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Land-use change and hydrologic processes: a major focus for the future

R. DeFries[1]*
K. N. Eshleman[2]

[1] *Department of Geography and Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA*
[2] *University of Maryland Center for Environmental Science, Appalachian Laboratory, Frostburg, MD, USA*

*Correspondence to:
R. DeFries, Department of Geography, 2181 LeFrak Hall, University of Maryland, College Park, MD 20742, USA.
E-mail: rdefries@geog.umd.edu

Conversion of land to feed and shelter the growing human enterprise has been one of the primary modes for human modification of the global environment. Over the coming decades, expansion and intensification of agriculture, growth of urban areas, and extraction of timber and other natural resources will likely accelerate to satisfy demands of increasing numbers of people at higher standards of living. Human transformation of the Earth's land surface has multiple consequences for biophysical systems at all scales, ranging from local urban heat islands (Kalnay and Cai, 2003) and alterations in streamflow patterns (Storck *et al*., 1998; Rose and Peters, 2001) to altered patterns of global atmospheric circulation (Werth and Avissar, 2002) and long-term extinction of species (Pimm and Raven, 2000). Land-use change is a major issue for this century. Some suggest that the consequences may outweigh those from climate change (Sala *et al*., 2000; Vorosmarty *et al*., 2000).

To date, much of the research investigating the consequences of land-use change has focused on two issues: (1) the effects of land-use change on climate, either indirectly through emissions of carbon dioxide and other greenhouse gases from burning and decaying biomass (Houghton, 1995), or directly through altered exchanges of energy, water, and momentum between the land surface and atmosphere (Bonan, 1997), and (2) the effects of habitat loss on biodiversity (Sala *et al*., 2000). Although the study of linkages between vegetative cover, hydrologic processes and water quality has a relatively long history based on modelling, experimental watersheds, and measurements, the consequences of anthropogenic land-use change for hydrology have received little attention in the study of land-use change (Lambin *et al*., 2002).

We suggest that understanding the consequences of land-use change for hydrologic processes, and integrating this understanding into the emerging focus on land-change science (Turner *et al*., 2003), are major needs for the future. These consequences include: changes in water demands from changing land-use practices, such as irrigation and urbanization; changes in water supply from altered hydrological processes of infiltration, groundwater recharge and runoff; and changes in water quality from agricultural runoff and suburban development. Understanding these consequences requires transcending traditional boundaries between disciplines such as hydrology, ecology, geography and even the social sciences.

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Identifying and quantifying the hydrological consequences of land-use change are not trivial exercises, and are complicated by: (1) the relatively short lengths of hydrological records; (2) the relatively high natural variability of most hydrological systems; (3) the difficulties in 'controlling' land-use changes in real catchments within which changes are occurring; (4) the relatively small number of controlled small-scale experimental studies that have been performed; and (5) the challenges involved in extrapolating or generalizing results from such studies to other systems. Given the diversity and complexity of land-use changes that are taking place about the globe, satisfactory techniques for analysing the hydrological consequences of land use must be considered to be in an early stage of development. The development of mathematical tools (i.e. models) for reliably predicting the hydrological effects of future land-use changes is literally in its infancy (Beven, 2000).

Much of our present understanding of land-use effects on hydrology is derived from controlled, experimental manipulations of the land surface, coupled with pre- and post-manipulation observations of hydrological processes, commonly precipitation inputs and stream discharge outputs. Most notable are studies of the effects of forest management practices (including cutting, removal activities, and regrowth of forest vegetation) on annual and seasonal water yields, evapotranspirative losses, interception rates, and flood peaks that have been conducted in forests throughout the world, including the pioneering work completed at Coweeta (Swank and Crossley, 1988) and Hubbard Brook (Hornbeck *et al.*, 1970; Likens *et al.*, 1977) in the eastern USA. Forest cutting and removal activities usually cause increases in water yield (Bosch and Hewlett, 1982) and flood peaks (Hornbeck *et al.*, 1970; Harr *et al.*, 1975; Harr, 1981, 1986) for several years following disturbance, but some studies have suggested that these effects can be at least partially attributed to soil compaction during road and skid trail construction (Reinhart *et al.*, 1963; Jones and Grant, 1996; Whitehead and Robinson, 1993). Comparable experimental studies of urbanization and agricultural management practices are much less common in the literature, but both of these types of disturbance have generated an extensive literature of their own, mostly from analysis of observational data from 'comparative' or 'case' studies (Hollis, 1975; Potter, 1991; Rose and Peters, 2001). Two of the more widely used models for assessing the effects of land-use practices on hydrological response (the rational method and the USDA-SCS curve number approach) were based on field data collected from these types of study. The literature contains very few examples of controlled studies of the effects of permanent land 'conversions' (e.g. forest to agriculture, agriculture to urban, etc.), however.

A major limitation of paired watershed studies is the obvious lack of experimental replication across a full range of natural conditions. Fortunately, paired studies usually provide very high quality experimental data with which to advance our mechanistic understanding of the hydrologic response of watersheds to land-use change and allow testing of mathematical models. Therefore, we expect that experimental approaches combining hydrometric measurements from paired watersheds with process modelling will serve to unravel rapidly the response to land-use change of watersheds of varying size, topography, and spatial configuration and contribute to a progressive 'whitening' of the watershed 'black box'.

Several factors now make a focus on the hydrological impacts of land-use change feasible. First, the feasibility of observing land-cover changes with satellite data is unprecedented. Landsat data are now collected systematically around the world (Goward and Williams, 1997) and data from moderate-resolution sensors, such as MODIS, are freely available (Justice *et al.*, 2002). Laboratories can now manage the data volumes and image processing not possible a decade ago. Satellite data, appropriately calibrated and validated with ground data, provide spatial information on the distribution of land cover types and changes over time (Hansen and DeFries, 2004). Whereas such information could previously only be obtained over small areas from ground surveys or aerial photographs, satellite data extend the coverage over larger areas at more frequent time intervals. Information on land-use over larger areas allows new kinds of investigation, such as the effects of spatial patterns of land-use within a watershed on hydrological processes and modelling of large drainage basins. For example, quantifying the effects of nitrate leaching on fisheries in the Mississippi Delta requires study of the land-use within the entire Mississippi River basin (Donner *et al*., 2002).

Second, modelling capabilities for evaluating and predicting hydrological consequences of land-use change at multiple scales have advanced at a rapid rate in recent years, owing largely to technological improvements in data collection and computing capabilities. Satellite remote sensing now has the potential to provide extensive coverage of key variables such as precipitation (Smith *et al*., 1996; Sturdevant-Rees *et al*., 2001), soil moisture (Sano *et al*., 1998) and flooding (Townsend and Foster, 2002), as well as many of the parameters such as vegetation cover (Nemani *et al*., 1993), vegetation change (Nemani *et al*., 1996) and imperviousness (Slonecker *et al*., 2001) that are important inputs to modern hydrological models. These inputs would have been virtually impossible to obtain through traditional data collection techniques (Entekhabi *et al*., 1999). At the same time, computational improvements now allow far faster data processing and more rigorous testing of hydrological paradigms. Modelling of land-use change has thus rapidly evolved from simple empirical approaches (e.g. unit hydrographs; Jakeman *et al*., 1993) to lumped-parameter models (Blackie and Eeles, 1985; Eeles and Blackie, 1993) and to spatially distributed methods (Abbott *et al*., 1986; Adams *et al*., 1995; Dunn and Mackay, 1995) that can make use of high-resolution information on land-use patterns and processes.

Third, collaboration among scientists from different disciplines, though still problematic, is gaining acceptance as a necessary approach to addressing global environmental issues (Steffen *et al*., 2003). Perspectives from fields such as remote sensing to observe land cover, from economics and other social sciences to develop future land-use scenarios, from ecology to assess the biological implications of changes in water flow and quality, as well as from hydrology to understand hydrological effects of land-cover changes in a watershed, are all required to comprehend fully the hydrological consequences of land-use change.

In summary, we propose that interactions between land-use change and hydrologic processes will be a major issue in the decades ahead. Research aimed towards explicit understanding of these interactions will provide necessary input to decisions that must balance trade-offs between the positive benefits of land-use change and potentially negative unintended consequences. Such a research focus calls for a multidisciplinary approach with a comprehensive view towards the hydrologic processes that maintain ecological health and human requirements for food, water, and shelter.

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