EVALUATING RELATIONSHIPS BETWEEN NATURAL RESOURCE MANAGEMENT, LAND USE CHANGES, AND FLOODING IN THE APPALACHIAN REGION

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Abstract.—The Appalachian Region has a long history of natural resource management and recurrent history of frequent and large-scale floods. Land use activities such as urbanization, mining, forest harvesting, and agriculture can have a noticeable effect on the volume, magnitude, timing, and frequency of floods. Determining the effects of land use on flooding is difficult for many reasons, and there are no exact methods of identifying the impacts of land use on flood generation across larger scales. To ascertain the potential effects of land use changes on flooding in this region, a flood production metric was developed by using retrospective analysis between the proportions of land use and flood count data for 420 counties in 13 states. Generalized linear models were used to identify landscape and climate attributes that explain the largest variations in flood data during 2000, 2001, and 2002. Results show that forests, agriculture, riparian forest, impervious surfaces, precipitation, topographic slope, and surface coal production explain variations in floods in this region. Future changes in land use have the potential to increase or decrease flooding and should be considered in natural resource management with respect to the mosaic of land uses in the Appalachian Region.

INTRODUCTION

The ability of a watershed to mitigate or control runoff is primarily influenced by local climate, geology, and topography, as well as the nature and extent of land use conditions. Watersheds with large proportions of land use in agriculture, forest harvesting, surface mining, and urbanization are more likely to produce runoff compared to watersheds that are predominantly forested and to some extent covered with wetlands. Numerous studies have shown the importance of forested headwater catchments as they provide many valuable ecosystem services, including flood mitigation, that link the streams to the people living in these areas (Meyer and Wallace 2001). Land use activities such as urbanization (Gremillion et al. 2000), mining (Bonta 2000, Messinger 2003), forest harvesting (Zégre et al. 2010), and agriculture (Dye and Croke 2003) can have a noticeable effect on the volume, magnitude, timing, and frequency of floods.

In contrast, intact forests and wetlands mitigate storm runoff by returning water to the atmosphere through plant transpiration and interception or by temporarily storing runoff that is released over time. Additionally, runoff is a function of slope (the steeper the slope, the less the storage), latitude (regional climate), and watershed size. Land use activities that alter or remove vegetation have the potential of increasing stormflow volume by reducing the overall amount of water lost to the atmosphere through forest canopy interception and evapotranspiration, thereby increasing the volume of water delivered to a stream (Bosch and Hewlett 1982). Activities that reduce infiltration capacity of soils, such as roads, heavy grazing, surface mining, and heavy machinery, can increase

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surface runoff by translating a larger proportion of precipitation to runoff rather than being stored in soil. Roads and drainage infrastructure increase the connectivity of a watershed to the stream, resulting in reduced travel times of water and increased peakflow at the watershed outlet. Land use activities can also increase erosion and sedimentation, modifying channel geometry and thereby reducing storage capacity of the stream channel.

Determining the effects of land use on flooding is nevertheless challenging because floods along streams and rivers represent the accumulated runoff from many watersheds with heterogeneous landscape characteristics and a vast array of process interactions that are difficult to measure. In addition, flood-producing precipitation is spatially and temporally heterogeneous, unevenly distributing rainfall across the landscape. As such, there are no exact methods of identifying the impact of land use changes on flood generation across large scales.

In this study we use ordinary least squares regression, land use data, and flood count data to evaluate the integrated effects of land use changes, natural resource management, urbanization, and precipitation to explain variations in floods for counties located in the Appalachian Region.

METHODS

Study Area and Extent

The Appalachian Region (AR) consists of approximately 205,000 square miles, covering 420 counties in 13 states (Fig. 1). It extends more than 1,000 miles, from southwestern New York to northeastern Mississippi, and is home to 24.8 million people. The AR has a long history of natural resource extraction, including coal, timber, and natural gas. Though much of the region is mainly forest, large-scale changes attributed to mining and forest harvesting are the predominant driver of changes in land use and land cover in the region (Townsend et al. 2009).

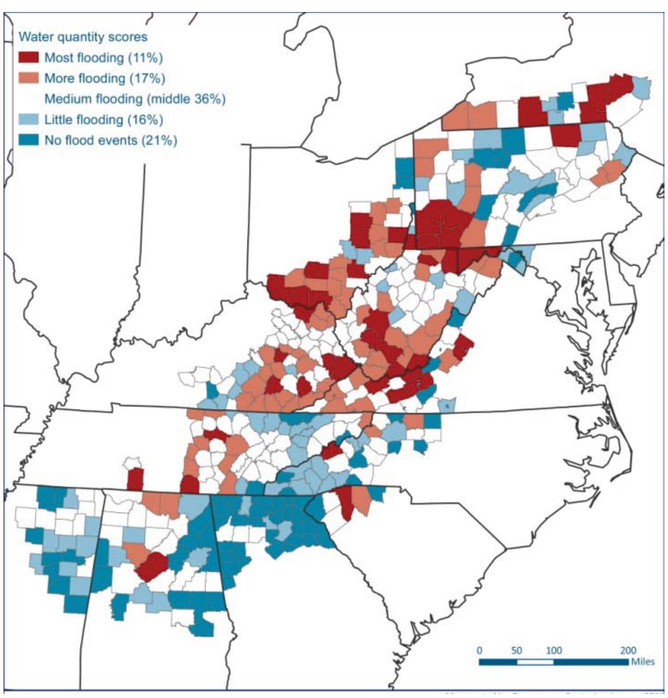

Figure 1.—Flood count data by county for the Appalachian Region. Flood count data are normalized by the number of floods per county area and are presented on a relative scale.

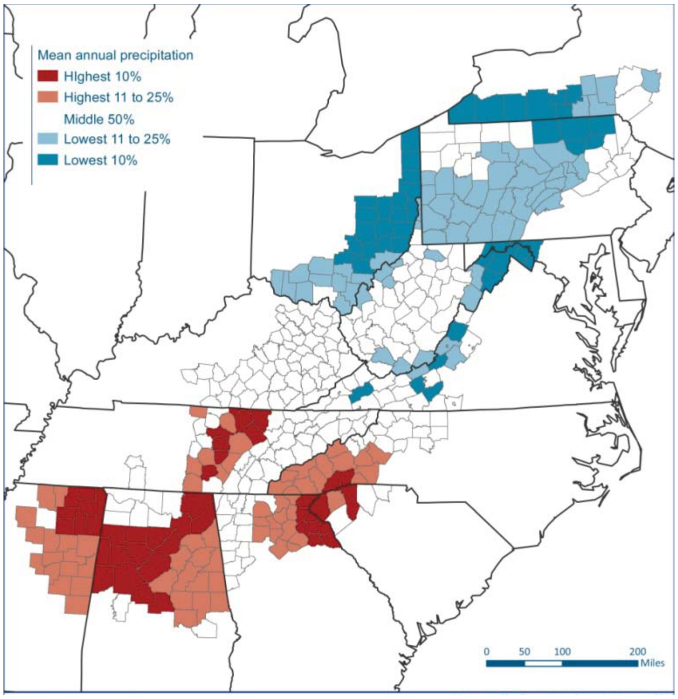

Figure 2.—Mean annual precipitation (MAP) by county for the Appalachian Region. Data are normalized by the depth of annual precipitation per county area and are presented on a relative scale.

Data and Analyses

To ascertain the potential effects of land use on flooding in AR counties, a model was developed by using retrospective analysis between the proportions of a county under given land use, climate, and flood count data. Land use for the 420 counties was derived from the 2001 national land cover dataset (NLCD). Specifically we are interested in landscape attributes that potentially mitigate or exacerbate flooding. As such, the 2001 NLCD was queried for the proportion of county under forest, agriculture, riparian forest, wetlands, and impervious surface (including roads, houses, and buildings); average topographic slope; and coal production per square mile, calculated as tons of surface-mined coal between 1983 and 2009 divided by county area.

Mean annual precipitation (MAP) from the National Oceanographic and Atmospheric Administration's National Climatic Data Center (NCDC) was included to account for regional differences in climate, namely precipitation and air temperature. When the spatial distribution of county-level MAP was mapped, a clear regional pattern emerged (Fig. 2); therefore, MAP was classified as three regions: region 1 – lower MAP range (New York, Pennsylvania, Ohio, Maryland, and Virginia), region 2 – moderate MAP range (West Virginia and Kentucky), and region 3 – upper MAP range (Tennessee, North Carolina, South Carolina, Georgia, Alabama, and Mississippi).

Flood count data for each county were compiled from the NCDC storm events database (SED). Floods are technically defined by streamflow events that rise above the streambanks and exceed the capacity of the stream channel. The SED contains data for weather events from 1996-present for the United States. Floods and flash floods are reported as count data (i.e., occurrence of flood) by location or county, date and time of event, magnitude, deaths, injuries, property damage, and crop damage. Our analysis was limited to the occurrence of floods or flash floods; reporting of other associated data was inconsistent across events, counties, and states.

The SED was queried for all floods that occurred during U.S. Geological Survey (USGS) water years (wy) 2000, 2001, and 2002 in all AR counties. A USGS water year is defined as October 1-September 30 for each year and is used to account for seasonal changes in water storage. These water years were selected to represent land use cover status 1 year before, during, and 1 year after the 2001 NLCD coverage. Flood occurrences during wy 2000, 2001, and 2002 were totaled for each county. A total of 1,433 storms were reported for all AR counties during the analysis period.

A generalized linear model (GLM) was developed to identify the landscape and climate attributes that explain the largest amount of variations in flood count data by county. The dependent variable, flood count, was regressed on explanatory variables thought to either mitigate or exacerbate floods. To account for skew in the flood count data (e.g., preponderance of no events in some counties when events occurred in other counties), regression models were fit by using a Poisson distribution. The Poisson distribution is important for describing random occurrences when the probability of occurrence is small. For example, an extreme event during any given year has a lower probability of occurring compared to an event closer to average conditions.

Because different landscape and climate attributes affect flooding differently (e.g., a unit area of forest and unit area of impervious surface may not mitigate or exacerbate flooding equally), each attribute was weighted based on its relative contribution in explaining variations in flood count data. Regression model slope coefficients were used to determine how each attribute affects flooding. A positive slope coefficient indicates that the attribute exacerbates flooding; a negative slope coefficient suggests a reduction or mitigation of flooding. The value of the slope coefficient describes a 1-unit change (increase or decrease) in flood response, given the slope coefficient for each attribute. To account for the differing effects of each attribute on flooding, each explanatory variable was multiplied by the associated slope coefficient and rescaled to between 0 and 100. Rescaled attributes were then weighted to account for their relative contribution in explaining model variance. The weight of each variable was calculated by using deviance and null deviance from analysis of variance and calculated as:

$$\text{weight} = [\text{null deviance} - \text{deviance}]/\text{null deviance}$$

where null deviance is the deviance explained by the null model and deviance is the relative contribution of each variable in explaining model variance. Weights were rescaled by comparing individual weight value to the range of all weights. Rescaled attributes were then multiplied by weighting factors to produce regression-weighted attributes that either exacerbate or mitigate flooding in the AR counties.

RESULTS AND DISCUSSION

During 2000, 2001, and 2002, 1,433 floods and flash floods were reported for the 420 AR counties. Kentucky had the greatest number of floods reported with 242, followed by 230 in West Virginia, then Ohio with 191 floods. Georgia, Maryland, and South Carolina had the fewest floods reported with 10, 19, and 26, respectively. When data were normalized by area, Kentucky, Maryland, and Ohio had the greatest number of floods.

Pike County, Kentucky, experienced the greatest number of floods of all AR counties with 22 floods reported in the SED during 2000 through 2002. The large number of floods trends well with the land use. Though Pike County is largely forested (77 percent) and has minimal agriculture (0.025 percent), its topography is very steep, with average slopes of 45 percent. The county has high surface coal production per square mile (45,165 units). Similarly, Boone County, West Virginia, has a large number of floods relative to flooding in all AR counties, with 10 reported flood events. Boone County is heavily forested (85 percent) with minimal agriculture (0.01 percent), is very steep (42 percent slope), and produces approximately 64,233 units of surface coal production per square mile. Under the National Flood Insurance Program, a total of $33,358,385 has been paid to Pike County residents, $262,360,845 to Kentucky, $1,618,554 to Boone County residents, and $283,436,665 to West Virginia since 1978 on account of flooding (Federal Emergency Management Agency, N.d.).

In contrast, Unicoi County, Tennessee, reported no floods during these years. Approximately 86 percent of Unicoi County is forested and 0.02 percent is agriculture. This county has steep slopes (35 percent) and no surface coal mine production per square mile. Since 1978, a total of $108,990 has been paid to Unicoi County residents and $298,515,927 to Tennessee on account of flooding (Federal Emergency Management Agency, N.d.).

Regression analysis suggests that percentages of forest, agriculture, riparian forest, and impervious surface; precipitation; slope; and surface coal production per square mile were significant in explaining variations in flood data for AR counties. Based on this analysis, directional changes in land use and topography can increase or decrease flood count data for each county. For example, either a 0.26-percent increase in forest cover or an 18.6-percent increase in riparian forest has the potential to decrease floods by one flood count unit (Table 1). Alternatively, a 0.00001-percent increase in surface coal production or a 0.03-percent increase in topographic slope has the potential to increase flooding by one unit.

Table 1.—Results of GLM regression analysis to identify significant land use attributes for Appalachian Region counties

Coefficient	Deviance	Residual deviance	Slope Coefficient [null-dev]/null*100	Weighting	Slope coeff[a]
Null	1409.3	-	-	-	-
% Forest	8.9	1400.4	0.63	0.10	-0.26
% Ag	34.6	1365.8	2.46	0.37	1.06
% Rip For	92.3	1273.5	6.55	1	-18.6
% Imperv	4.9	1268.6	0.35	0.05	9.525
MAP region	70.5	1198.1	5.00	0.76	-0.3
% Slope	60.0	1138	4.26	0.65	0.03
coal/sq mi	7.0	1131	0.49	0.08	0.00001

[a] Slope coefficient shows directional change in unit flood count data per change in slope parameter; (-) indicates a decrease in flood response and (+) indicates an increase in flood count data.

CONCLUSIONS

Regression analysis shows how directional changes in land use and topography can increase or decrease flood count data for each county. Land use activities that reduce soil infiltration capacity, such as heavy grazing, surface mining, and heavy machinery, or that convert or remove vegetation, have the potential to increase streamflow. Such activities translate a larger proportion of precipitation to runoff, rather than allowing it to be stored in soil, and reduce the overall amount of water lost to the atmosphere through interception and evapotranspiration. Therefore, future changes in land use have the potential to increase or decrease flooding and should be considered when addressing economic development, resource management, and evaluation of AR water assets.

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LITERATURE CITED

Bonta, J.V. 2000. **Impact of coal-surface and reclamation on suspended sediment in three Ohio watersheds.** Journal of the American Water Resources Association. 36(4): 869-887.

Bosch, J.M.; Hewlett J.D. 1982. **A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration.** Journal of Hydrology. 55: 3-23.

Dye, P.J.; Croke, B.F.W. 2003. **Evaluation of streamflow predictions by the IHACRES rainfall-runoff model in two South African catchments.** Environmental Modelling & Software. 18: 705-712.

Federal Emergency Management Agency. [N.d.] **National flood insurance program.** Available at http://www.fema.gov/about/programs/nfip/index.shtm. (Accessed January 2011).

Gremillion, P.; Gonyeau, A.; Wanielista, M. 2000. **Application of alternative hydrograph separation models to detect changes in flow paths in a watershed undergoing urban development.** Hydrological Processes. 14: 1485-1501.

Messinger, T. 2003. **Comparison of storm response of streams in small, unmined and valley-filled watersheds, 1999-2001, Ballard Fork, West Virginia.** Water-Resources Investigations Report 02-4303. Charleston, WV: U.S. Geological Survey. 22 p.

Meyer, J.; Wallace, J. 2001. **Lost linkages and lotic ecology: rediscovering small streams.** In: Press, M.; Huntly, N.; Levin, S., eds. Ecology: achievement and challenge. Oxford, UK: Blackwell Science: 295-317.

Townsend, P.A.; Helmers, D.P.; Kingdon, C.C.; McNeil, B.E.; de Beurs, K.M.; Eshleman, K.N. 2009. **Changes in the extent of surface mining and reclamation in the Central Appalachians detected using a 1976-2006 Landsat time series.** Remote Sensing of Environment. 113: 62-72.

Zégre, N.; Skaugset, A.E.; Som, N.A.; McDonnell, J.J.; Ganio, L.M. 2010. **In lieu of the paired catchment approach: hydrologic model change detection at the catchment scale.** Water Resources Research. 46: W11544. DOI: 10.1029/2009WR008601.