for hydrometeorological forcings and non-stationarity) provides a robust cost-effective tool to characterize Maryland's water resources.
- Within the existing Maryland stream gauge network we found no watersheds in which exurban fragmentation represented the *dominant* watershed-scale landuse change. For the streamflow records available in Maryland, a quantitative estimate of the specific hydrologic effect of exurban fragmentation could not be uniquely distinguished from the other dominant processes affecting observed streamflow.
- Landsat images did not correspond to – and were generally unavailable for- historical periods with the most significant changes in baseflow characteristics. MD Property View data provided useful information quantifying the watershed-scale development history of Maryland's landscapes.

- Hydrometeorological water balances at the scale of Maryland's climate divisions captured the dominant hydrometeorological forcings in Maryland streamflow, enabling the inherent hydroclimatic signal in baseflow to be distinguished from non-climatic forcings (such as the effects of land transformation and water infrastructure).
- Clear non-stationarity was identified in the stream record from Seneca Creek at Dawsonville, one of the reference gauges used by MDE for groundwater allocation. Ironically, both baseflow and streamflow for Seneca Creek showed a strong statistically significant increasing trend. This "apparent" increase in groundwater availability (as MD currently allocates its groundwater resources) is associated with increases in the discharge of treated wastewater from municipal supply originating outside the basin, combined with the operation of Little Seneca Reservoir for minimum instream flows.

### Significance

The results have direct applicability and significance for the current regulatory approach to ground water appropriation in the State of Maryland. Current regulatory practice relies on recharge estimated from gauged streamflow. Non-stationarity of reference gauges used for this purpose suggests the need to revisit these regulatory resource assessments. The ability of multimetrix trend methods developed in this project to distinguish human alteration of baseflow characteristics (including effects from infrastructure and interbasin transfers) identifies a regulatory paradox in allocating groundwater resources. In watersheds that may have significant "artificial recharge" from leaking water infrastructure, the decoupling of heuristic baseflow (derived from gauged streamflow), from the functional recharge of groundwater, highlights the *limitations* of streamflow analysis alone. The limitations and potential risks from appropriating groundwater based only on the characteristics of observed streamflow highlight the value of a more process-based understanding of Maryland's coupled surface water- groundwater resource.

The methods developed in this project demonstrate clear consistent insights into the interaction of human activities and sustainable water resources, and are directly transferable to other gauged watersheds of the Chesapeake Bay watershed. Where available, streamflow information can provide a rich reliable diagnostic tool to quantify human impacts to the hydrologic system and the baseflow signatures of sustainable water resources.

## Appendices

**Appendix 1 – Baseflow & Baseflow metrics**

**Appendix 2 – Hydrometeorology and Hydroclimatology of Baseflow**

**Appendix 3 – Baseflow Characteristics Tables**

**Appendix 4 – Testing for Trend and SlowFlow Gauge Templates**

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