Longitudinal Study of the Impacts of Land Cover Change on Peak Flows in Four Mid-sized Watersheds in New York State, USA

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Abstract

In humid, temperate regions, there remains limited direct evidence of the influence of land cover changes on hydrologic response (e.g. peak discharge), especially across larger watersheds. Using historic aerial photography in conjunction with long-term stream gaging data, we assessed the role of land cover change on hydrologic response over multi-decadal periods in four watersheds in New York State. All four watersheds had increases in forest cover accompanied by small increases in urban land cover. Hydrologic response was evaluated by establishing an empirical function relating precipitation, watershed wetness, and discharge for each era of distinct land cover. This function was then used to estimate discharge for fixed precipitation amounts and wetness levels, allowing weather variables to be controlled across eras. One watershed (Limestone Creek) exhibited virtually no change in hydrologic response despite forest cover increasing by over 100%. One watershed (Fall Creek) exhibited a slight increase in hydrologic response with a greater than 100% increase in forest cover. The two other watersheds exhibited a greater than 20% decrease in hydrologic response, but we speculate the changes in these two watersheds were in part due to the construction of numerous small dams (Wappinger Creek) and a possible loss of riparian wetlands (Sterling Creek). This work demonstrates that the effects of land cover on hydrologic response are not always consistent with standard hydrologic intuition (i.e. increasing forested land does not always reduce peak discharge) and that often other factors may be more important than basic land cover in controlling hydrologic response.

Keywords: land cover change, dams, hydrology, floods
1. Introduction

Engineering hydrology has long made use of modeling frameworks that strongly emphasize the sensitivity of runoff production to aggregate land cover. In particular, nearly all engineering hydrology textbooks introduce the Curve Number method (USDA SCS 1972) as a simple tool to model rainfall-runoff relationships. The Curve Number equation is fundamentally a one-parameter model in which the single model parameter is dependent in part on soil type but mainly on land cover. For instance, based on the Curve Number method, a transition from forested to row crop agriculture in a watershed would result in a 50% increase of runoff for a 51 mm precipitation event. Besides its direct use as an event-based rainfall-runoff tool, the Curve Number method is embedded in commonly used computational hydrologic models such as SWAT (Arnold et al. 1990) and AGNPS (Young et al. 1994). One could reasonably say that the notion that hydrologic response is closely tied to land cover is deeply ingrained in engineering hydrology.

Despite the broad acceptance of the Curve Number method and the accompanying implicit assumption of the dominant control of land cover on hydrologic response, direct experimental measurements remain limited in their ability to quantify the sensitivity of hydrologic response to land cover change. These limitations arise from four sources: 1. mismatches in scale between experiments and application, 2. difficulty in separating weather variability from variations due to land cover, 3. difficulty in controlling for watershed features besides land cover, and 4. a focus of many studies on drastic changes in land cover (forest to urban; forest to clear cut) but not on more moderate changes in land use. Below we briefly discuss how each of these four limitations have been addressed in different experimental designs.
Some of the very earliest hydrology experiments focused on discerning the role of land cover on hydrologic response (e.g. Bates and Henry 1928). These experiments took the form of “paired” watershed studies in which two nearby watersheds were selected and then land cover in one of the basins was modified, typically by removing trees. Discharge in the paired basins would be correlated prior to disturbance to establish a baseline and then correlation between post-disturbance discharge would be compared to the baseline measurements. These paired watershed studies are ideal to control for non-land cover features that may regulate hydrologic response as well as for controlling for weather variability. However, to allow for direct modification of the watershed they are often conducted on watersheds less than 2 km² in area (Andreassian 2004) and often only entail relatively dramatic transitions in land cover such as from fully vegetated conditions to clear cut conditions.

For larger watersheds that better represent the heterogeneities of most basins, studies typically follow a “comparative” approach where multiple basins of varying land cover are compared to each other over the same period of time (e.g. Rose and Peters 2001, Poff et al. 2006). In this case, there is limited control on non-land cover features, but weather variability can be controlled for as long as basins are evaluated over the same time period and receive similar storm events. Non-land cover features can include such things as geology, soils, and topography.

A third option is to conduct a “longitudinal” study in which the same basin is analyzed over time. A longitudinal study requires that the basin has land cover change over the period in which it is gaged. Because of the often gradual change in land cover, such basins need to be monitored over many decades. There are relatively few examples of longitudinal studies in the literature (e.g. Beighley and Moglen 2002). Where comparative studies are limited by their ability to control for non-land cover features, longitudinal studies are limited by their ability to control for weather. Arguably though, it is easier to
control for weather than to control for innate watershed features. By normalizing precipitation input within the same time scale of the hydrologic response being assessed (e.g. calculating runoff ratio or some variant), one can reasonably account for variations in weather drivers over time (Sriwongsitanon and Taesombat 2011, Beighley and Moglen 2002).

This paper uses a longitudinal approach to evaluate sensitivity to land cover change, specifically focusing on the transition from agricultural to forested land in New York State. Most North American studies to date focus on differences between urban and non-urban land cover (Burns et al. 2004, Schoonover et al. 2006, Boggs and Sun 2011). While there are recent studies in developing countries (predominantly in tropical regions in the southern hemisphere) that have looked at the transition from forest to agricultural land use (Bradshaw et al. 2011, Bathhurst et al. 2007, Sriwongsitanon and Taesombat 2011), most of these studies are not necessarily representative of the processes driving hydrological response in humid, temperate regions in northern latitudes.

In this study, we make use of an historical aerial photography dataset dating back to the 1930’s that covers relatively large swaths of New York State. By using the same watershed but looking at long-term changes, we remove the possible influence of non-land cover features. By controlling for precipitation input and antecedent moisture, we account for long-term variations in weather. The study focuses on moderate sized watersheds with moderate land cover change (transition on approximately 25% of watershed area) thus filling in a knowledge gap regarding moderate, but not drastic, land cover change.

2. Methods
The overarching objective of this study is to match hydrologic response to land cover statistics in different eras for individual watersheds to assess whether land cover changes translate to changes in hydrologic response. There are two primary methodological tasks: 1. compiling geo-referenced land cover maps and 2. calculating the hydrologic response metric for each era.

We analyzed four mid-sized watersheds in New York State. Since the early 1900’s, large tracts of farm land in rural parts of New York have been abandoned and allowed to revert back to forest. The watersheds were selected based on availability of long-term USGS stream gaging records, availability of precipitation data from the National Weather Service, and availability of historic aerial imagery. Mid-sized watersheds on the order of 100 km$^2$ were selected in order to reduce heterogeneity in precipitation inputs across the watershed, to not require overwhelming effort to accurately classify land cover change, and to minimize the importance of in-channel travel time in assessing hydrologic response. In terms of in-channel travel times, the daily precipitation is the cumulative flux reported in the early-morning on the reporting day while daily streamflow is the 24-hour average extending from midnight to midnight on that same reporting day. Thus, the difference in reporting protocols for streamflow and precipitation innately account for travel time delays on the order of hours.

2.1 Watershed Characteristics

Watershed locations are indicated in Figure 1. Fall Creek and Limestone Creek are situated within the Appalachian Plateau physiographic region of New York. Soils in the Appalachian Uplands tend to consist of glacial till on hillslopes and glacial fluvial deposits (sand and gravel outwash) in the valley bottoms (Lumia 1991). The northern portion of the Limestone Creek watershed intersects an outcropping of Devonian limestone. This formation dips to the south, so much of the subsurface of the watershed is presumably underlain by this limestone formation. There have been no geohydrological studies of
surface-subsurface interactions within the Limestone Creek watershed, but studies in karst geology in the
same formation further east in New York State indicate the possible presence of extensive subsurface
karst drainage networks that interact with more surficial flow paths (Baker 1973). Wappinger Creek is
located in the Appalachian Valley and Ridge province. The watershed primarily overlays sedimentary
bedrock, but there are zones of metamorphic rock in outcroppings. Extensive deposits of sand and gravel
can be found in the valley bottoms. In general, the Limestone, Fall, and Wappinger Creek watersheds are
relatively similar, consisting of shallow soils overlaying shale (with some limestone and dolomite) on
moderate to gently sloping terrain (Lumia 1991). The geology and soils of the Sterling Creek watershed
are somewhat different. It is located in the central lowlands (lake plain) province of New York (Lumia
1991). Soils in the central lowlands are primarily glaciolacustrine in origin and tend to be poorly drained
with a high water table. The terrain is primarily flat with the exception of several drumlins in the southern
portion of the watershed. Basic watershed characteristics are summarized in Table 1.

 Besides differences in innate physical features, we noted a distinct difference in the degree of
anthropogenic hydrologic modification across the study sites. In particular, the Wappinger Creek
watershed has a large number of small impoundments created by small dams. Based on the New York
State Department of Environmental Conservation (NYS DEC) dam inventory available through the New
York State GIS Clearinghouse (http://gis.ny.gov/gisdata/inventories/member.cfm?organizationID=529;
last accessed 11/25/2013), Wappinger Creek has 85 dams within its boundaries, while Fall Creek has 29,
Limestone Creek has 14, and Sterling Creek has seven. Wappinger Creek has more than twice as many
dams per unit watershed area than the other three watersheds. Additionally, 50% of the dams in
Wappinger Creek appear to have been built between 1950 and 1990 with many of the larger ones built
during this time, directly overlapping with the period of land cover transition we evaluated. While other
watersheds also had some dam building between 1950 and 1990, the largest dams tended to be built
earlier or later. We will consider the possible influence of these dams in more depth later in the paper.
2.2 Land Cover Mapping

Sterling Creek watershed land cover was digitized as part of a prior research project; geo-referenced raster maps of land cover for the watershed were available from the Cornell University Geospatial Repository (CUGIR) for the 1950’s, 1980’s, and 2000’s. For the Fall Creek and Limestone Creek watersheds, non-digitized historic aerial photographs from 1930s and 1960s were obtained from the Cornell Institute for Resource Information Systems (IRIS) Aerial Photograph Collection (http://aerial-ny.library.cornell.edu/; last accessed 11/25/2013). These photographs were panchromatic, direct contact prints (i.e. printed directly from negative to paper with no enlargement or reduction) taken vertically using aerial mapping cameras. A total of 108 and 55 photographs were obtained for deriving land cover maps of Fall Creek and Limestone Creek, respectively. The photographs were registered to 2006 digital orthoimagery (New York State Digital Orthoimagery Program; http://gis.ny.gov/gateway/mg/; last accessed 11/25/2013) using a well distributed group of at least 10 reference points representing road intersections common to both images. Georeferenced aerial photographs for the 1930’s for the Wappinger Creek watershed were obtained directly from the New York State GIS Clearinghouse.

The primary goal of the land cover classification was to identify three classes—urban, agriculture, and forested regions—within the Fall Creek, Limestone Creek, and Wappinger Creek watersheds. Because of the low spectral resolution in the available imagery, experimentation showed that a two-step classification procedure was required. This experimentation also suggested that there was no advantage to using advanced classifiers, thus an unsupervised classification was used. The first step consisted of performing a preliminary image classification to identify forest and transitional land cover from each geo-referenced photograph using the Iso Cluster tool in the ArcGIS 10 software package (Esri 2011). Transitional areas were identified with sparsely distributed shrub or tree-like vegetation and were assumed to be abandoned agricultural land in a period of successional growth. These transitional areas were included in the tally of
forested land cover. This preliminary image was then edited manually to identify urban areas and correct any obvious inconsistencies in the classification of forest and transitional areas. Figure 2 shows a representative example of an aerial image and the area classified as forest land cover. Any areas not identified as urban or forest were assumed to be agricultural land. Individual classified images were combined into a watershed-wide layer using the mosaic function of ERDAS IMAGINE (ERDAS Inc., Norcross, GA) software. Land cover maps for the 1990s were obtained from the 1992 National Land Cover Dataset (Vogelmann et al. 2001). Land cover for each watershed in each era is summarized in Table 2.

2.3 Hydrologic Response Metrics

Stream discharge is a direct outcome of hydroclimatological controls. If there are few large precipitation events in a given era, then there will be few large discharge events. Thus, it is understood that a key requirement of a longitudinal study of land cover change is to control for variations in precipitation. Past studies (Sriwongsitanon and Taesombat 2011, Beighley and Moglen 2002) that have controlled for precipitation inputs have calculated runoff ratios, the ratio of discharge (normalized by watershed area) to precipitation. However, there is also recent recognition that peak stream discharges are not dictated by event precipitation alone but are also dependent on antecedent water storage across a catchment (Van Steenbergen and Willems 2013, Merz and Blöschl 2009, Shaw and Walter 2009). Thus, we control for both event precipitation amount and antecedent conditions prior to peak discharge events.

Instead of using the runoff ratio, we use a related metric that, like the runoff ratio, is also calculated only from observed area normalized discharge ($Q$) and precipitation ($P$):

$$S = \frac{P^2}{Q} - P \quad \text{Eqn. 1}$$
where $S$ is the conceptual available watershed moisture storage. The advantage of this metric over the standard runoff ratio is that it directly accounts for non-linearity in the rainfall-runoff relationship (i.e. higher precipitation amounts will result in disproportionately higher discharge). Notably, this metric moves inversely to the runoff ratio; a high runoff ratio indicates a low $S$, as would be expected given that $S$ is representative of available watershed moisture storage. Equation 1 originates from algebraic manipulation of the Curve Number equation. We hesitate to introduce Equation 1 as the Curve Number equation since it does not make use of the tabulated Curve Number values that are the defining feature of the Curve Number equation in practice. When solving directly for $Q$, we consider Equation 1 to be a simple, one-parameter rainfall-runoff model in the same sense that the runoff ratio can be used as a simple one-parameter rainfall-runoff model ($Q = \text{Runoff Ratio} \times P$).

Using Equation 1, we calculate event $S$ values for upwards of 30 different storm events in each era within each watershed. Storm events are selected so as to have spatially uniform precipitation across the basin and be relatively temporally isolated such that there is an obvious impulse-response relationship between observed precipitation and observed discharge. We control for snow by looking at snowfall records where available; otherwise we only use events between April 1 and December 1. Spatial uniformity is determined by using events in which precipitation between multiple rain gages is within 50%. Any events with less than 10 mm of precipitation are excluded to minimize sensitivity to the initial abstraction necessary to initiate runoff. The event discharge is calculated by computing the aggregate stream discharge volume during the precipitation period and up to four days following the end of precipitation or when event discharge returns back to pre-event baseflow levels. Because events are selected to be temporally isolated, baseflow is accounted for by simply subtracting off the stream discharge on the day immediately prior to the precipitation event ($Q_{\text{prior}}$).
As has been observed previously, $S$ is not a constant but varies with antecedent conditions. Prior work has found that $Q_{prior}$ is a suitable estimator of antecedent conditions (Shaw and Walter 2009). Any comparisons of $S$ need to control for differences in $Q_{prior}$. Thus, to relate changes in $S$ to changes in land cover, we can compare the $S$ versus $Q_{prior}$ relationship among different eras. Because of scatter in this relationship, we apply a boot strapping approach that constructs a linear, best-fit regression line for 5000 samples of the dataset for each era; we sample without replacement to generate the 5000 samples. From this, we can establish the degree of uncertainty of the slope and intercept associated with each $S$ versus $Q_{prior}$ relationship for each era (Table 3).

Because there is not a direct, linear linkage between $S$ versus $Q_{prior}$ and peak discharge (i.e. discharge is determined from the non-linear Eqn. 1), we also calculated a peak discharge representative of a large storm event ($Q_{peak}$) by randomly drawing a $Q_{prior}$ value, calculating an $S$ by plugging $Q_{prior}$ into an $S$ versus $Q_{prior}$ linear regression relationship generated by boot strap, pairing this $S$ value with a fixed precipitation amount (51 mm), and calculating a $Q_{peak}$ using the inverse of Equation 1 (i.e. $Q = P^2/[S + P]$). We used uniformly distributed $Q_{prior}$ values between 2 and 4 mm d$^{-1}$. The advantage of calculating $Q_{peak}$ from back-calculated $Q_{prior}$ versus $S$ values (instead of directly comparing the original Q values from the raw data) is that we can control for differences in weather variables across eras. We generated 5000 $Q_{peak}$ values using the 5000 boot strapped $S$ versus $Q_{prior}$ relationships for each era for each watershed.

3. Results

With the exception of the Sterling Creek, the watersheds exhibited sizable changes in land cover during the period of analysis (Table 2, Figures 3 to 6). However, Sterling Creek had a rapid increase in forest cover between the 1980’s (when stream gaging ended) and early 2000. Since we only analyze the period when stream gaging records are available, we do not directly consider the 2000 land cover in Sterling
Creek in the analysis, but we do show it in Figure 5. As expected, this change in land cover across the watersheds is dominated by a transition from agricultural to forested land cover. There was also an increase in urbanized land cover across all the basins. This new “urbanized” land cover occurs in a relatively rural setting and in most cases consists of single-family residential homes on large lots. As an exception, Wappinger Creek, does have some concentrated commercial development in the southern portion of the watershed near the cities of Poughkeepsie and Wappinger Falls.

We investigate the $S$ versus $Q_{prior}$ relationship to assess the sensitivity of hydrologic response to changes in land cover. In general, we would assume that a reduced sensitivity in hydrologic response would be reflected by an increasing $S$ value, corresponding to an increase in available watershed moisture storage. Figure 7 displays the $S$ versus $Q_{prior}$ plots for all four watersheds for each era in which they were analyzed. Across all four watersheds, there are subtle visual distinctions among different eras. For instance, in Wappinger Creek, above 0.8 mm d$^{-1}$, the $S$ values for the 1990’s appear to be systematically larger than those of the 1930’s. Notably, in Limestone Creek the $S$ versus $Q_{prior}$ plot appears to slightly diverge from a linear curve and flatten at higher values of $Q_{prior}$. We presume this may be due to the karst geology providing some additional deep storage at high flows. However, because the linear regression line fits relatively well ($R^2 > 0.64$) and because there does not appear to be any change in outcome were the non-linearity to be directly accounted for, we still only use the linear relationship to evaluate changes among eras in Limestone Creek.

To more quantitatively assess possible differences between eras, one can examine the boot strapped mean and standard deviations of the slope and intercepts associated with each $S$ versus $Q_{prior}$ curve (Table 3). In comparing intercept and slope means across eras within the same watershed, we assume that differences in means greater than two standard deviations apart would indicate a significant statistical difference at
approximately the 5% level. In Fall Creek, differences in slope are well within one standard deviation of each other, but intercepts between the 1930’s and 1990’s are nearly two standard deviations apart, suggesting a meaningful shift in hydrologic response. A similar difference between slopes and intercepts is also seen in Wappinger Creek between the 1930’s and 1990’s, suggesting a meaningful shift in S, and thus hydrologic response, in this watershed too. Limestone Creek does not appear to have any significant shift in slope or intercepts across eras. Sterling Creek has a moderate shift on the order of one standard deviation in both slope and intercept. Due to the interaction of slope and intercept, it is ambiguous in terms of which era has a higher S in the Sterling Creek watershed. Therefore, we also used the boot-strapped S versus $Q_{prior}$ relationship to directly estimate changes in discharge between eras for a fixed sized precipitation event. This analysis can provide further insight into changes in hydrologic response in Sterling Creek as well as further validate changes in the other three watersheds inferred by looking at slope and intercepts alone.

In Table 4, we compare changes in discharge as based on the traditional tabulated Curve Number method and as based on discharge values (referred to as $Q_{peak}$) determined from the boot-strapped S versus $Q_{prior}$ relationships. For the calculations presented in Table 4, we evaluate the hydrologic response at a single precipitation value of 51 mm, a moderately large precipitation event on the order of the one-year return period storm in the locale of our watersheds. We replicated the calculations for precipitation values of 20.5 and 102 mm and found similar changes in hydrologic response, thus only the results for a 51 mm event are shown. For $Q_{peak}$ calculations, we indicate the fraction of the 5000 boot-strapped trials in which the percent change in greater than zero. Fractions of $Q_{peak}>0$ near 50% indicate that the change is little different from zero. Only when the Fraction of $Q_{peak}>0$ approaches zero or 100 does it suggest that the change is statistically significant.
The traditional Curve Number method is meant to give some sense of typical expectations of how land cover change would influence hydrologic response. In applying the traditional Curve Number method, we use a Curve Number (CN) value of 55 for forest cover and 92 for urban land. Because of the range in typical CN values related to agricultural and use, we assess two scenarios in which agricultural land is assigned a CN of either 68 or 75. A CN range from 68 to 75 approximately spans CN’s related to pasture and row crops for a class B hydrologic soil group. Based on the traditional Curve Number method, all four watersheds see a decline in peak flow. Sterling Creek sees a limited decline because of the only slight shift in land cover proportions. In all four watersheds, the traditional Curve Number method suggests that declining agricultural land offsets any increases in urban land and that conversion to forest land will result in at least some diminishment in peak flows.

The calculation of $Q_{peak}$ results in very different outcomes relative to the Curve Number method. In Fall Creek, $Q_{peak}$ drops between the 1930’s and 1960’s, and then increases above the 1930’s value by 10.8% by the 1990’s (Table 4). Greater than 90% of the trials have a positive increase, indicating a sizable difference from a zero percent change. In Limestone Creek, $Q_{peak}$ does not experience a change different from zero between the 1930’s and 1960’s or the 1930’s to 1990’s. In Sterling Creek, there is an average decline of 22.8% in $Q_{peak}$ with 84.5% of the trials having a negative decline. The large decrease in Sterling is particularly surprising giving the limited change in land cover between eras, although as noted earlier the land cover must be in transition given the large increase in forest cover by 2000. In Wappinger Creek, there is a nearly 30% decline in mean $Q_{peak}$ with 93.2% of the trials having a negative decline. The large decrease in Wappinger Creek is in the same direction as might be expected given the traditional Curve Number method, but of much greater magnitude. For the most part, the changes in $Q_{peak}$ between eras are consistent with changes in slope and intercept presented in Table 3.
4. Discussion

Based on the boot-strap based $Q_{\text{peak}}$, changes in hydrologic response differ among watersheds. More so, these changes are not to the degree expected by the traditional Curve Number method and not necessarily in the direction one would normally anticipate. We consider this boot-strap based $Q_{\text{peak}}$ to be a particularly robust means of assessing differences in hydrological response. Specifically, while there may be an inclination to simply use a collection of direct discharge measurements for a given era (e.g. mean annual peak flows during the 1960’s versus mean annual peak flows during the 1990’s), we suggest the approach presented here is more robust because it accounts for variations in external, causative factors at the time of discharge. In particular, it is quite evident from Figure 7 that antecedent moisture (as represented by $Q_{\text{prior}}$) strongly influences hydrologic response and a failure to account for this factor may obscure perceived differences between discharge in different eras. The implementation of a computational hydrologic model could be an alternative to our calculation and boot-strapping of $S$ versus $Q_{\text{prior}}$ relationships. However, the advantages of our approach relative to a more standard computational model are that it is simple, relatively transparent, and it does not impose a model structure a priori (it instead originates from the empirical relationship present in the data).

Of particular value in establishing the $S$ versus $Q_{\text{prior}}$ relationships (Figure 7) is that the difficulty in discerning differences in hydrologic response among eras becomes quite evident. While the basic relationship between $P$, $Q$, and $Q_{\text{prior}}$ appears quite robust, there admittedly remains significant scatter. Ideally, within eras, $S$ values would display a near one-to-one correspondence to $Q_{\text{prior}}$; instead for any given $Q_{\text{prior}}$ value there is a nearly order of magnitude range of possible associated $S$ values. This suggests that there are other weather variables that remain unaccounted for. These variables likely remain difficult to incorporate, especially in historic periods dating back to the 1940’s, and possibly include sub-daily variations in precipitation intensity and fine-scale spatial variations in precipitation amounts. Thus, the
method provides insights into inherent limitations in discerning differences among eras and highlights the difficulty in isolating land cover factors when weather variables vary among discharge events.

We cannot make a universal statement regarding the influence of land cover change on hydrologic response given the varied changes in $Q_{peak}$ among the four watersheds. But we can offer several specific observations for why hydrologic response may have changed in certain ways in certain watersheds. In Fall Creek, the moderate increase in $Q_{peak}$ may be due to the moderate increases in urbanized land cover (Table 2). Somewhat unexpectedly, the Limestone Creek watershed was found to have a larger change in the degree of urban land cover between eras but only exhibited a marginal increase in hydrologic response (Table 2). It is possible that features of urban land cover that cannot be distinguished from aerial photographs account for this difference between watersheds. For example, the degree of connectivity between impervious surfaces and stream channels may have evolved differently in the two watersheds such as from differences in the extent of roadside ditch network and other drainage conveyances (Buchanan et al. 2013). It is also possible that the presence of karst geology under the Limestone Creek watershed provides enhanced storage relative to Fall Creek even as the watershed urbanizes.

Even with some urbanization, a doubling of forested land might still be expected to result in a change in hydrologic response. But, the relative lack of sensitivity of hydrologic response to this change is not that unexpected in glaciated watersheds in temperate, humid weathers. Most event discharge in these watersheds is expected to occur due to saturation excess runoff generation (Walter et al. 2003, Dunne and Black 1970). That is, runoff generation occurs on portions of the watershed where the full depth of the pore space in the soil profile becomes filled. Runoff is typically generated near the base of hill slopes as subsurface lateral flow from upslope areas combines with direct precipitation to saturate the soil column. The degree of saturation excess runoff is primarily dependent on the depth to a confining layer and
porosity (Buda et al. 2009), factors which do not change significantly with land cover. Other work supports the notion of the limited connection of hydrologic response to land use glaciated landscapes in humid, temperate zones. Merz and Blöschl (2009) found that runoff ratios in Austria were not well predicted by curve number, and thus land use alone. Along these same lines, it has often been found that the Curve Number works best when CN values are back-calculated and not taken from a table (e.g. Huang et al. 2012).

We suggest that Wappinger Creek and Sterling Creek may have secondary factors besides land cover which dominates changes in $Q_{peak}$. Forty-four small dams were constructed in the Wappinger Creek watershed between 1950 and 1990. The exact amount of water that can be impounded behind these dams for an extended period after storm events is not exactly known, but the NYS DEC dam inventory does report the normal water level storage and the maximum water storage. The difference between total normal storage and total maximum storage was almost 700,000 m$^3$ (565 ac-ft). If spread over five days, this storage could reduce peak flow by 0.30 mm d$^{-1}$, partially accounting for the approximately 2 mm d$^{-1}$ difference between $Q_{peak}$ from 1930 to 1990. It is possible that the reported difference between normal water level storage and maximum storage is only a rough estimate of available storage and that the dams actually provide much greater storage that accounts for a larger portion of this 2 mm discrepancy. While the other three basins did have several dams constructed in the time period during which hydrologic studies were evaluated, the number of new dams was much smaller than found in the Wappinger Creek watershed. Prior studies often note the disturbance in hydrologic regime due to large dams on main channels (e.g. Fitzhugh and Vogel 2011, Poff et al. 2006), but the aggregate influence of small dams (which individually impound stores of only several acre-feet) has not often been quantified (Vedachalam and Riha 2013).
The behavior of Sterling Creek is less easily explained. Notably in this case, the negative change in $Q_{peak}$ is only present in 85.5% of all the bootstrapped trials (Table 4). Thus, there is some reasonable possibility this change is within the range of uncertainty of the data. This watershed is also different from the other three, having limited topographical relief, the likelihood of a high water table, and presumably more active wetlands. Finer classification of land cover indicates that in the 1950’s 14% of the watershed consisted of woody wetlands, primarily in riparian areas. It appears that by the 1980’s, much of this woody wetland was identified as forest. It is possible this land was partially drained, potentially reducing rapid runoff generation from these near stream areas.

These findings that reforestation (or presumably the reverse, deforestation) do not predictably influence hydrologic response are in contrast to other studies, notably those in more tropical and sub-tropical regions. However, such differences in outcomes are likely attributable to differences in hydrologic processes in the different regions. In tropical and subtropical regions, forested watersheds do tend to have very high surface infiltration rates and event flow tends to be dominated by lateral subsurface flow (Elsenbeer 2001). However, when disturbed and converted to agricultural land, tropical soils often see sharp declines in hydraulic conductivity. This has been attributed to intensive agricultural practices that lead to soil compaction as well as a sharp decline in soil organic matter due to rapid rates of decomposition and a failure to replace organic material (Recha et al. 2012). High soil organic matter content is essential to maintain soil structure and high infiltration rates. In temperate regions, due to cooler temperature, organic matter loss is much less and conversion to agricultural land (and back to forest land) would likely see less change in soil structure.

5. Conclusions
Many existing studies of land cover change do not directly control for both variability in weather and changes in non-land cover factors within watersheds. Additionally, many only examine dramatic changes in land cover, not more moderate changes. To address limitations of existing studies, we longitudinally assessed multi-decadal changes in four humid, temperate region watersheds using a variant of the runoff ratio to account for weather variability. This is one of the few examples of such studies in the literature that attempts to control for weather (by way of the runoff ratio variant) and innate watershed features (by way of using a longitudinal approach).

A more refined understanding of the sensitivity of hydrologic response to land use is important for informing decision making regarding land use management to reduce flood risks. Particularly with weather change, there is an interest in devising adaptation strategies. While minimizing the extent of urbanization may be useful, converting agricultural land to forest (the primary transition considered in this study) was not observed to consistently reduce hydrologic response. This work suggests reforestation alone may not always be an effective means to minimize future flooding in large glaciated, temperate region watersheds.

Additionally, this work indicates that measures of spatially aggregated land cover may not translate into meaningful measures of differences in hydrologic behavior. Quite simply, the runoff response in these watersheds may not be strongly sensitive to land cover change, possibly in contrast to places where infiltration excess overland flow is more dominant. Or, there may be important confounding features that overwhelm the role of land cover. Such features may relate to connectivity of disturbed areas to the main channel (Roy and Shuster 2009) or direct human influences on the hydrology such as withdrawals, impoundments, or interbasin transfers (Weiskel et al. 2007). In this case, in one of our study watersheds (Wappinger Creek), we found that a decrease in peak flow between the 1930’s and 1990’s corresponded
to the installation of numerous small dams in the same period. While hydrologists are certainly familiar
with the influence of large dams on major waterways, the aggregate impact of numerous small dams not
necessarily intended for flood control has not been extensively documented. There remains a need for
additional work to understand what type of fine scale features drive differences in hydrologic response
and to understand when land cover change will be superseded by changes in other landscape features.

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References


Tables

Table 1. Summary information for watersheds.

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<thead>
<tr>
<th>Watershed</th>
<th>Total Area (km²)</th>
<th>USGS Gage No.</th>
<th>USGS Gage Period of Record</th>
<th>NWS Precipitation Gages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall Creek</td>
<td>323</td>
<td>04234000</td>
<td>1928 – present</td>
<td>Locke, Cortland, Freeville</td>
</tr>
<tr>
<td>Limestone Creek</td>
<td>219</td>
<td>04245000</td>
<td>1939 - 1986</td>
<td>DeRuyter, Morrisville</td>
</tr>
<tr>
<td>Sterling Creek</td>
<td>114</td>
<td>04232100</td>
<td>1957 - 1995</td>
<td>Fulton, Oswego East</td>
</tr>
<tr>
<td>Wappinger Creek</td>
<td>463</td>
<td>01372500</td>
<td>1928 - present</td>
<td>Dutchess Ct. AP, Millbrook, Wappinger Falls</td>
</tr>
</tbody>
</table>

Table 2. Percentage land cover type in each watershed in different eras.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>1930’s</th>
<th>1950’s/1960’s</th>
<th>1980’s/1990’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall Creek</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>26.8</td>
<td>36.0</td>
<td>52.3</td>
</tr>
<tr>
<td>Agricultural</td>
<td>71.7</td>
<td>61.7</td>
<td>45.0</td>
</tr>
<tr>
<td>Urban</td>
<td>1.5</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Limestone Creek</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>19.9</td>
<td>33.4</td>
<td>51.5</td>
</tr>
<tr>
<td>Agricultural</td>
<td>77.0</td>
<td>62.1</td>
<td>40.1</td>
</tr>
<tr>
<td>Urban</td>
<td>3.1</td>
<td>4.5</td>
<td>8.4</td>
</tr>
<tr>
<td>Sterling Creek</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>---</td>
<td>38.1</td>
<td>40.2</td>
</tr>
<tr>
<td>Agricultural</td>
<td>---</td>
<td>60.1</td>
<td>57.5</td>
</tr>
<tr>
<td>Urban</td>
<td>---</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Open Water</td>
<td>---</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Wappinger Creek</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td>35.0</td>
<td>---</td>
<td>65.0</td>
</tr>
<tr>
<td>Agricultural</td>
<td>64.0</td>
<td>---</td>
<td>25.9</td>
</tr>
<tr>
<td>Urban</td>
<td>1.0</td>
<td>---</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Table 3. Mean and standard deviation of the slope and intercept of a linear regression line fit to 5000 trials of bootstrapped $S$ and $Q_{prior}$.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Era</th>
<th>Events in Era</th>
<th>Slope</th>
<th>Intercept</th>
<th>Mean $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>St. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>Fall Creek</td>
<td>1930’s</td>
<td>33</td>
<td>-1.100</td>
<td>0.075</td>
<td>4.815</td>
</tr>
<tr>
<td></td>
<td>1960’s</td>
<td>41</td>
<td>-1.120</td>
<td>0.063</td>
<td>4.899</td>
</tr>
<tr>
<td></td>
<td>1990’s</td>
<td>30</td>
<td>-1.167</td>
<td>0.109</td>
<td>4.572</td>
</tr>
<tr>
<td>Limestone Creek</td>
<td>1930’s</td>
<td>43</td>
<td>-1.618</td>
<td>0.157</td>
<td>5.753</td>
</tr>
<tr>
<td></td>
<td>1960’s</td>
<td>56</td>
<td>-1.484</td>
<td>0.149</td>
<td>5.567</td>
</tr>
<tr>
<td></td>
<td>1990’s</td>
<td>32</td>
<td>-1.444</td>
<td>0.190</td>
<td>5.500</td>
</tr>
<tr>
<td>Sterling Creek</td>
<td>1950’s</td>
<td>34</td>
<td>-1.113</td>
<td>0.106</td>
<td>5.100</td>
</tr>
<tr>
<td></td>
<td>1980’s</td>
<td>32</td>
<td>-1.007</td>
<td>0.105</td>
<td>5.370</td>
</tr>
<tr>
<td>Wappinger Creek</td>
<td>1930’s</td>
<td>49</td>
<td>-0.911</td>
<td>0.075</td>
<td>5.606</td>
</tr>
<tr>
<td></td>
<td>1990’s</td>
<td>33</td>
<td>-0.817</td>
<td>0.080</td>
<td>5.854</td>
</tr>
</tbody>
</table>

Table 4. Percentage change in watershed discharge between different eras when $P=51$ mm and $Q_{prior}$ is between 2 and 4 mm day$^{-1}$. The “CN Method” columns use land cover fraction reported in Table 2. $Q_{peak}$ is calculated from bootstrapped $S$ vs. $Q_{prior}$ relationships. Fraction Trials % Change >0 indicates the portion of the 5000 trials that result in a % change in $Q_{peak}$ greater than zero.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Transition</th>
<th>Change in $Q$ (when $P=51$ mm)</th>
<th>$Q_{peak}$</th>
<th>Fraction Trials % Change &gt;0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CN Method (Ag CN=75) CN Method (Ag CN = 68)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall Creek</td>
<td>1930’s to 1960’s</td>
<td>-4% -2%</td>
<td>-3.7%</td>
<td>36.3</td>
</tr>
<tr>
<td></td>
<td>1930’s to 1990’s</td>
<td>-13% -8%</td>
<td>10.6%</td>
<td>90.1</td>
</tr>
<tr>
<td>Limestone Creek</td>
<td>1930’s to 1960’s</td>
<td>-9% -6%</td>
<td>2.1%</td>
<td>58.1</td>
</tr>
<tr>
<td></td>
<td>1930’s to 1990’s</td>
<td>-16% -8%</td>
<td>3.3%</td>
<td>55.2</td>
</tr>
<tr>
<td>Sterling Creek</td>
<td>1950’s to 1980’s</td>
<td>3% -1%</td>
<td>-22.8%</td>
<td>14.5</td>
</tr>
<tr>
<td>Wappinger Creek</td>
<td>1930’s to 1990’s</td>
<td>-14% -6%</td>
<td>-28.5%</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1. Location map of study watersheds and precipitation gages.

Figure 2. Representative comparison of aerial imagery and land cover classified as forest. This example is taken from the Limestone Creek watershed due west of Cazenovia, NY during the 1930’s. The dark band near the apex of the curve in State Rt. 20 is due to shadowing from a steep hillside to the west. The dark band at the upper right hand corner is the border of an overlapping image.

Figure 3. Forest land cover in the Fall Creek watershed in the 1930’s is indicated in black. Forest land cover added between the 1930’s and 1960’s is shown in dark gray while forest land cover added between the 1960’s and 1990’s is the light tone.

Figure 4. Forest land cover in Wappinger Creek watershed in the 1930’s is indicated in black. Forest land cover added between the 1930’s and 1990’s is shown in dark gray.

Figure 5. Forest land cover in the Sterling Creek watershed in the 1950’s is indicated in black. Forest land cover added between the 1950’s and 1980’s is shown in dark gray while forest land cover added between the 1980’s and 2000’s is the light tone.

Figure 6. Forest land cover in the Limestone Creek watershed in the 1930’s is indicated in black. Forest land cover added between the 1930’s and 1960’s is shown in dark gray while forest land cover added between the 1960’s and 1990’s is the light tone.

Figure 7. Storage versus $Q_{prior}$ curves for the four watersheds. Different symbols indicate different eras.
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