An Auxiliary Method to Reduce Potential Adverse Impacts of Projected Land Developments: Subwatershed Prioritization

Latif Kalin · Mohamed M. Hantush

Abstract An index based method is developed that ranks the subwatersheds of a watershed based on their relative impacts on watershed response to anticipated land developments, and then applied to an urbanizing watershed in Eastern Pennsylvania. Simulations with a semi-distributed hydrologic model show that computed low- and high-flow frequencies at the main outlet increase significantly with the projected landscape changes in the watershed. The developed index is utilized to prioritize areas in the urbanizing watershed based on their contributions to alterations in the magnitude of selected flow characteristics at two spatial resolutions. The low-flow measure, $7Q10$, rankings are shown to mimic the spatial trend of groundwater recharge rates, whereas average annual maximum daily flow, $\overline{Q}_{AMAX}$, and average monthly median of daily flows, $\overline{Q}_{MMED}$, rankings are influenced by both recharge and proximity to watershed outlet. Results indicate that, especially with the higher resolution, areas having quicker responses are not necessarily the more critical areas for high-flow scenarios. Subwatershed rankings are shown to vary slightly with the location of water quality/quantity criteria enforcement. It is also found that rankings of subwatersheds upstream from the site of interest, which could be the main outlet or any interior point in the watershed, may be influenced by the time scale of the hydrologic processes.

L. Kalin (✉)
School of Forestry and Wildlife Sciences, Auburn University, 602 Duncan Drive, Auburn, AL 36849-5418, USA
e-mail: latif@auburn.edu

M. M. Hantush
United States Environmental Protection Agency, National Risk Management and Research Laboratory, 26 West Martin Luther King Drive, Cincinnati, OH 45268, USA

Introduction

With the ever increasing population of the world, the demand of mankind for land and natural resources is amplified. As a result of this demand, residential, commercial, and transportation areas encroach upon rural landscapes, such as agricultural, forested, pastoral, etc., a phenomenon known as urbanization. Urbanization leads to an increase in impervious areas (Paul and Meyer 2001) which decreases the amount of water that infiltrates into the soil (Dunne and Leopold 1978; Klein 1979; Harbor 1994). Impervious surfaces such as pavements also show much less resistance to flow and therefore lead to increased runoff velocity. A natural consequence of urbanization is, thus, quicker and larger pulses in the flow hydrograph (Dunne and Leopold 1978; Neller 1988; Beighley and others 2003). Furthermore, due to diminishing infiltration, base-flow contribution to stream flow is reduced resulting in reduction of flows during prolonged inter-storm periods (Rose and Peters 2001; Wang and others 2001). Accordingly, the frequency of observing extremes, both at the high and low-flow end, increases (Lazaro 1990; Shaw 1994; Moscrip and Montgomery 1997; Rose and Peters 2001). Increased peak-flows not only increase the chance of more frequent flooding and associated monetary losses, but also impact stream habitat adversely and can cause serious environmental damage. Higher flow velocities cause increased stream power that may eventually lead to scouring and widening of stream beds (Hammer 1972; Graf 1975; Booth 1990). Maintaining adequate streamflow is

crucial for the sustainability of fish habitat and preservation of aquatic ecosystems. Not only minimum flow periods are important metrics for fish survivability, but also during which concentrations of many contaminants are usually elevated thus posing additional threat to aquatic ecosystems.

The negative consequences associated with urbanization on the ecology and environment have been the subject topic of many disciplines. Several researchers presented evidence that as low as 10% increase in impervious surface area could result in stream degradation (Schueler 1995; Booth and Jackson 1997; Bledsoe and Watson 2001). Studies have shown that high amounts of impervious surface can lead to increased nutrient and sediment loading into streams (Harden 1992; Arnold and Gibbons 1996; Nelson and Booth 2002). Urban developments have also shown to increase heavy metals (Callender and Rice 2000), bacteria loadings (Gregory and Frick 2000; Schoonover and others 2005), and stream temperatures (Brooker 1981; Krause and others 2004). The potential consequences of changes in the land use/cover (LULC) have also been studied at large scales. For instance, Zhang and others (2007) explored the linkage between LULC dynamics and carbon (C) sequestration in the southeastern U.S. and found that urbanization had accounted for 29% of the total C loss from this area.

When an area is expected to undergo significant LULC alterations, for the health and benefit of the environment, the potential impacts of these LULC changes should be critically appraised. It is essential to develop effective and efficient management strategies, if the projected LULC changes are predicted to have significant impacts on the water quality and/or quantity of a watershed. Informed management decisions may benefit from the identification of portions of the watershed that have the highest contribution to the reduction/increase in the water quality/quantity of interest. Efforts and resources can then be focused on those areas. Alternatively, if a portion of a given watershed is to be developed and flexibility exists as to the location of the developments, the question to be posed is: where in the watershed should the development proceed for the anticipated changes to be minimal? Of course, socioeconomic and policy matters may interfere with and preclude the implementation of such a rationale, but knowing beforehand (i.e., before land development) critical areas in the watershed nevertheless provides science-based guidance to the planning process and informed decision making.

To the best of the authors' knowledge, there are limited applications in the literature exploring the aspect of identifying or apportioning areas within a watershed based on their relative contributions to flow at the main outlet. Saghafian and Khosroshahi (2005) address a similar

problem by focusing on flood source areas and they also emphasize lack of applications of this type.

This article investigates the impact of LULC changes on the watershed response by aiming at prioritizing areas in the Pocono Creek watershed based on their contributions to the increase/decline of several key flow characteristics. The implication of this prioritization is that highest impact areas could be targeted first and management measures be implemented to mitigate negative impacts (increased flood hazard and reduced base flow). A simulation-based index method is proposed to rank the subwatersheds and applied to Pocono Creek watershed as a case study. The watershed is divided into subwatersheds which are then ranked based on their relative contributions to changes in flow characteristics as a result of the projected build out. The rest of the article is structured as follows: The following section describes the proposed index method, the utilized hydrologic model, and the study watershed. In the subsequent section, the impact of the projected LULC on the hydrology of the study watershed is investigated followed by application of the index method at varying scales. A summary and conclusion is provided at the end.

Methods

λ-Index

Saghafian and Khosroshahi (2005) recommended the use of a unit response approach to prioritize flood generating areas in a watershed. The watershed is divided into subwatersheds and by removing (or turning off) each subwatershed at a time the absolute and relative impacts of each subwaterhed are quantified. Our approach parallels that by Saghafian and Khosroshahi (2005), and aims to identify those areas in the watershed likely to play major roles on the water quantity or quality changes if the LULC of the watershed is to be altered. The method described in this article differs from the work of Saghafian and Khosroshahi (2005) in that it is tailored for LULC changes, and in addition to high-flows, low and median-flow characteristics are also investigated. Further, the focus is on long-term, continuous flow rather than event-based storms.

The following model development is based on flow, yet the method could equally be expanded to any water quality constituent. Let's assume that a given watershed is divided into k number of subwatersheds, which henceforth will be referred to as "elements." There are two LULC conditions; current condition (c) and future projection (f). A watershed-scale hydrologic model is required, preferably (but not necessarily) calibrated and validated for the study watershed. The calibrated model is run with the future LULC scenario for a given duration to generate the flow

Fig. 1 Schematic representation of the computation of λ-index. In panels "**a**" and "**b**," all the elements (subwatersheds) have the current (c) and future (f) LULC, respectively. Panel "**c**" is the same as panel "**b**" except element j ($j = 1$ in the figure) retains its current LULC

$$\lambda_j = \frac{P^{f,j} - P^f}{P^f} \times \frac{A}{A_j}$$
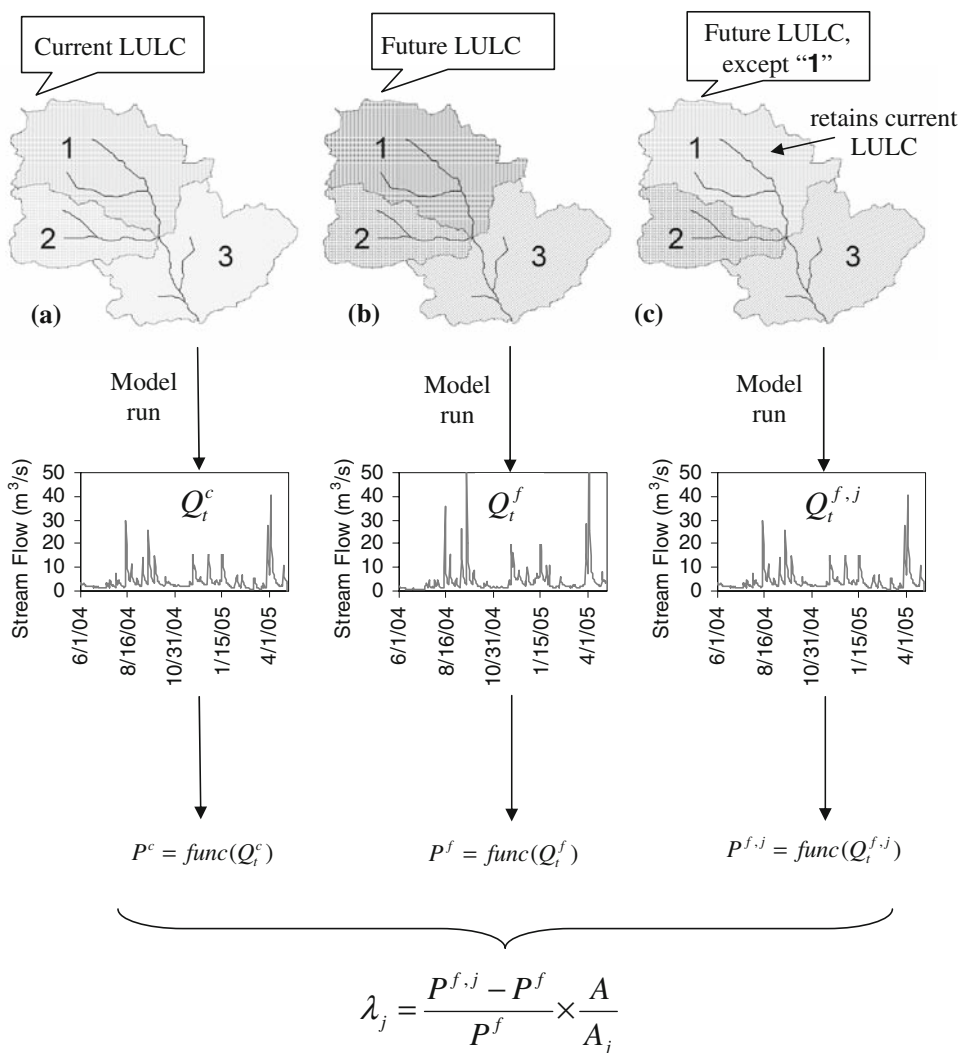
time series Q_t^f at the watershed outlet. Now, suppose that all the elements in the watershed have the future LULC with the exception of element j retaining its current LULC status. The model generated flow time series at the main outlet with this LULC setup will be denoted as $Q_t^{f,j}$. From both flow time series, Q_t^f and $Q_t^{f,j}$, any flow characteristics of interest, say $P = f(Q)$, can be computed and designated as P^f and $P^{f,j}$, respectively. The flow quantity P, could be a low-flow index such as 7Q10, $Q_{0.05}$ (flow exceeded 95% of the time), a high-flow index such as average annual maximum flow, $Q_{0.95}$ (flow exceeded only 5% of the time), or any other design parameter depending on the problem of interest. The following index is defined to assess the potential relative impact of element j on the flow characteristic P as a result of the projected LULC modifications

$$\lambda_j = \frac{P^{f,j} - P^f}{P^f} \times \frac{A}{A_j} \qquad (1)$$

where A_j and A indicate areas of element j and the whole watershed, respectively. The λ-index signifies the

anticipated relative impact of element j on the flow quantity P due to future LULC. It could be interpreted as the relative gain or loss in P normalized by the percentage area of element j (A_j/A) exclusively due to land use changes in element j. In other words, λ is a measure of strength of the impact of development and is suitable for assessing the impact of LULC changes per unit area. The normalization factor therefore is intended to filter out bias due to the size of the subwatershed. Figure 1 depicts this procedure of λ-index computation. By computing λ_j for $j = 1,…,k$ one can rank the areas in the watershed from most critical to least. Note that the order of ranking could differ with the flow characteristic of interest, P.

Hydrologic Model

Several promising watershed scale hydrologic models are available to implement the method outlined above such as HSPF (Bicknell and others 2001), SWAT (Neitsch and others 2002a, b), MIKE-SHE (Graham and Butts 2006),

WAM (SWET 2006), etc. The Soil and Water Assessment Tool (SWAT) is used in this study to evaluate the potential changes in the hydrology of the Pocono Creek watershed owing to projected LULC alterations. Since this article builds on previous modeling efforts with SWAT in the Pocono Creek Watershed (Kalin and Hantush 2006a, b; Hantush and Kalin 2008), SWAT was the logical choice. The SWAT model is a semi-distributed, deterministic process-based hydrologic and water quality model. It was essentially developed to quantify the impact of land management practices in large, complex watersheds with varying soils, LULC, and management conditions over a long period of time, in the order of years. SWAT uses readily available inputs and has the capability of routing runoff and chemicals through streams and reservoirs, adding flows and input measured data from point sources, and is capable of simulating long periods for computing the effect of management changes.

Input data needed to run the SWAT model includes soil, LULC, weather, rainfall, management conditions, stream network, and watershed configuration data. The ArcView GIS interface for SWAT, AVSWAT (Di Luzio and others 2002) automates most of the data extraction from readily available GIS maps and databases such as Digital Elevation Models (DEM), LULC maps, State Soil Geographic database (STATSGO) soil maps, etc. SWAT requires the watershed be partitioned into subunits including subbasins, reach/main channel segments, impoundments on main channel network, and point sources to set up a watershed. Subbasins are further divided into hydrologic response units (HRUs) which are portions of subbasins with unique LULC/management/soil attributes. AVSWAT enables extraction of input parameters easily. It uses DEMs as input to extract the channel network and delineate the watershed and subwatersheds.

SWAT model computes surface runoff, interflow and baseflow components of the streamflow separately. Hence, one can calibrate baseflow and surface runoff related model parameters more effectively by separating baseflow from the streamflow data. SWAT can compute surface runoff from each HRU either through SCS Curve Number (CN) approach or through Green-Ampt infiltration model. The former is used in this study as varying LULCs can be better parameterized with CNs. Flow routing from the subwatersheds to the watershed outlet is carried out using the Muskingum method. SWAT utilizes shallow aquifer storage to compute groundwater flow contribution to total stream flow. The shallow aquifer is recharged by percolation from the bottom of the root zone. A recession constant is used to lag flow from the aquifer to the stream. Soil percolation is computed by a storage routing technique to predict flow through each soil layer in the root zone. SWAT allows for downward flow when the field capacity of a soil layer is exceeded with the condition that the underlying layer is not saturated.

Study Area

The focus area of this article is the Pocono Creek Watershed (Fig. 2) which is experiencing population growth and accompanying urbanization. The Pocono Creek, which drains 120 km² of an area in Monroe County, PA has very good water and biological quality and is designated as Special Protection Waters by the State and the Delaware River Basin Commission. The Creek has a wild brown trout population, which is significant to outdoor recreation and the largest economic generator of the region. Due to its proximity to the New York City and Philadelphia metropolitan regions, the natural resources of the Pocono Mountain communities attract many new residents each year. The area has the second fastest growing population in the state of Pennsylvania due to its: (i) strategic location and quick access to major metropolitan centers; (ii) remaining natural resources; (iii) second home markets, and (iv) history as a tourist destination area. The population of Monroe County has nearly doubled from 1980 to 2000,
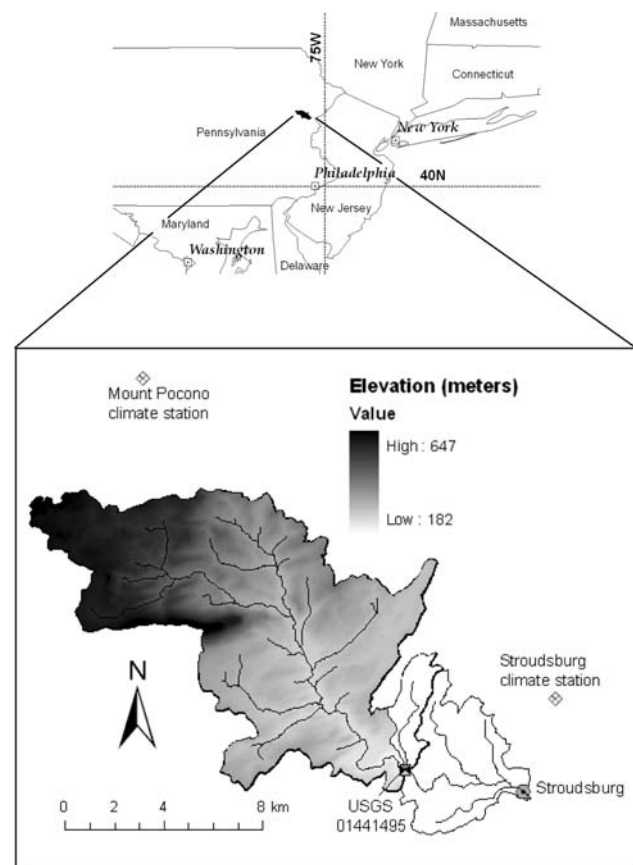
Fig. 2 Pocono Creek Watershed: location and topography

Fig. 3 Current (2000) and future (2020) LULC distributions in the Pocono Creek watershed
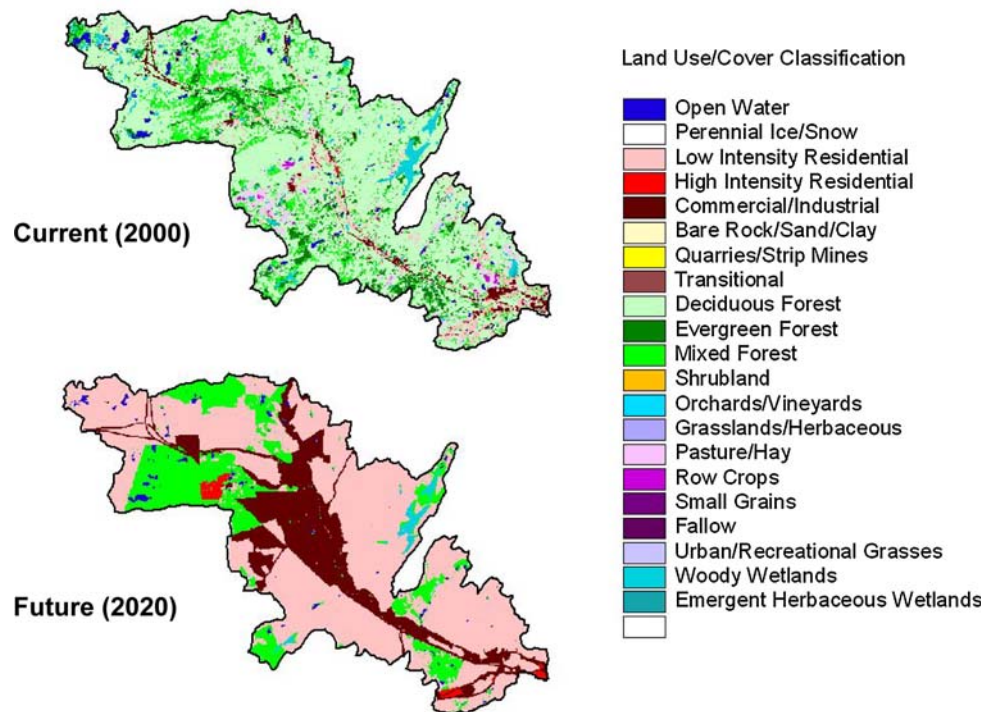
and was projected to grow by an additional 60% by the year 2020. Potential impacts of this population growth include degradation and loss of the forested and agricultural lands, increased tax burdens for infrastructure development, and erosion of the local quality of life. Specifically, the concern is that the projected growth and LULC change along with the accompanying anticipated increase in groundwater withdrawals in the watershed could well exceed sustainable levels, depleting groundwater and stream flows and resulting in the loss of the Creek's wild brown trout. Such a result would have undesirable environmental and economic consequences for the area.

The Pocono Creek's 26 km long watershed valley drains from the Pocono Plateau in its headwaters eventually into the Brodhead Creek, a tributary into the Delaware River. The model is constructed for the area above the U.S. Geological Survey stream gauge (USGS 01441495) which is located about 6.4 km upstream from the mouth near the city of Stroudsburg, PA (Fig. 2) and drains an area about 98.8 km². Interstate 80 runs along the Pocono Creek floodplain to the south. Route 611, the county's primary commercial artery also runs parallel to the creek to the north.

The LULC of the watershed (Fig. 3) based on year 2000 is mainly forest (85.2%). Residential, commercial, and transportation areas comprise about 5.8% of the watershed, including the commercially developed Route 611 corridor, Big Pocono State Park, Camelback Ski Area, the Nature Conservancy's Tannersville Cranberry Bog, and state gamelands. Remaining area is composed of 3.5% pasture, 3.8% wetland and 1.4% water. Agriculture constitutes a negligible portion of the watershed at 0.2%. The post year 2020 projected build out, provided by the Delaware River Basin Commission http://www.state.nj.us/drbc, foresees significant changes in LULC distribution which is estimated as 44.2% low density residential, 8.0% medium density residential, 0.8% high density residential, 22.8% commercial or transportation, and 18.7% forest (Fig. 3).

The dominant soil type in the watershed is silt loam (85%). Sandy loam and loam make up about 11% and 4% of the watershed, respectively. The elevation in the watershed changes from 183 m at the outlet to 648 m near the Camel Back Ski Area. The average slope in the watershed is 11%. A 30-m resolution DEM is used in extraction of the stream network and delineation of the watershed boundary. The SWAT built-in STATSGO soil database was relied upon to extract and compute soil related model parameters.

## Results and Discussion

Impact of Land Use Changes

The SWAT model has been successfully calibrated (Mass balance error, MBE = 4.0%, coefficient of determination, $R^2 = 0.74$, Nash-Sutcliffe Efficiency, $E_N = 0.74$) and

validated (MBE = 5.5%, R^2 = 0.72, E_N = 0.71) at the daily time scale for the study watershed by Kalin and Hantush (2006a) using the time periods (7/1/2002–5/31/2004) and (6/1/2004–4/30/2005), respectively. Model calibration was performed manually in a systematic manner by moving from coarser time scale (annual) to finer (monthly and daily), with the objective being minimizing the MBE and maximizing R^2 and E_N between model simulations and USGS streamflow data at the watershed outlet. Unfortunately no flow data from interior locations were available to perform nested model calibration. We refer interested readers to Kalin and Hantush (2006a) for further detail on model calibration. Since we focus on low, medium, and high-flows in this study, it is useful to compare flow duration curves (FDC) obtained from observed data and model simulations. Figure 4 shows those FDCs generated for the period 7/1/2002 to 4/30/2005. As can be seen the model performance is remarkable with model performance measures of R^2 = 0.99 and E_N = 0.93. From Fig. 4 (inner panel) it is seen that the model systematically overestimates flows having probability of exceedance above 85%. However, we consider this acceptable considering the higher uncertainties involved in low flow estimations (Hantush and Kalin 2005; Kalin and Hantush 2006b; Hantush and Kalin 2008).

The calibrated model is used in evaluating the impact of projected LULC changes in the Pocono Creek watershed on flow characteristics by Kalin and Hantush (2006b). The calibrated model is run with 50 randomly generated 20 years long precipitation data (see Kalin and Hantush 2006b for details) to generate an ensemble of 50 daily flow time series both with LULC of 2000 and the projected LULC for post 2020. Henceforth those two land use
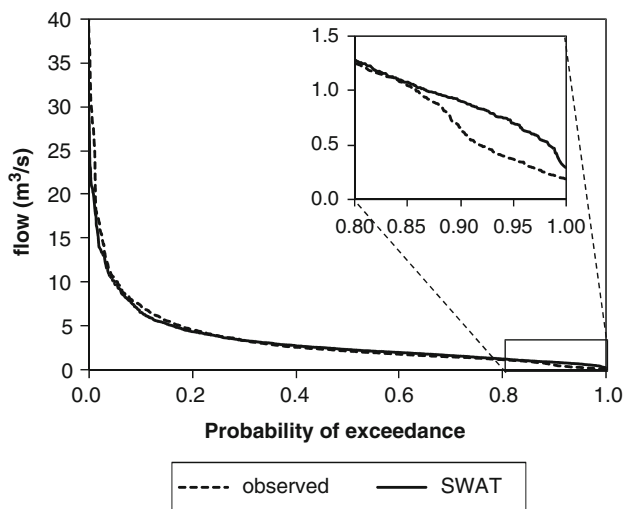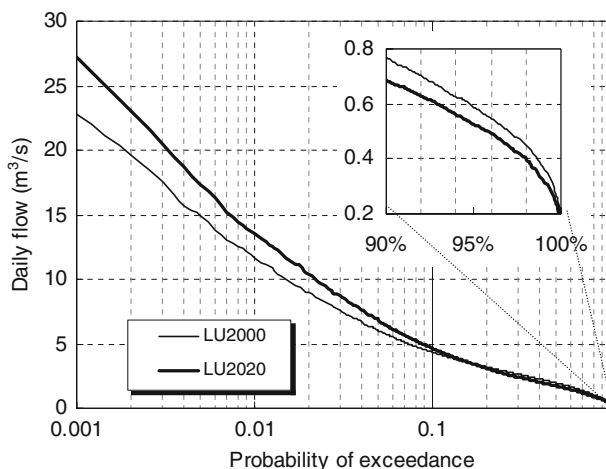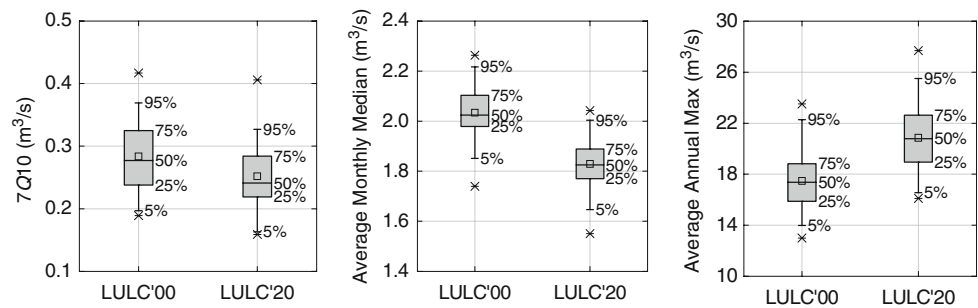

Fig. 5 Median of the ensemble of flow duration curves computed from model simulations driven by 50 independently generated precipitation data. Bold thick line corresponds to simulations with LULC'20; thin line corresponds to simulations with LULC'00

scenarios will be denoted as LULC'00 and LULC'20. A flow duration curve is obtained from each of the generated daily flow time series. The medians of daily duration curves based on LULC'00 and LULC'20 are plotted in Fig. 5. The probability of exceeding high-flows and the risk for flood hazard are predicted to increase owing to projected LULC changes. Figure 5 shows that, on average, the likelihood of exceeding a threshold daily flow greater than 4 m^3/s is predicted to increase with the build out (e.g., flow exceeded less than 1% of the time is predicted to increase more than 13%). On the other hand, flow exceeded at least 90% of the time (<0.8 m^3/s based on LULC'00) is predicted to decrease up to about 13% with the projected LULC, as depicted by the inner panel of Fig. 5. Equivalently, this means that the chance for the flow to be less than or equal to a given low-flow threshold increases. Therefore, base flows are likely to decrease with the projected land use changes. This is, of course, excluding the effect of the anticipated increase in groundwater withdrawals which will further reduce base flows. Figure 5 also indicates that, on average, median-flow (probability of exceedance = 0.5) with the LULC'20 is slightly smaller than the one with LULC'00.

Three flow quantities are selected as metrics representing low, medium, and high-flow conditions. Figure 6 illustrates these three important flow quantities, namely 7Q10 (7 days average low-flow with a 10 year return period), average monthly median of daily stream flow ($\overline{Q}_{MMED}$) and average annual maximum daily stream flow ($\overline{Q}_{AMAX}$), computed from each flow time series by employing LULC'00 and LULC'20. The quantity 7Q10 represents a low-flow condition, whereas $\overline{Q}_{AMAX}$ is a high-flow measure. The flow measure $\overline{Q}_{MMED}$ is a required

Fig. 4 Flow duration curves of observed and model simulated flows generated for the period 7/1/2002 to 4/30/2005

Fig. 6 Projected variations in $7Q10$, $\overline{Q}_{MMED}$, and $\overline{Q}_{AMAX}$ due to LULC changes

metric for the assessment of wild trout habitats in Pennsylvania. The projected land use change is expected to cause 10 to 15% reduction in $7Q10$, about 10% decline in $\overline{Q}_{MMED}$, and approximately 19% increase in $\overline{Q}_{AMAX}$. It is evident from model predictions that the projected LULC changes in the Pocono Creek watershed have the potential of increasing $\overline{Q}_{AMAX}$, and reducing $7Q10$ and $\overline{Q}_{MMED}$ at the watershed outlet. The environmental and ecological consequences of these reductions and increases in the flow quantities are beyond the scope of this work.

Worth noting is the relatively high variations (due to precipitation) of relative changes in $7Q10$ compared to $\overline{Q}_{MMED}$ and $\overline{Q}_{AMAX}$. The coefficient of variation in percent change for $7Q10$ is -1.00; 0.16 for $\overline{Q}_{AMAX}$, and -0.06 for $\overline{Q}_{MMED}$, thus indicating higher precipitation-induced uncertainty associated with the estimate of this low-flow index. Its worth pointing out that a thorough uncertainty analysis is not the topic of this article and has been treated separately (Hantush and Kalin 2008). Nevertheless, precipitation uncertainty is considered here because precipitation data needed to be generated for healthier comparison of LULC'00 and LULC'20 driven flow characteristics.

The curve number approach in SWAT model operates at daily time scale. For a given daily rainfall depth, SWAT computes daily volumes (or depths) of initial abstractions, surface runoff and infiltration to the soil for each hydrologic response unit. The spatial configurations of different LULC types, especially impervious surfaces make no difference in the resultant estimated runoff depth from a subwatershed provided that the watershed is divided into sufficient number of subwatersheds. This is because SWAT does not rout flow from individual HRUs to the subwatershed outlet. On the other hand, this limitation of SWAT and the CN approach is not crucial for this watershed and at the daily time scale. For studies requiring subdaily time scales, such as studies focusing on individual event hydrographs, and for which SWAT model is not recommended to begin with, the spatial configuration of different land use types and their hydraulic relations with the drainage system potentially play a more critical role on the resultant hydrograph. For instance, peak flow timing and magnitude at the hourly time scale could be impacted by the spatial configurations of

LULC patches. However, daily average flow is less likely to be affected in watersheds comparable in size to Pocono Creek Watershed or smaller.

Identification of Critical Areas

For the purpose of this article we will assume that the fluctuations in the flow regime due to LULC changes are consequential. The question is then, what parts of the watershed are most accountable in these reductions or increases of the flow quantities aforementioned? We now attempt to answer this question by following the index-based procedure outlined above. In applying the SWAT model, the same model set up of Kalin and Hantush (2006a) is employed where the Pocono Creek watershed is divided into 29 subwatersheds, numbered from 1 to 29 with subwatershed 29 being the most downstream (Fig. 7a). This discretization resulted in the closest match with the actual streams based on data provided by the Delaware River Basin commission (DRBC). For management purposes this discretization might be too detailed. Hence, as an alternative, we aggregated those 29 subwatersheds to come up with 7 management areas (Fig. 7b) that correspond to management areas defined in a pilot study (Pocono Creek Pilot Study 2001). Analyses are performed at both scales, i.e., at the subwatershed scale (finer) and management area scale (coarser), and the impact of spatial resolution on the area prioritization is discussed.

Coarser Subdivisions

Model simulations are performed using the 29 subwatershed resolution with the 50 sets of generated 20 years duration daily precipitation data. Flow time series Q_t^f and $Q_t^{f,j}$, $j = 1,...,7$ are then generated by running the model respectively with LULC'20, and LULC'20 modified by replacing the LULC of element j with LULC'00. From these flow time series the quantities P^f and $P^{f,j}, j = 1,...,7$ are computed with P denoting $7Q10$, $\overline{Q}_{MMED}$ and $\overline{Q}_{AMAX}$. Finally, the λ-index is computed from these P values. Table 1 summarizes the computed λ-indexes with this coarser spatial resolution for
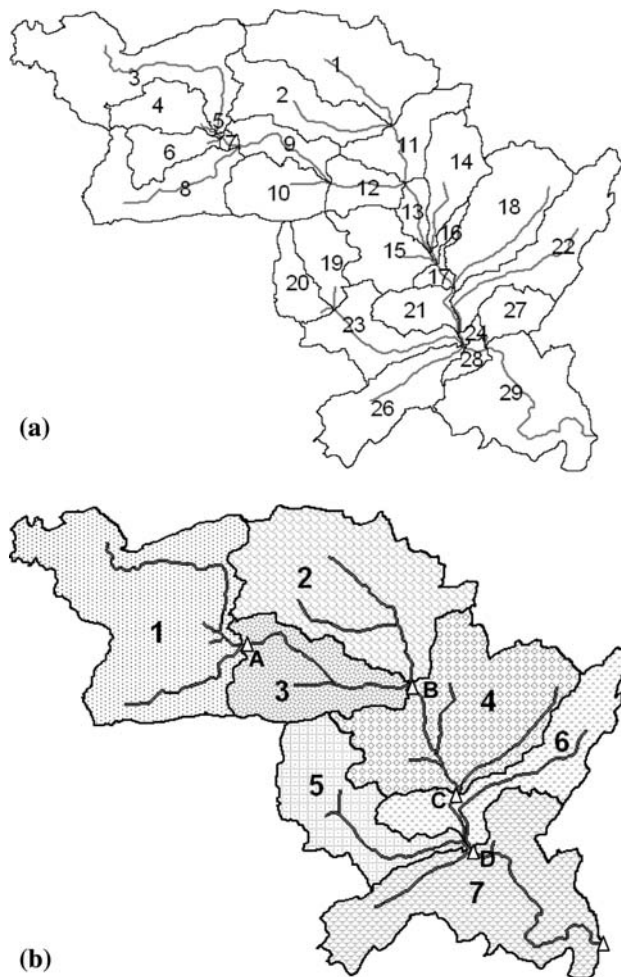
Fig. 7 Watershed subdivisions used in determination of critical areas that contribute more to reduction/increase of flow characteristics due to change in LULC, (**a**) finer, (**b**) coarser

Table 1 Computed λ-indexes for the 7 management areas for $7Q10$, average monthly median of daily flows ($\overline{Q}_{MMED}$), and average annual maximum daily flows ($\overline{Q}_{AMAX}$)

Rank	$7Q10$		$\overline{Q}_{MMED}$		$\overline{Q}_{AMAX}$		Average[a]	
	j	λ_j	j	λ_j	j	λ_j	j	λ_j
1	5	0.54	4	0.15	7	–0.32	4	0.31
2	4	0.51	7	0.14	4	–0.23	7	0.30
3	7	0.41	2	0.12	6	–0.22	5	0.24
4	2	0.35	5	0.09	1	–0.11	2	0.20
5	6	0.22	1	0.09	2	–0.10	6	0.17
6	3	0.17	6	0.08	3	–0.07	1	0.13
7	1	0.17	3	0.07	5	–0.05	3	0.10

[a] (−) of $\overline{Q}_{AMAX}$ are used in averaging

the three flow quantities, with Fig. 8 showing their spatial variations. Also given in the table are the rankings of each area based on the λ-index for each flow characteristics. The last column in the table represents the arithmetic average of

the λ-indexes of the three flow metrics for each management area. Note that arithmetic averaging assigns equal weights to each flow metrics. The end user or the decision maker could assign different weights to each flow characteristics depending on their significance. Using a combined index is useful when more than one flow characteristics are of concern. For instance a decision maker may simultaneously be concerned with low and high flows. Similarly, from a water quality perspective, increased nutrient (N, P) and sediment loadings need to be often addressed together, which necessitates a combined index. Since λ_j for $\overline{Q}_{AMAX}$ has negative values (i.e., retaining LULC causes reduction) as opposed to the positive values (i.e., retaining LULC causes increase) for $7Q10$ and $\overline{Q}_{MMED}$ (see Table 1), for consistency, the absolute value of λ_j for $\overline{Q}_{AMAX}$ is rather considered in computing the average λ-index given in the last column.

The index values summarized in Table 1 are calculated from the average of the 50 P^f and $P^{f,j}$ values that are computed from the 50 flow time series generated by running the model with 50 synthesized precipitation scenarios, each 20 years long (refer to Kalin and Hantush 2006b on the precipitation synthesis). An alternative approach is to compute indexes from each flow time series and then averaging them. The index values for $\overline{Q}_{MMED}$ and $\overline{Q}_{AMAX}$ varied by less than 0.5% between the two averaging procedures. The λ-indexes for $7Q10$ displayed as much as 5% variation due to the method of averaging. However, the differences were systematic with the latter resulting in slightly larger index values each time. The rankings are, hence, unaffected by the averaging strategy.

In all three flow quantities, Area 4 appears either first or second in rankings. Interestingly, Area 5 is ranked first and last in $7Q10$ and $\overline{Q}_{AMAX}$, respectively. Such a reversal in rankings is not observed with the other areas. The reason for this behavior of Area 5 will be explained shortly. Note that the rankings of areas in $\overline{Q}_{MMED}$ and the average index are very similar.

Table 2 provides mean annual groundwater recharge estimates (SWAT output) based on LULC'00 and LULC'20. Insight into the variations of low-flows may be gained by recognizing that base flow is directly related to groundwater recharge. Note that in the table reductions are computed relative to LULC'20 as we are interested in the potential changes (reductions or increase) in the predicted future flow characteristics. This is also consistent with the definition of λ-index. The last column presents the relative reduction in average annual recharge normalized by the percent area of each element. The numbers within parenthesis shown in superscripts are the rankings of each element. Close examination of $7Q10$ flow rankings along with the recharge rates reveals that they follow very similar trends. Area 5 and 4 are clearly expected to have the 1st and 2nd highest recharge reductions per unit area, whereas
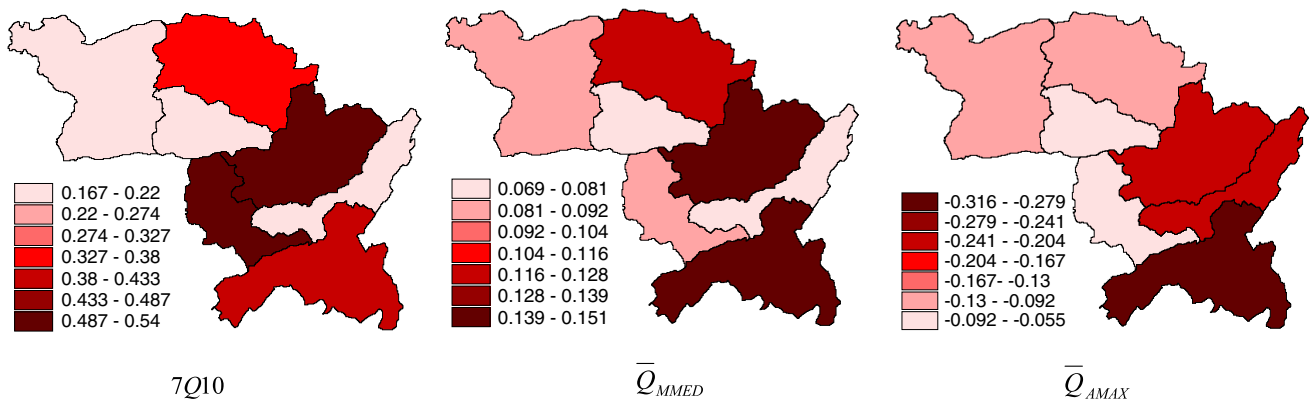
$7Q10$ $\overline{Q}_{MMED}$ $\overline{Q}_{AMAX}$

Fig. 8 Spatial variation of λ-index for $7Q10$, $\overline{Q}_{MMED}$, and $\overline{Q}_{AMAX}$ based on coarser resolution. Darker colors indicate higher index and vice versa

Table 2 Estimated average annual recharge values based on LULC'00 and LULC'20 (coarser scale)

Element	Area (km²)	Average annual recharge (10⁶ × m³)		Reduction		
		LULC'00 (10⁶ × m³)	LULC'20 (10⁶ × m³)	Absolute (10⁶ × m³)	Relative (%)	Relative/(% Area)
1	21.4	8.47	6.57	−1.91	−29.0	−1.34[7]
2	17.2	7.24	5.21	−2.03	−38.9	−2.23[6]
3	8.4	2.21	1.66	−0.55	−33.1	−3.87[4]
4	16.7	7.88	4.51	−3.38	−74.9	−4.44[2]
5	9.0	4.19	2.58	−1.61	−62.6	−6.84[1]
6	8.9	4.36	3.23	−1.14	−35.3	−3.90[3]
7	17.1	7.55	5.09	−2.46	−48.2	−2.78[5]

Relative changes are computed by considering LULC'20 as the base condition, i.e. (absolute reduction)/(LULC'20 recharge). The numbers within parenthesis in the last column denote rankings of each element

Area 1 is expected to have the least reduction. This order is also observed in λ-index rankings of $7Q10$. This is apparently not surprising as low-flow index $7Q10$ is strongly correlated with base flow. It appears that the dominating factor in low-flow reductions is the decrease in the recharge rates more than topography and proximity of areas to the outlet. Yet, this argument may not hold true for the finer resolution as the more the number of areas, the more the interactions among them will be.

The ranking of areas based on their impacts on $\overline{Q}_{AMAX}$ is dissimilar to the rankings based on their impacts on $7Q10$ and $\overline{Q}_{MMED}$. Predicted significant reductions in the annual groundwater recharge volumes in Areas 4 and 7 due to projected land use changes means a significantly greater fraction of precipitation would be available for runoff in these areas. Combining this with the importance of proximity to the main outlet in high-flow situations most likely resulted in Area 7 being the most influential element on the $\overline{Q}_{AMAX}$. Area 4 has the 2nd highest impact.

Although Area 5 has the highest impact on $7Q10$, it is ranked last in terms of its impact on $\overline{Q}_{AMAX}$. This is most likely stemming from the upper portions of management Area 5, which are among the steepest parts of the watershed (Fig. 2). Flow from this area reaches the receiving channels quicker than the flow from other subwatersheds. Once flow reaches the channels, it discharges much more rapidly downstream. Hence, the contribution of management Area 5 to the flow hydrograph at the watershed outlet could be expected to be mostly during its rising stage. This flow-time concept is further discussed in the next section.

Finer Subdivisions

The rankings presented in the previous section were based on seven management areas. In this section we repeat the same analysis for the original, finer watershed subdivisions. As mentioned earlier, the Pocono Creek watershed was divided into 29 subwatersheds. The average size of these 29 subbasins is 3.41 km². To simplify the analysis, subwatersheds having areas smaller than 25% of the average subwatershed size, i.e., $A_j < 0.85$ km², $j = 1,...,29$, are excluded from further analysis. Consequently, only 22 elements are considered to study their impacts on the three flow characteristics.

Table 3 Computed λ-indexes for the 22 subwatersheds for 7Q10, average monthly median of daily flows ($\overline{Q}_{MMED}$), and average annual maximum daily flows ($\overline{Q}_{AMAX}$)

Rank	7Q10		$\overline{Q}_{MMED}$		$\overline{Q}_{AMAX}$		Average[a]	
	j	λ_j	j	λ_j	j	λ_j	j	λ_j
1	14	0.73	13	0.31	13	−1.20	13	0.71
2	21	0.72	21	0.23	21	−0.63	21	0.53
3	27	0.66	11	0.17	29	−0.38	11	0.35
4	20	0.65	14	0.17	11	−0.31	14	0.33
5	15	0.65	3	0.16	9	−0.20	29	0.32
6	23	0.64	29	0.15	3	−0.18	15	0.30
7	13	0.63	1	0.15	26	−0.16	23	0.29
8	11	0.56	4	0.14	12	−0.15	27	0.28
9	19	0.55	26	0.13	23	−0.13	20	0.27
10	4	0.54	15	0.12	15	−0.13	3	0.26
11	1	0.54	12	0.12	27	−0.10	4	0.25
12	18	0.52	18	0.10	14	−0.10	1	0.24
13	3	0.45	20	0.10	18	−0.07	18	0.23
14	29	0.42	19	0.09	4	−0.07	26	0.23
15	26	0.41	27	0.09	2	−0.07	12	0.20
16	12	0.33	23	0.09	20	−0.06	19	0.19
17	10	0.11	9	0.06	8	−0.04	9	0.12
18	9	0.09	10	0.04	22	−0.04	2	0.06
19	2	0.07	2	0.02	6	−0.03	22	0.04
20	22	0.05	22	0.02	1	−0.03	10	0.03
21	8	−0.34	8	0.00	10	0.08	8	−0.10
22	6	−0.47	6	−0.06	19	0.08	6	−0.16

[a] (−) of $\overline{Q}_{AMAX}$ are used in averaging

Table 3 summarizes the computed λ-indexes at this finer spatial scale for 7Q10, $\overline{Q}_{MMED}$ and $\overline{Q}_{AMAX}$, as well as their arithmetic averages after taking the absolute value of λ_j for $\overline{Q}_{AMAX}$. Also, given in the table are the rankings of each element for each flow characteristics. Figure 9 depicts the spatial variation of λ-index for visual purposes. Not surprisingly, the highest ranked subbasins for all three flow characteristics, which are subwatershed 14 for 7Q10 and subbasin 13 for the other two, are both part of management area 4 of the coarser resolution. At the coarser spatial scale, management area 4 was ranked either first or 2nd in all occasions. Subbasin 21 has the 2nd highest impact on all three flow characteristics. It constitutes about one-fourth of management area 6 under the coarser resolution which was ranked 5th and 6th among the 7 management areas on its impact on 7Q10 and $\overline{Q}_{MMED}$, respectively. Subwatershed 22 comprises the remaining 75% of management area 6 and is consistently listed among the low-impact areas in Table 3. Almost 50% of subwatershed 22 is covered by wetlands in both LULC scenarios, which was designated as a no-planning zone and where flow-through conditions are assumed. Hydraulically, it is assumed impervious where precipitation becomes surface runoff. Similarly, subbasin 11, ranked 3rd on its impact on $\overline{Q}_{MMED}$ and 4th on its impact on $\overline{Q}_{AMAX}$, occupies 21% of management area 2 of the coarser resolution, where management area 2 holds the 4th and 5th places out of possible 7 based on its impacts on the respective flow characteristics. Conversely, subwatershed 2 which makes up 30% of management area 2 is ranked with the bottom pack (Table 3). It is clearly seen that the use of coarser resolution could lead to overlooking high-impact areas as evidenced above. Rankings of areas in $\overline{Q}_{MMED}$ and the average index are similar roughly for the 6 highest and lowest rankings. It is somewhat scrambled in the middle, which seems to be related to the index values being clustered within a small range ([0.09–0.15] for $\overline{Q}_{MMED}$ and [0.19–0.30] for average index).

Table 3 reveals some interesting results in $\overline{Q}_{AMAX}$. The λ-index is positive for subbasins 10 and 19. This means keeping the current LULC in these elements would lead to higher annual maximum flows at the watershed outlet compared to the case when the whole watershed undergoes LULC change as projected. At first glance, this may seem counter intuitive considering the fact that both subbasins 10
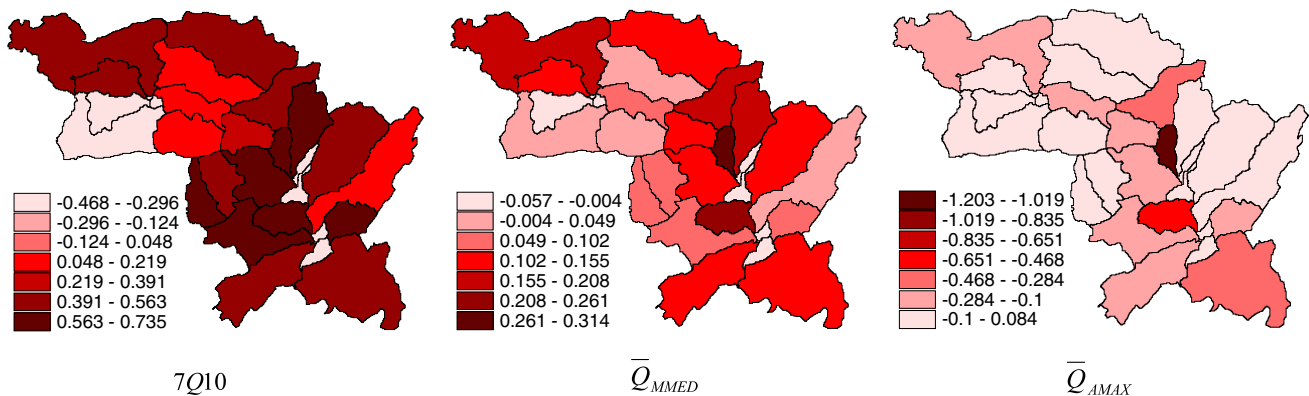
Fig. 9 Spatial variation of λ-index for 7Q10, $\overline{Q}_{MMED}$, and $\overline{Q}_{AMAX}$ based on finer resolution. Darker colors indicate higher index and vice versa

and 19 are projected to be significantly urbanized. The annual maximum daily flows at the respective outlets of subbasins 10 and 19 are found to increase due to urbanization as anticipated (results not shown), yet this is not reflected at the main outlet. Subbasins 10 and 19 have steeper slopes than all the other subbasins. As a result, the time to peak flow at the outlets of subbasins 10 and 19 are much shorter than the time to peak flow of other subbasins. The high-flows in the channel reaches coming from these subbasins are attenuated owing to lack of high-flow contribution from other subwatersheds. By the time the peak flow is observed at the watershed outlet, a significant portion of flow coming from subbasins 10 and 19 will have already left the watershed. In other words, subbasins 10 and 19 contribute more to the rising limp of the outlet hydrograph. This underscores the importance of interaction between geomorphology and geographic proximity to the point of interest (i.e., the outlet) on the watershed response.

Role of Design Point

The λ-index based analyses presented thus far only focused on flow at the main watershed outlet. Often, in addition to the main watershed outlet flow characteristics at a location somewhere inside the watershed are also of interest. For instance, in the Pocono Creek watershed the main concern is the response of brown trout population to potential fluctuations in the low-flow regime as a result of the expected population growth and built out. In this case the potential impacts of the projected LULC changes on the flow regime should be investigated at several points along the Pocono Creek and its tributaries. A question of interest is how the rankings of the areas upstream of a point inside the watershed compare to their rankings generated with the main outlet being the point of interest.

To address this question to some extent four design points are selected inside the watershed, denoted with letters A, B, C, and D (as shown in Fig. 7b) with A and D being the most upstream and downstream sites, respectively. The drainage areas for these sites are nested within each other (Fig. 7b). The λ-indexes are computed for those subwatersheds upstream of those selected sites for two cases. In the first case the impact at the selected site is considered. The second case is based on the impact at the main watershed outlet. Table 4 summarizes the λ-index rankings for each site, computed for the three flow characteristics. Rankings based on the arithmetic average of λ-indexes are also shown in the table for completeness.

From Table 4 it is seen that variations in order of rankings are dependent on the design flow measure and the location of design points. The most disparity is in $\overline{Q}_{AMAX}$ and the least discrepancy in 7Q10. Also, the variations in rankings amplify as we move from upstream sites

to downstream sites (A to D) and this is believed to stem from the increase in the number of subwatersheds. The highest ranked areas are preserved when the design point is switched from the main outlet to site D, both for $\overline{Q}_{MMED}$ and 7Q10. However, this is not the situation with $\overline{Q}_{AMAX}$. The rankings are highly sensitive to the location where $\overline{Q}_{AMAX}$ is computed. Except for site A, rankings generated based on interior locations differ substantially from their counterparts generated by considering the main outlet as the compliance point. For instance, when D is the design point, subwatershed 6 is ranked first, whereas when the main watershed outlet is the design point subwatershed 19 becomes the most critical subwatershed, which was ranked 11th when D was the design point. Note that $\overline{Q}_{AMAX}$ is dominated by quick-flow, while 7Q10 and typically $\overline{Q}_{MMED}$ are dictated by base flow. Therefore, we can conclude that the underlying hydrological processes and naturally the time scale play a significant role on the order of rankings. This is primarily due to the effect on runoff by the complex interactions between the channel morphology and geographic proximity to the downstream point of interest. On the other hand, during slow-flow processes such as base flow, the importance of such interactions diminishes due to the relatively much larger groundwater residence time compared to the watershed saturation time.

Tukey's Hypothesis Testing

Although the areas shown in Fig. 9 seem to have different levels of impacts, the differences may not be statistically significant. The Analysis of Variance (ANOVA) test can be used to find out whether there is a significant difference between group means. Nonetheless, it does not answer which means are different. The post hoc test of Tukey can be performed to answer this. The Tukey test is simply as follows.

- Perform a one-tailed ANOVA test to determine if all the means are statistically equal or not, based on a selected α-level. If means are all equal, no need to perform Tukey test.
- If the ANOVA test for the selected α-level reveals that not all the means are equal, then rank the means from largest to smallest and compute the difference between each successive pair of means.
- Compute the following quantity:

$$\Omega = Q_{t,\alpha,df} \cdot \sqrt{mse/j} \qquad (2)$$

where $Q_{t,\alpha,df}$ is the t statistic of the studentized range distribution for degree of freedom $df = i(j - 1)$ in which i is the number of means being tested (number of subbasins = 22), j is the number of samples (number of model simulations = 50), and mse is within the group mean square error which is computed during the ANOVA test.

Table 4 Subwatershed rankings when the design points (A, B, C, D) are inside the watershed (see Fig. 7b) compared to rankings when design point is the main watershed outlet (shown with subscript "out" for each case)

	Subwatersheds																		
	1	2	3	4	6	8	9	10	11	12	13	14	15	18	19	20	21	22	23
$7Q10$																			
A			2	1	4	3													
A_{out}			2	1	4	3													
B	2	7	4	3	10	9	8	6	1	5									
B_{out}	3	8	4	2	10	9	7	6	1	5									
C	4	11	8	6	14	13	12	10	3	9	7	2	1	5					
C_{out}	6	12	8	5	14	13	11	10	4	9	3	1	2	7					
D	7	15	12	6	19	18	16	14	10	13	8	1	3	11	4	2	5	17	9
D_{out}	10	16	12	9	19	18	15	14	7	13	6	1	4	11	8	3	2	17	5
$\overline{Q}_{MMED}$																			
A			2	1	4	3													
A_{out}			1	2	4	3													
B	1	8	4	2	10	9	7	6	3	5									
B_{out}	3	8	2	4	10	9	6	7	1	5									
C	2	12	6	4	14	13	11	10	3	8	5	1	7	9					
C_{out}	5	12	4	6	14	13	10	11	2	8	1	3	7	9					
D	4	16	7	6	19	18	15	13	3	10	1	2	8	12	9	11	5	17	14
D_{out}	6	16	5	7	19	18	14	15	3	9	1	4	8	10	12	11	2	17	13
$\overline{Q}_{AMAX}$																			
A			4	3	1	2													
A_{out}			4	3	1	2													
B	10	4	8	7	1	5	3	2	11	9									
B_{out}	2	5	8	6	3	4	9	1	10	7									
C	12	4	9	7	1	5	3	2	14	10	11	13	8	6					
C_{out}	2	5	11	6	3	4	12	1	13	10	14	8	9	7					
D	16	4	14	12	1	5	6	2	19	15	18	17	13	7	11	8	10	3	9
D_{out}	3	8	15	9	4	6	16	2	17	14	19	11	12	10	1	7	18	5	13
Average																			
A			2	1	4	3													
A_{out}			1	2	4	3													
B	2	7	4	3	10	9	8	6	1	5									
B_{out}	4	7	2	3	10	9	6	8	1	5									
C	4	11	7	6	14	13	12	10	3	9	5	1	2	8					
C_{out}	7	11	5	6	14	13	10	12	2	9	1	3	4	8					
D	4	16	10	6	19	18	15	14	3	11	2	1	5	13	8	9	7	17	12
D_{out}	10	15	8	9	19	18	14	17	3	12	1	4	5	11	13	7	2	16	6

– Compare the differences within each pair to Ω. If the difference for a particular pair is larger than Ω, then the means of that pair are statistically different.

Figure 10 shows the Tukey test results based on λ-index, for $7Q10$, $\overline{Q}_{MMED}$, and $\overline{Q}_{AMAX}$, respectively. In each matrix in Fig. 10, subwatersheds are ranked based on the λ-index with decreasing order of importance from top to bottom and from left to right. Each cell represents two subwatersheds. If the cell is shaded, then with 95% confidence the corresponding subwatersheds can be considered as having the potential to cause the same amount of reduction/increase in the design flow criteria at the watershed outlet. Conversely, if a cell is not shaded, than the impacts of the corresponding subwatersheds are statistically different. Further, each of the $7Q10$, $\overline{Q}_{MMED}$, and $\overline{Q}_{AMAX}$ matrixes (gridded-tables) are composed of separate and overlapping shaded square blocks. In each shaded square block of size of at least two subwatersheds, the
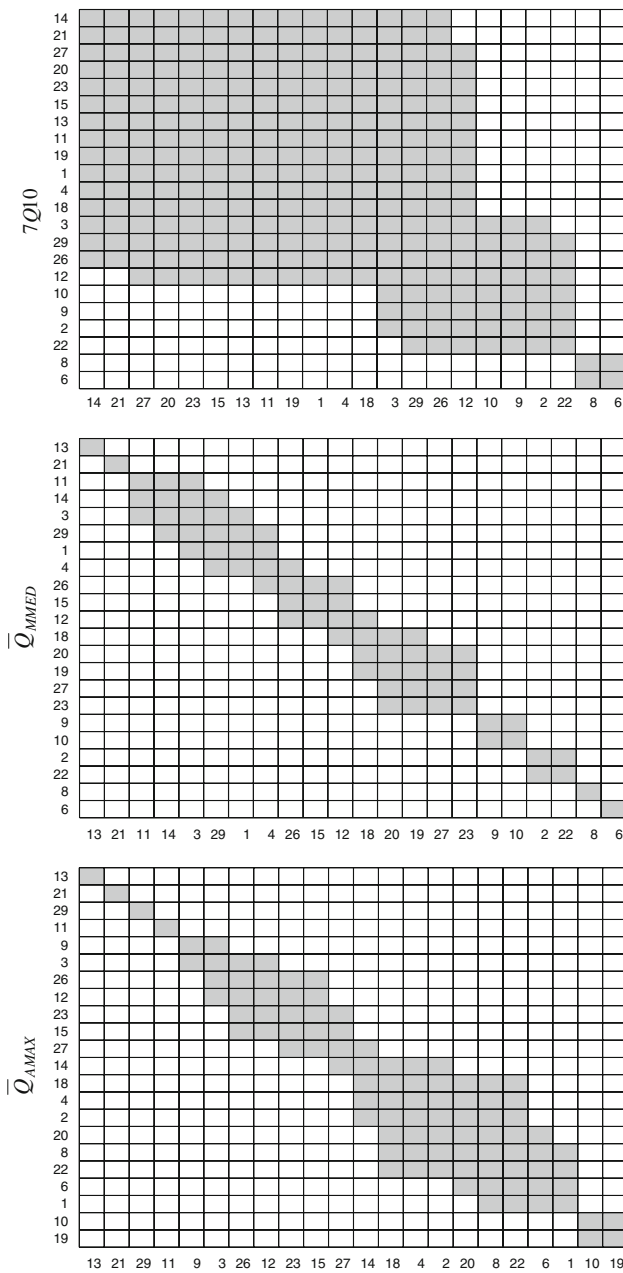
Fig. 10 Tukey test results with the 22 subbasins based on λ-index, for $7Q10$, $\overline{Q}_{MMED}$, and $\overline{Q}_{AMAX}$, respectively. In a specific row or column, shaded elements can be considered having the same impact on the design flow criteria at the watershed outlet with 95% confidence. Index values decrease from top to bottom and left to right

impacts of the corresponding subwatersheds are statistically insignificant. For instance, it can be argued that statistically no area can be isolated as being the highest impact area on $7Q10$, yet subwatersheds 6 and 8 could be identified as low-impact areas based on the projected LULC. Overall, the impacts of subbasins on the $\overline{Q}_{MMED}$ are more distinctive (less shaded areas) compared to $7Q10$ and $\overline{Q}_{AMAX}$, with $7Q10$ being the least distinctive (more shaded areas). This is in accordance with the precipitation-induced

uncertainty levels. Recall that the coefficient of variation in percent change for $7Q10$ was -1.00; 0.16 for $\overline{Q}_{AMAX}$, and -0.06 for $\overline{Q}_{MMED}$. Also note that the impacts of the sub-basins on $\overline{Q}_{AMAX}$ are more distinguishable than their impacts on $\overline{Q}_{MMED}$, toward the upper left-hand corner of the matrix, i.e., for the higher-ranked subwatersheds. For both of these quantities subbasins 13 should clearly be targeted first followed by subwatershed 21.

Summary and Conclusions

An index based method is developed to identify areas in a watershed that could likely be targeted to reduce anticipated undesirable ramifications in some of the flow quantities as a result of projected changes in the land use/ cover (LULC). The λ-index articulates the impact of land use changes per unit area. It measures the strength of the impact of the development and is useful when identifying where in the watershed to start urbanization and focus management practices or measures to mitigate anticipated changes in the watershed response. For instance, if the concern is flood peak then it could be suggested that per-viousness of high index areas be increased to enhance infiltration and/or increase the number of detention reser-voirs. If the concern is low-flow, groundwater resources should be appropriately managed, such as by limiting withdrawals from high index areas and meeting demand by exporting ground water from low impact areas. This, however, needs to take into account important socioeconomic and political factors that may influence where and how management practices are implemented.

The index based method was applied to the urbanizing Pocono Creek watershed in Eastern Pennsylvania. Comparison of the flow duration curves generated based on LULC of 2000, and projected LULC of the year 2020 with the SWAT model has shown that projected LULC changes in the watershed are predicted to increase low and high-flow frequencies at the main outlet. Three flow quantities are assessed; a low-flow index ($7Q10$), monthly median of daily flows ($\overline{Q}_{MMED}$), and annual maximum daily flow ($\overline{Q}_{AMAX}$) for two LULC scenarios; LULC from 2000 (LULC'00) and projected future build out (LULC'20). The method was applied at two spatial resolutions: at the sub-watershed scale, and at the management area scale, where each management area corresponds to an aggregate of several subwatersheds.

Using the λ-index, management areas and subwater-sheds were ranked based on their potentials to impact changes in the streamflow characteristics due to projected build out in the watershed. Groundwater recharge, area, topographic features, and proximity to the streamflow gauge station may have contributed to the ranking results.

The most downstream management area (#7), ranked first in terms of impact on $\overline{Q}_{AMAX}$, and second in terms of impact on $\overline{Q}_{MMED}$. Estimated groundwater recharge variations due to LULC changes showed good correlations with 7Q10 rankings. Management areas 5 and 4, associated with the largest groundwater recharge reductions in that order, were also ranked first and second based on the λ-index, with regard to the impact on 7Q10. Groundwater recharge appears to be the dominant factor in 7Q10 rankings. On the contrary, $\overline{Q}_{AMAX}$ standings are more complex, as both recharge rates and proximity to watershed outlet have control over the rankings.

The same analysis conducted by employing management areas as the spatial scale is also performed using the subwatersheds as the level of spatial detail. Analysis showed that some of the highly ranked subwatersheds were found to fall in moderately to lowly ranked management areas. This draws the attention to using appropriate scale, as coarser resolutions may conceal some of the critical areas because of the averaging affect when some portions of the management area are less critical.

Results clearly showed that, especially with the higher resolution, areas having quicker responses are not necessarily the more critical areas for high-flow scenarios. The flow hydrograph at the watershed outlet is formed by contributions from many subwatersheds. The temporal distribution of flow from these individual subwatersheds and interactions in the landscape play a major role in the hydrograph shape. Therefore, the subwatershed expected to generate the highest flow peak may contribute too early and may not be crucial at all as far as high-flows at the main watershed are concerned. As pointed out by Saghafian and Khosroshahi (2005), a distributed type of modeling approach is a necessity to identify such areas.

The impact of the location of the point of interest on the subwatershed rankings, where the water quality or quantity is of concern, was also investigated. It was shown that subwatershed rankings vary with the compliance point but not substantially. It was further found that rankings show more variability for $\overline{Q}_{AMAX}$ compared to $\overline{Q}_{MMED}$ and 7Q10, when impacts at the main outlet are compared to impacts at sites inside the watershed. These variations may be attributed to disparity in time scales associated with surface water and groundwater hydrologic processes.

The ad hoc statistical test of Tukey is applied to shed light on whether the impacts of subwatersheds are statistically different or not. The test results at the 95% confidence level indicated that the impacts of subwatersheds on 7Q10 are less distinctive than their impacts on $\overline{Q}_{MMED}$ and $\overline{Q}_{AMAX}$. It was further concluded that high-impact areas become more distinguishable as we move from low-flow quantity (7Q10) to high-flow quantity ($\overline{Q}_{AMAX}$). The Tukey test results provided further evidence

for the need of improving SWAT model capability to simulate low-flows, a problem which is also symptomatic of other, more physically based models.

It should be pointed out that the results presented and the conclusions drawn so far could possibly be specific to the way SWAT model is calibrated. How would the results differ if the same exercise is repeated with another watershed model? Can we expect the same rankings? Ongoing research is expected to provide an answer to these questions.

The results of this study point toward significant changes in flow characteristics in Pocono Creek, should the watershed be urbanized according to the projected build out. Plans should be put in place and management measures may be implemented to mitigate the impacts of land-use changes due to anticipated population growth and urbanization in the watershed. The results provided by this study in combination with adequate monitoring may provide guidance to a sustainable planning process. Often land use projections are driven by socioeconomic demands and policy only, without critical assessment of their impacts on the environment. The developed index method in this article could be used to guide planning for future land developments in other watersheds that meet socioeconomic needs and policy requirements, but with tolerable negative environmental impacts.

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