CHAPTER 8

Water Quality and Exurbanization in Southern Appalachian Streams

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Introduction

Research at Coweeta Hydrologic Laboratory in western North Carolina, USA, began over 75 years ago and for most of that time was focused on intensive and long-term study of small catchments. The Coweeta research presented 20 years ago at the Conservation and Management of Rivers Conference in 1990 followed that tradition by synthesizing the results of intensive study of one small stream responding to catchment deforestation (Webster *et al.*, 1992). Research by scientists now working at Coweeta has gone beyond single catchments and even beyond the boundaries of the laboratory itself. They are now studying streams and catchments throughout the Upper Little Tennessee River Basin of the southern Appalachian Mountains (Plate 13). This shift reflects the expansion of ecological research from site-based science to regional and global scales (Peters *et al.*, 2008) as well as the expansion of its conceptual scope to embrace other scientific disciplines (Liu *et al.*, 2007; Collins *et al.*, 2010).

These shifts are not only taking place in ecological research in the United States, but in many other areas of the world (du Cros *et al.*, 2004; Maass *et al.*, 2010; Metzger *et al.*, 2010).

The Upper Little Tennessee River Basin is in a rural area with relatively low population density, but it is increasingly subject to exurbanization pressures from surrounding metropolitan areas including Atlanta, Charlotte, Greenville, Asheville, and Knoxville. Exurbia first gained popular attention when A.C. Spectorsky (1955) described its residents in his book, *The Exurbanites*. Berube *et al.* (2006) described exurbia this way, 'Exurbs... lie somewhere beyond the suburbs. At the urban-rural periphery, outer suburbs bleed into small-town communities with an agricultural heritage.' Homebuyers are drawn to the natural amenities of these rural areas. This, coupled with increasing willingness to commute long distances, mobility at retirement age, and telecommuting, has allowed people to move to the countryside (Radeloff *et al.*, 2010). The 2000 US Census indicates that 79.2% of the United States population resides in urban

areas, while the balance of nearly 20% resides in rural areas. However, what is not revealed in the US Census by virtue of how 'urban' and 'rural' are defined is that an increasingly large segment of the United States population (37%) now live in the urban–rural interface (Sutton et al., 2006).

Traditionally, people living in the Upper Little Tennessee River Basin had farms and lived in the valleys. In contrast, people moving from the cities or building second homes frequently purchase land and build on the sides and tops of mountains. The objective of this study was to determine how development, and particularly mountainside development, is affecting stream chemistry in the Upper Little Tennessee River Basin.

The terms 'land cover' and 'land use' have often been used interchangeably, or, even when the difference is acknowledged, land cover has been used as a surrogate for land use. A few studies have integrated some land-use information into land-cover data (Osborne and Wiley, 1988; Groffman et al., 2004) but land cover and land use were not analysed separately. Turner and Meyer (1994) noted that land cover is principally the concern of natural science, while land use is the concern of social science. While land cover denotes the physical state of the land, land use denotes the human deployment and accompanying property rights associated with the land (Turner and Meyer, 1994). A number of studies have examined how economic and other social factors influence land cover (Turner et al., 1996), but we are not aware of previous studies where the conjoint effect of land use and land cover have been examined. In this collaboration of natural and social scientists, land-cover data based on satellite imagery, and land-use data, based on tax records tied to parcel boundaries within catchments, were used as independent variables to examine their effect on stream water quality.

Site description

The Upper Little Tennessee River Basin is located in western North Carolina and north Georgia, USA, in the Blue Ridge Physiographic Province. This 1130 km^2 area of the southern Appalachian Mountains is predominantly forested (79% forest cover, Plate 13). The valley is largely within the Tallulah Falls geological formation, which mostly comprises metasedimentary gneiss, schist, and metagraywacke. The regional geology is characterized by metamorphic rocks (largely gneiss, schist, and metagraywacke) with scattered windows of older basement rocks (mainly granitic gneiss) with similar hydraulic properties and yielding low levels of dissolved solids in groundwater (Hatcher, 1988; Velbel, 1988; Daniel and Payne, 1990; Robinson et al., 1992; Mesko et al., 1999). Soils within the area are generally classified as Inceptisol and Ultisol soil orders. Soils are approximately 1 m deep and underlain by regolith of saprolite (Velbel, 1988). The saprolite mantle is 1–30 m thick and drapes the ridges and slopes (Hewlett, 1961), and substantial colluvial deposits are present on benches, coves, and footslopes (Southworth et al., 2003; Leigh and Webb, 2006).

The regional climate is considered humid subtropical at the lowest elevations and marine humid temperate at higher elevations, with mild winters with little snowfall and mild summers with temperatures seldom exceeding 30°C. Rainfall is distributed rather evenly throughout the year. The regional average annual precipitation is about 1400 mm, but there is considerable spatial variability related to elevation and considerable annual variability related to drier and wetter climatic periods.

The basin includes two towns, Franklin and Highlands. Franklin has a population of 3931 within the town limits, but the population in Macon County, which contains Franklin, is 32 607. Highlands has a resident population of 1058 but a summer population of about 18 000.

Methods

Fifty-eight synoptic stream sites in the Upper Little Tennessee River Basin (Plate 13) were sampled in February and June 2009 during periods of baseflow to characterize both growing and

non-growing seasons without the influence of elevated discharge. These sites were selected to represent the range of land cover and land use within the basin. During both seasons, measurements were made over a 3-day period of stable weather and discharge. Field measurements included specific conductance (YSI Model 30) and turbidity (Hach Model 2100P). Three replicate grab samples were filtered in the field (Whatman GF/F). Because of the large number of samples, it was necessary to freeze all samples prior to analysis, which may have influenced some of the chemical parameters. Three larger volume samples (1–4 L) were also collected for particle analysis.

Thawed samples from each site were analysed for dissolved organic carbon (DOC), total dissolved and soluble reactive phosphorus (TDP, SRP), nitrate, ammonium, dissolved organic nitrogen (DON), total dissolved nitrogen (TDN), chloride, sulphate, and the cations calcium, magnesium, potassium, and sodium (methods given in Table 8.1). Total suspended solids (TSS) were determined within 24 h of collection. Samples were filtered onto preweighed glass fibre filters (Whatman GF/F), dried, weighed (TSS), ashed (1 h, 550 °C), and reweighed to determine the ash-free dry mass (AFDM) of suspended particles.

Catchment land-cover was derived from 2001 and 2006 NASA Landsat Thematic Mapper Imagery. Land cover was classified by Jeff Hepinstall and Hunter Allen (Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602). Catchment land-use was obtained from county parcel and tax records and US Census data. Catchments were ranked across three subjectively determined land-use categories: scale, activity, and diversity. Scale measures relate to the amount of land and land-use activity available for socio-economic analysis within each catchment. Activity measures relate to recent changes and predicted future changes in land use and ownership. Diversity measures relate to variation in land use, building stock, and household composition including population age structure, racial composition, renters versus owners, and the presence of children. Because areas for census measurements are relatively large and often do not follow catchment boundaries, there is unavoidable error in assigning census data to catchments and this error increases as catchment size decreases. So census data were determined for only a set of 15 larger catchments.

Data were analysed statistically in two steps. Cluster analysis and principal components analysis (Minitab, Minitab Inc., State College, PA) were first used to reduce the number of both dependent and independent variables. Correlation analysis and simple linear and multiple linear regressions

Table 8.1 Methods used for laboratory analyses of dissolved chemicals.

Chemical measured	Method	Instrument
Dissolved organic carbon		Shimadzu TOC-VCPH TN analyzer
Total dissolved phosphorus	Persulphate in-line UV digestion, ascorbic acid – molybdate colorimetric method	Lachat QuickChem FIA+
Soluble reactive phosphorus		Dionex 25A Ion Chromatograph using an AS18 column
Nitrate		Dionex 25A Ion Chromatograph using an AS18 column
Ammonium	Automated phenate method	Astoria 2 Autoanalyzer
Dissolved organic nitrogen	TN - (NH_4-N + NO_3-N)	
Total dissolved nitrogen		Shimadzu TOC-VCPH TN analyzer
Chloride		Dionex 25A Ion Chromatograph using an AS18 column
Sulphate		Dionex 25A Ion Chromatograph using an AS18 column
Ca, Mg, K, Na		Perkin Elmer Analyst300 Atomic Absorption Spectrometer

(SigmaPlot, Systat Software Inc., San Jose, CA) were then used to identify significant relationships among variables.

With 58 sites, two sample collection dates, 15 stream chemistry variables, 42 land-cover variables (14 land-cover types, 2001 data, 2006 data, and the change between 2001 and 2006), 12 variables from county tax records, and three variables from census records (already reduced from many more variables), it was first necessary to reduce the dataset to a more manageable size for statistical analysis. Some sites were deleted because of missing data. The remaining sites were separated by size into two groups and analysed separately so that sites upstream and downstream of each other were never included in the same analysis. This resulted in a set of 26 small catchments ranging in size from 0.4 to 14 km^2 and a set of 15 larger catchments ranging from 3 to 45 km^2. Two intermediate size sites, the only two sites with significant urban area, were included in both catchment groups.

Many chemistry variables were correlated. Cluster analysis was used to identify groups of chemistry variables that could be represented by single variables. Principal components analysis was used to determine which variables were useful in discriminating among sites. For example, winter and summer specific conductance were highly correlated (Figure 8.1), so only summer values were used. On the other hand, turbidity measurements from winter and summer were not correlated (Figure 8.1), so both values were retained. All nitrogen measurements (NO_3, NH_4, DON, TDN) were generally correlated, so only summer NO_3 was used. DOC was generally low for all sites and provided no useful discrimination among sites. TSS was strongly correlated with turbidity and therefore not used. The percentage of organic matter in particles in winter and summer were not very similar, but data were missing from many sites in winter owing to very low concentrations, so only summer values were used. In summary, six chemistry variables for analysis were used: summer specific conductance, summer nitrate concentration, winter and summer turbidity, summer percentage organic matter in particles, and total dissolved phosphorus.

Similarly, the number of independent variables was also reduced. The original 14 land-cover variables were reduced to four: developed, forest, scrub, and agriculture (Plate 13). For this study, all forms of agriculture were put in the one category. Agricultural land in the basin is primarily pasture with some hay fields and some small areas of row crops. Gardens and lawns were also included as agriculture. The land-use variables that proved most useful were: parcel area residential, parcel area commercial, parcel area agriculture, parcel area untaxed (primarily National Forest), and average land value in each catchment. From the tax record data, the estimated rank of potential real estate activity and the index of land ownership persistence (LOPI) were used. The census data were represented by the aggregated rank of demographic diversity.

Results

These data illustrate the importance of distinguishing between land cover and land use (Figures 8.2, 8.3). Agricultural land-cover and agricultural land-use (parcel area) were well correlated, but there were some distinct outliers in the data from the larger catchments (Figure 8.3). There is no land classified as agricultural in the Franklin catchment, but 13% of the area shows up in satellite imagery as agricultural land-cover. These areas probably represent lawns and small gardens. Also, several catchments have greater agricultural land-use than agricultural land-cover (Jones Creek, Cowee Creek, Hickory Knoll), probably as a result of abandoned agricultural land.

A similar contrast can be seen when forest and developed land-cover are compared with residential and commercial land-use. All but two catchments have more than 50% forest cover (Figure 8.2). Even the most urban catchments still have 30% forest cover. This forest cover is largely National Forest but also includes private forest land. Also, even though a large percentage of catchment area may be listed on the tax records as residential or commercial, it may not show up as developed
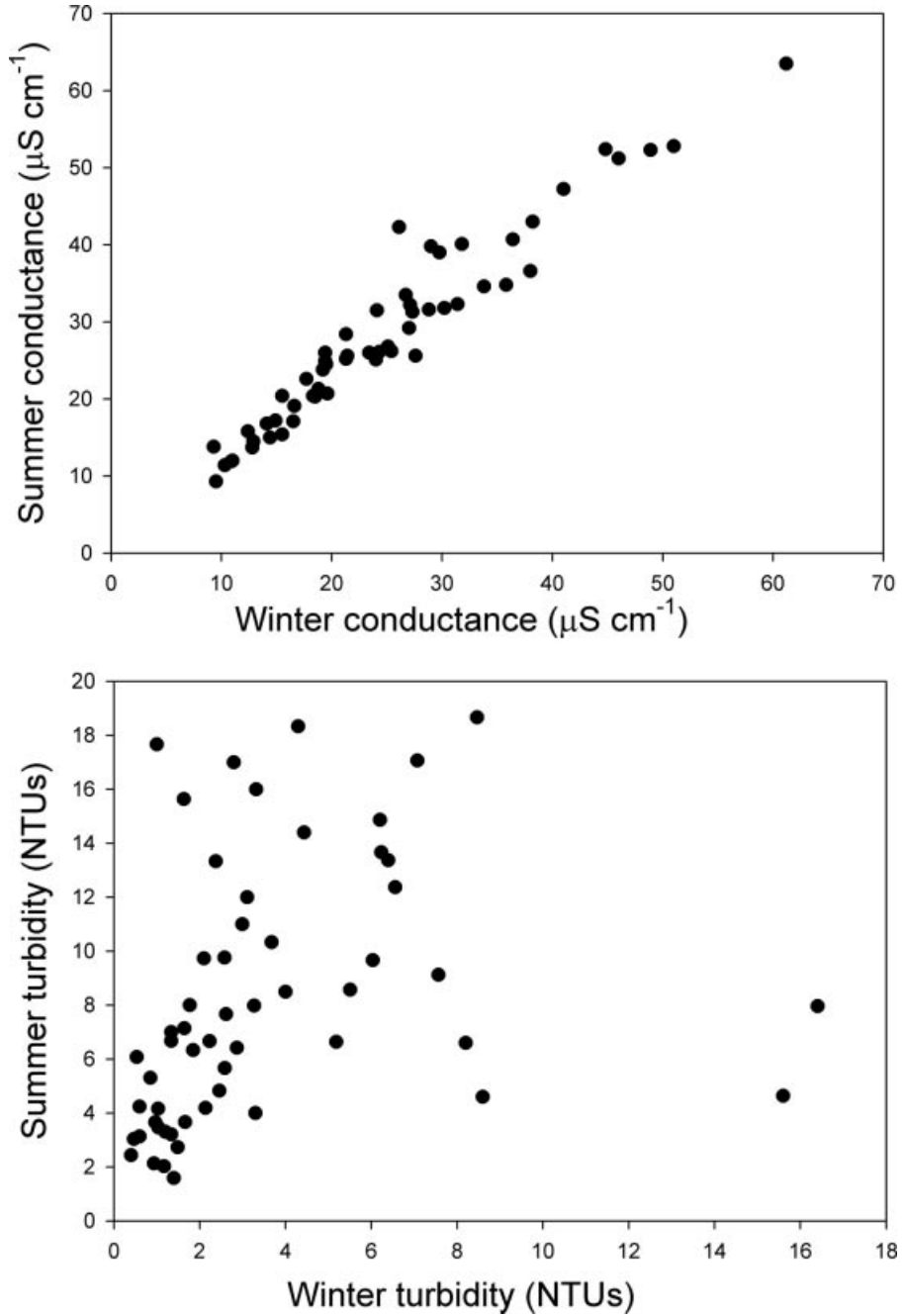
Figure 8.1 Relationships between winter and summer measurements of specific conductance and turbidity at all of the synoptic sampling sites.
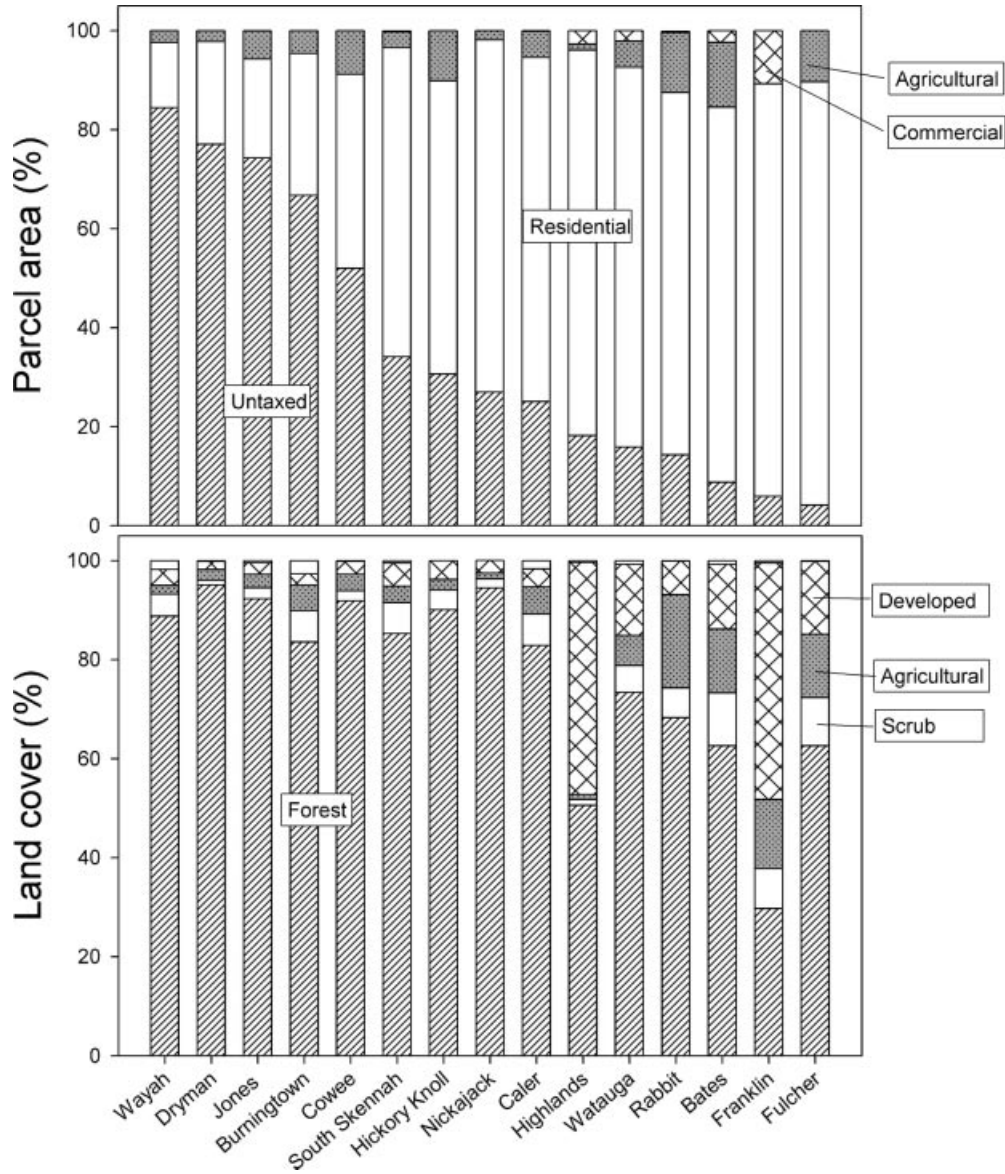
Figure 8.2 Percentage of parcel area (land use) and land cover for the 15 larger catchments.

land-cover in satellite images (Figure 8.3, lower panel).

Best subsets multiple regressions were used to identify the independent variables that most closely predicted the six dependent (chemistry) variables using data from both sets of catchments (Table 8.2). Specific conductance had a strong negative relationship with forest land-cover but also showed relationships with an assortment of variables reflecting development and commercial land-use (Table 8.2, Figure 8.4). Nitrate was highly variable among the catchments and related primarily to land-cover variables (Table 8.2, Figure 8.5). Winter turbidity was related to agricultural land-cover in
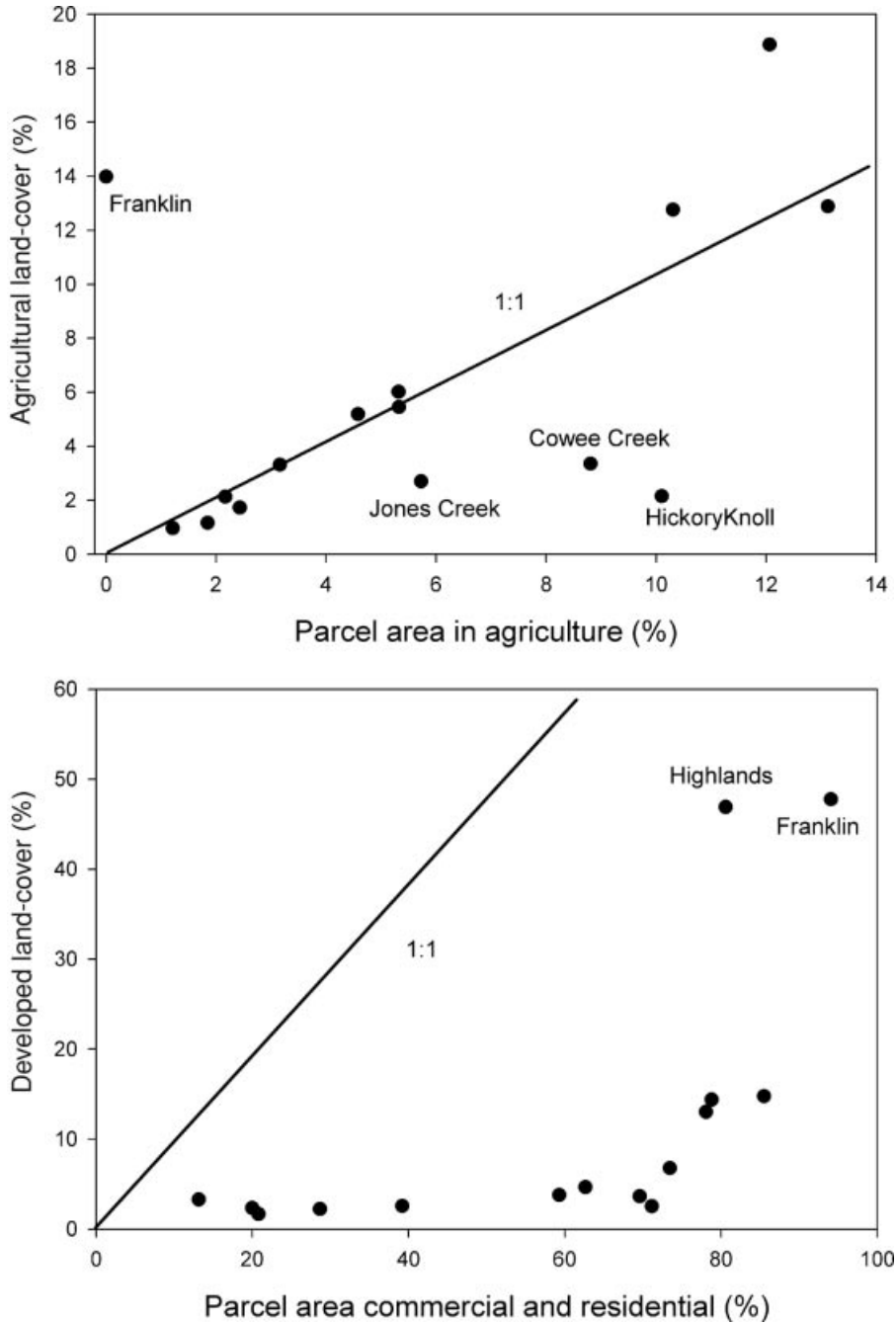
Figure 8.3 Relationships between agricultural land-cover and land-use (parcel area) (upper panel) and between developed land-cover and commercial and residential land-use (lower panel). Both graphs are for the 15 larger catchments. The lines in both panels are 1:1 lines.

Table 8.2 Best subsets multiple regression for 26 small catchments and 15 larger catchments. The predictors are the best simple regression, the best two-variable multiple regression, and the best three-variable multiple regression. LC = land cover (2006), LU = land use, devel. = developed, comm. = commercial, activity = real estate activity, res. = residential, LOPI = median land ownership persistence index, ag. = agriculture, change = land cover change between 2001 and 2006.

Water quality variable	Range, small catchments	Best predictors from small catchment data	R^2	Range, larger catchments	Best predictors from larger catchment data	R^2
Specific conductance (summer, μS cm^{-1})	9.3 – 63.5	Forest LC	0.65	15.4 – 52.8	Forest LC	0.65
		Forest LC; devel. change	0.78		Activity; land value	0.79
		Forest LC; devel. change; res. LU	0.80		Activity; comm. LU; devel. LC	0.86
Nitrate-N (summer, μg L^{-1})	20.1 – 390.5	Devel. LC	0.77	42.6 – 390.5	Forest LC	0.80
		Devel. LC; comm. LU	0.84		Ag. LC; devel. LC	0.89
		Devel. LC; comm. LU; forest change	0.87		Ag. LC; devel. LC; forest LC	0.95
Turbidity (winter, NTU)	1.6 – 17.7	Ag. LC	0.54	0.6 – 8.2	Res. LU	0.37
		Ag. LC; ag. LU	0.56		Diversity; comm. LU	0.54
		Forest LC; devel. LC; forest change	0.65		Comm. LU; res. LU; devel. LC	0.77
Turbidity (summer, NTU)	0.5 – 15.6	Res. LU	0.14	2.0 – 18.3	LOPI	0.15
		Ag. LC; devel. change	0.37		Res. LU; devel. LC	0.38
		Forest LC; res. LU; ag. LC	0.47		Comm. LU; res. LU; devel. LC	0.46
Percentage organic matter in particles (summer, %)	19.9 – 69.5	Res. LU	0.53	26.2 – 60.4	Res. LU	0.44
		Comm. LU; res. LU	0.56		LOPI; res LU	0.51
		Comm. LU; res. LU; devel. LC	0.58		Land value; res LU; devel. LC	0.57
Total dissolved phosphorus (summer, μg L^{-1})	2.5 – 13.3	Ag. LC	0.06	3.2 – 10.8	Ag. LC	0.22
		Res. LU; ag. LC	0.08		LOPI; ag. LC	0.38
		Forest LC; ag. LC; devel. LC	0.22		LOPI; ag. LU; ag. LC	0.60

the small catchments and to parcel data (land use) in the larger catchments, but summer turbidity was not very well related to anything measured (Table 8.2, Figure 8.6). Winter and summer turbidity relationships were very different (Figure 8.6), and the values were idiosyncratic. In general, turbidity was high in winter where cattle were upstream of the sample site and high in the summer if there were recent construction activities upstream. The percentage of organic matter in particles was most strongly related to parcel area (land use) data, but land value and land ownership persistence were also significant (Table 8.2, Figure 8.7). Total

dissolved phosphorus was generally very low in all streams and was not significantly related to any measured independent variables (Table 8.2).

To quantify mountainside development, the percentage of developed land-cover pixels that were also in the upper 60% of the catchment altitude was determined. Watauga Creek and Jones Creek catchments illustrate the two extremes (Figure 8.8). In both catchments, most of the developed pixels follow the streams and roads. In the Watauga Creek catchment, there is also a band of development along the major highway. About 5% of this catchment is mountainside
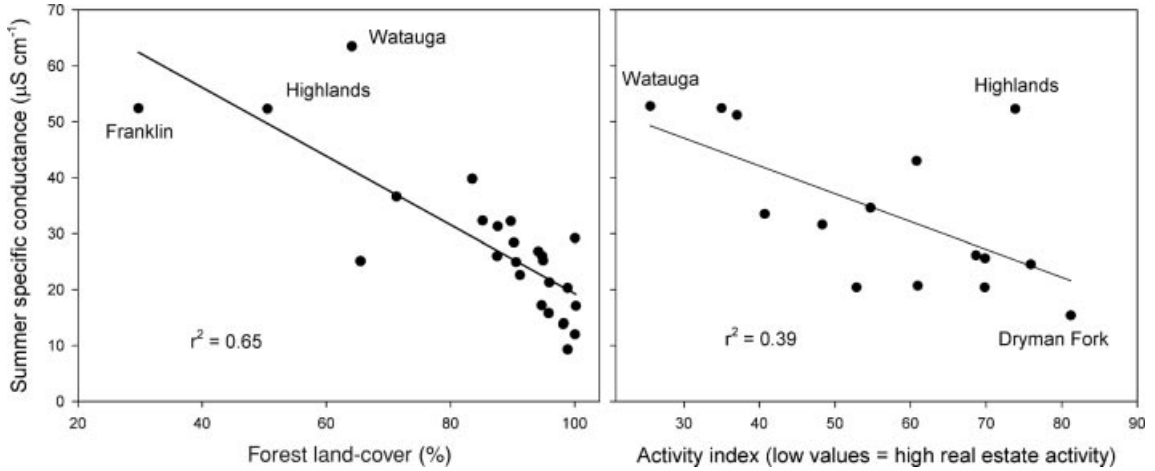
Figure 8.4 Relationships between summer specific conductance and forest land-cover and real estate activity. The left panel is for the smaller catchments and the right panel is for the larger catchments. Linear regression lines and coefficient of determination are shown in the figures.

development, much of it in a gated community established about 20 years ago. In contrast, Jones Creek is much less developed, and development follows traditional patterns with agricultural land and residences in the valleys (Figure 8.8).

Mountainside development was clearly correlated with land value (Figure 8.9), largely driven by the presence of Highlands, a town with a large seasonal population located at over 1250 m elevation. There was also a good correlation between nitrate concentration and the extent of mountainside development with two notable outliers: Franklin, where 11% of the parcel area is commercial, and Rabbit Creek, which is the only catchment with extensive row crop agriculture.
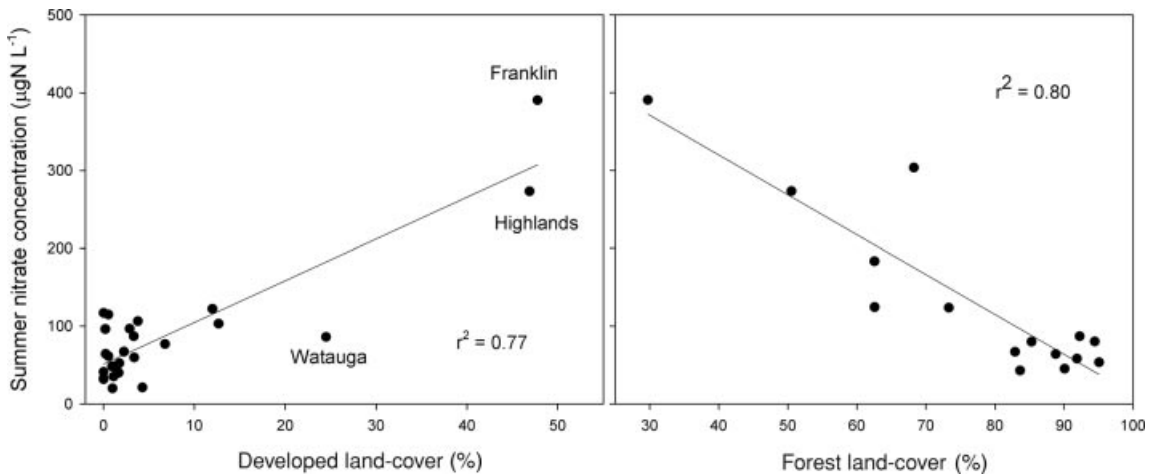

Figure 8.5 Relationships between summer nitrate concentration and developed and forest land-cover. The left panel is for the smaller catchments and the right panel is for the larger catchments. Linear regression lines and coefficient of determination are shown in the figures.
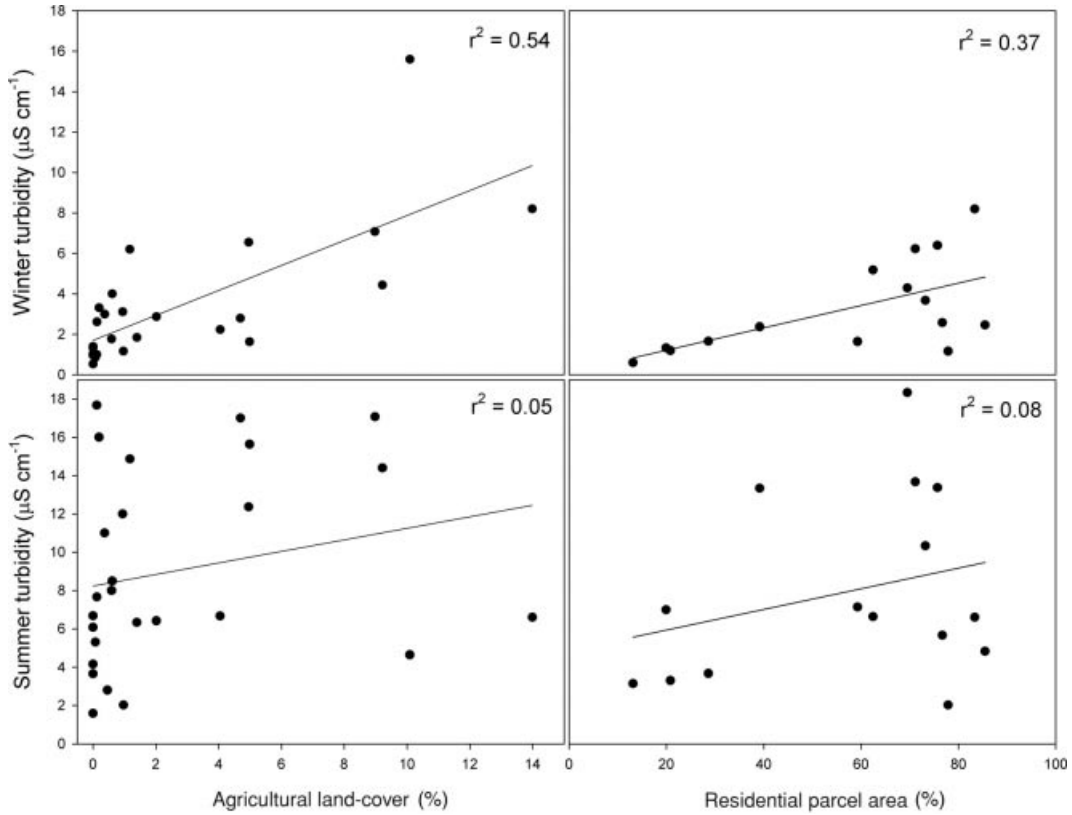
Figure 8.6 Relationships between winter and summer turbidity and agricultural land-cover and residential parcel area (land use). The left panels are for the smaller catchments and the right panels are for the larger catchments. Linear regression lines and coefficient of determination are shown in the figures.
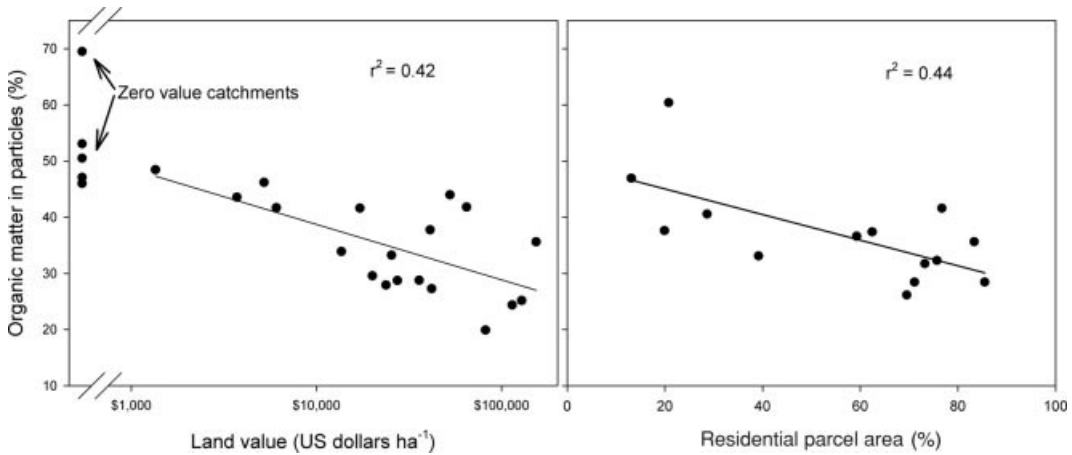

Figure 8.7 Relationships between the percentage of organic matter in particles and land value and residential parcel area (land use). The left panel is for the smaller catchments and the right panel is for the larger catchments. Regression lines and coefficient of determination are shown in the figures. For the regression in the left panel, land value was log transformed and used only the non-zero values.
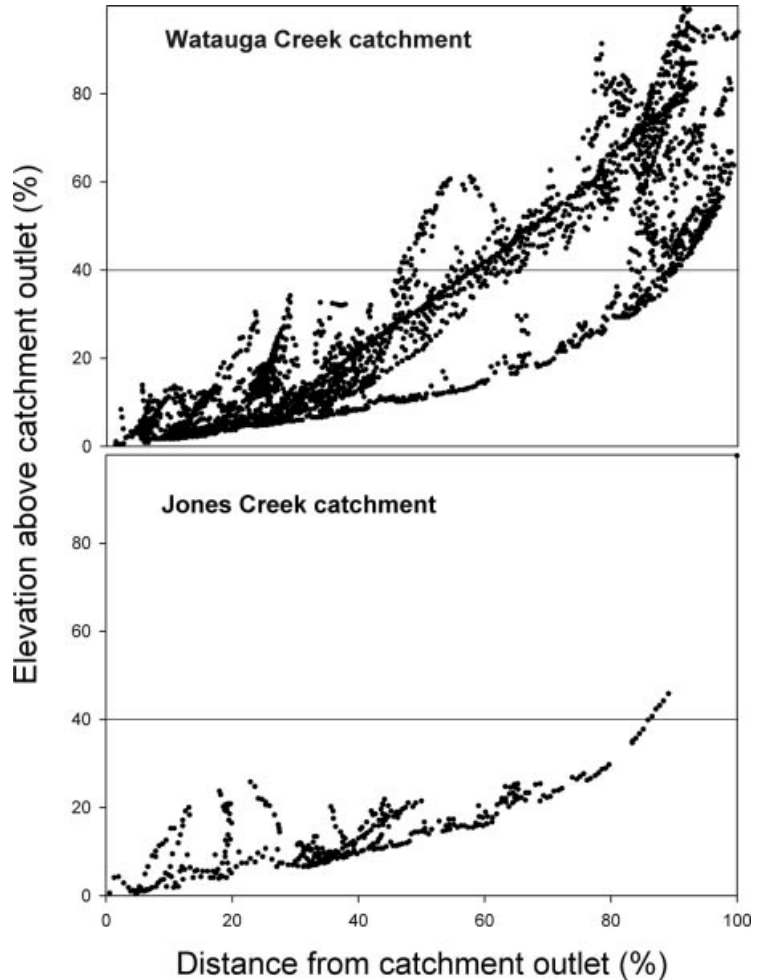
Figure 8.8 Elevation above and distance from the catchment outlet of developed areas in the Watauga and Jones Creek catchments. The axes are expressed as percentage of the total elevation or distance from the catchment. Lines are drawn at 40% elevation – developed areas above this line are considered mountainside development.

Discussion

Exurbanization is changing both the land cover and land use within the Upper Little Tennessee River Basin. The results of this study clearly indicate the value of distinguishing between land cover and land use (Figures 8.2, 8.3) in evaluating effects on stream water quality. While some variables were better predicted by land cover (specific conductance and nitrate), other variables were more related to land use in the exurbanizing landscape of the Upper Little Tennessee River Basin.

Many studies have compared the usefulness of whole catchment land-cover to riparian, near-stream corridor land-cover in predicting stream water chemistry (reviewed by Allan, 2004). The results have been highly variable, depending on the dominant land use, catchment topography, and the specific chemical variables considered. Most studies have shown that whole catchment land-cover is most useful for nitrate, other mobile chemicals, and specific conductance (Omernik *et al.*, 1981; Hunsaker and Levine, 1995; Jones *et al.*, 2001; Sliva and Williams, 2001; Sponseller *et al.*, 2001; Strayer *et al.*, 2003). On the other hand, riparian land-cover is a better predictor of forms of phosphorus, total suspended solids, and other sediment-related variables (Osborne
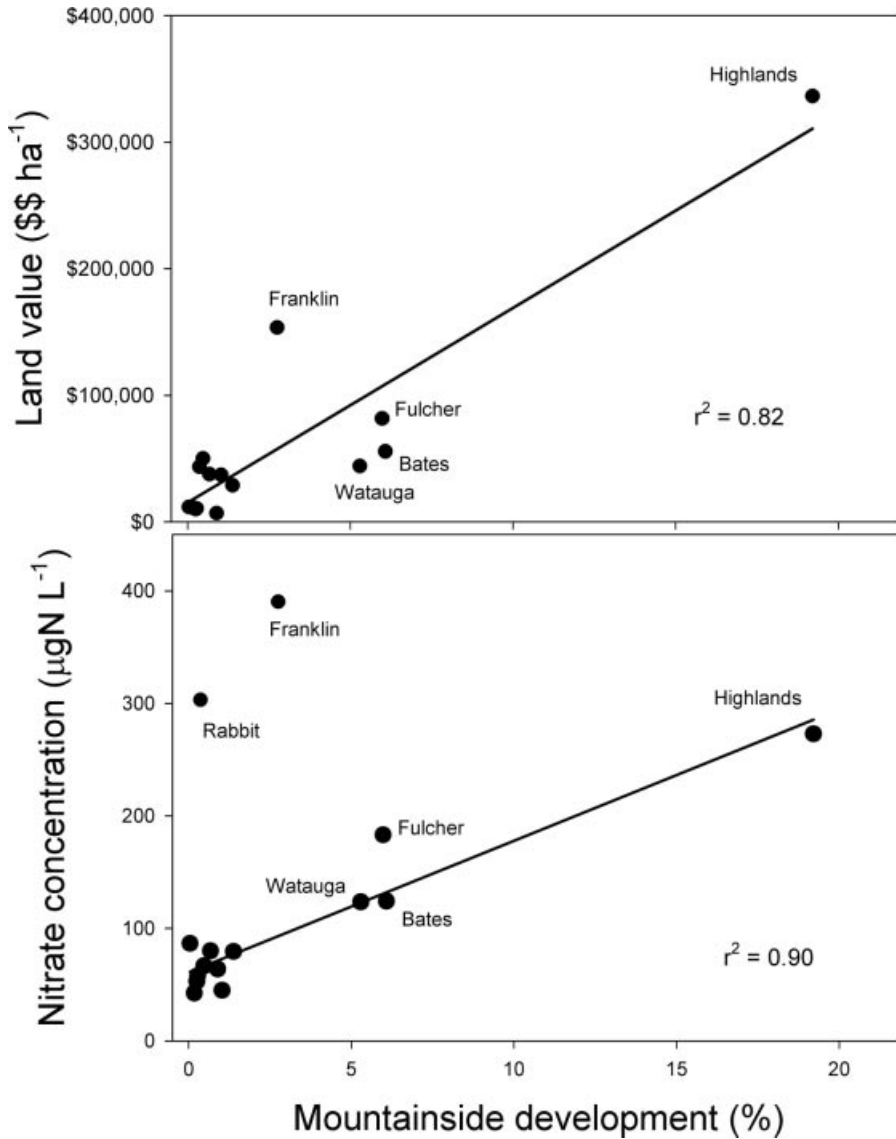
Figure 8.9 Nitrate concentration and land value (US dollars) relationships to mountainside development. Mountainside development was quantified as the percentage of developed land-cover area that was also in the upper 60% of the catchment altitude. Linear regression lines and coefficient of determination are shown in the figures. Data for Franklin and Rabbit Creek were not used in the regression shown in the lower panel.

and Wiley, 1988; Johnson *et al*., 1997; Jones *et al*., 2001). Other studies have shown little difference between using catchment and riparian land-cover (Johnson *et al*., 1997; Dodds and Oakes, 2008) for predicting stream responses. Most studies comparing land cover and stream chemistry have been conducted in areas of little topographic relief that are dominated by agriculture (Osborne and Wiley, 1988; Hunsaker and Levine, 1995; Johnson *et al*., 1997; Jordon *et al*., 1997; Dodds and Oakes,

2008) or with significant urban areas within the catchments (Sliva and Williams, 2001; Groffman *et al*., 2004). In agricultural and residential areas, input of chemicals as fertilizer is often a major cause of high solute levels in streams, and in urban areas point sources may contribute to high chemical loads. In many areas, it is difficult to separate riparian and whole catchment effects because the riparian corridor generally reflects the catchment land-cover (Johnson *et al*., 1997; Dodds and Oakes, 2008).

The Upper Little Tennessee River Basin differs in several ways from basins that have been the focus of previous studies. Except in a few areas (e.g. Rabbit Creek), there is relatively little agricultural fertilizer application, although fertilization of home lawns is probably common. Also, there are no intentional sewage inputs in any of the catchments analysed (though there are treated sewage inputs to the Little Tennessee River itself). Finally, in most catchments (other than those completely forested), there is a large difference between valley and mountainside land cover. When land cover in the whole catchment was compared with land cover in just the 200 m riparian corridor along streams, they were well correlated (riparian agricultural land-cover and catchment agricultural land-cover, r = 0.90; riparian developed land-cover and catchment developed land-cover, r = 0.99), but the percentage of agricultural and developed land-cover were both higher in the riparian corridor (11% versus 6% for agriculture, 15% versus 11% for developed).

In the mountainous Upper Little Tennessee River Basin, development and agriculture have traditionally been in the valleys, and the mountainsides have remained forested even though they have been repeatedly logged. Thus land-use change has been primarily a reflection of changes within the valley, along streams. In general, correlations of land use with riparian corridor land-cover were slightly greater than with catchment land-cover. For example, at the catchment level, agricultural land-use and land-cover were significantly correlated (Figure 8.3, r = 0.37), but when just riparian corridor land-cover was used, the correlation improved slightly (r = 0.40). Similarly, developed land-cover in the riparian corridor was slightly better correlated with residential and commercial land-use (r = 0.79, land cover log transformed) than was whole catchment developed land-cover (r = 0.78, Figure 8.3).

These relationships are consistent with the observation that land use is a better predictor of sediment-associated variables (turbidity, organic matter in particles, total dissolved phosphorus) because sediment travels relatively short distances and its presence during baseflow conditions generally reflects near-stream or instream activity. Had the streams been sampled during periods of elevated discharge, sediment concentrations may have reflected much more extensive areas of disturbance. Nitrate and chemicals contributing to specific conductance are more mobile than sediment and come from areas throughout the catchment (Strayer *et al*., 2003) and thus are better, or just as well-predicted, by catchment-level land-cover data.

High variability in nitrate concentration within the Upper Little Tennessee River Basin was observed and found to be closely correlated with catchment land-cover, as has been shown in many previous studies (Herlihy *et al*., 1998). Most of the basin was logged during the period of intense industrial logging in the early 20th century (Mastran and Lowerre, 1983). Areas that have not been subsequently disturbed are now very retentive of nitrogen (Swank and Vose, 1997). However, areas with more recent disturbances are approaching or are in the initial stages of nitrogen saturation (Swank and Vose, 1997), when the capacity of catchment vegetation to retain nitrogen has been exceeded (Aber *et al*., 1989). This study showed a good correlation between nitrate concentration and the extent of mountainside development. Even when land development occurs in relatively small areas, high in the catchment away from the riparian area and the stream channel, and with little change to forest land-cover, significant increases in stream nitrate concentration are seen (Figure 8.9).

Land use refers to human activities within a catchment and land-use change is the proximate factor driving land-cover change (Osborne and Wiley, 1988; Turner and Meyer, 1994), but there

is also feedback between land use and land cover (Turner and Meyer, 1994). In the Upper Little Tennessee River Basin, the view of forest-covered mountains is a primary driver of mountainside development and, in other parts of the southern Appalachians, parcels with protected mountain views have been shown to be more valuable (Chamblee *et al.*, 2011).

The most dire continental-scale projections of exurban expansion suggest that by 2030 only 10–20% of the people living in the Upper Little Tennessee River Basin will be living in rural housing (Theobald, 2005). Studies of other river basins in western North Carolina have shown the impacts of existing exurban development on landscape fragmentation (Pearson *et al.*, 1998). This type of development threatens stream systems, but the risks extend beyond the mountainous urban–rural interface itself and into the low-lying urban areas that depend on the mountains for water (Viviroli *et al.*, 2007). The paradox of exurbanization is that by moving from the city to enjoy forested and rural landscapes, people threaten not only the new homes they cherish, but also the old ones they left behind.

In conclusion, the southern Appalachian Mountains, with their abundant precipitation and dense stream networks, serve as a water tower (Viviroli *et al.*, 2007) for the south-eastern US. Drinking water is perhaps one of the most important ecosystem services provided by rivers draining the region, and thus high water quality must be a primary goal of river management. Our findings show the importance of distinguishing between land cover and land use as predictors of different water quality parameters in this rapidly exurbanizing landscape. Moreover, it is critical that managers consider both of these drivers at a basin-wide level in making management decisions to protect water resources. To ensure high water quality, management must extend to areas distant from streams – in addition to traditional riparian zone management and point-source effluent regulation in near-stream areas. High nitrate concentrations are of particular concern, and this study provides evidence that development in steep mountainous areas, far from streams, can be a major contributor to elevated stream nitrate levels. A major challenge for the future is to develop a more predictive understanding of how rapid changes in land cover and land use affect water quality in the traditionally rural area of the southern Appalachian Mountains and other developing landscapes of the world.

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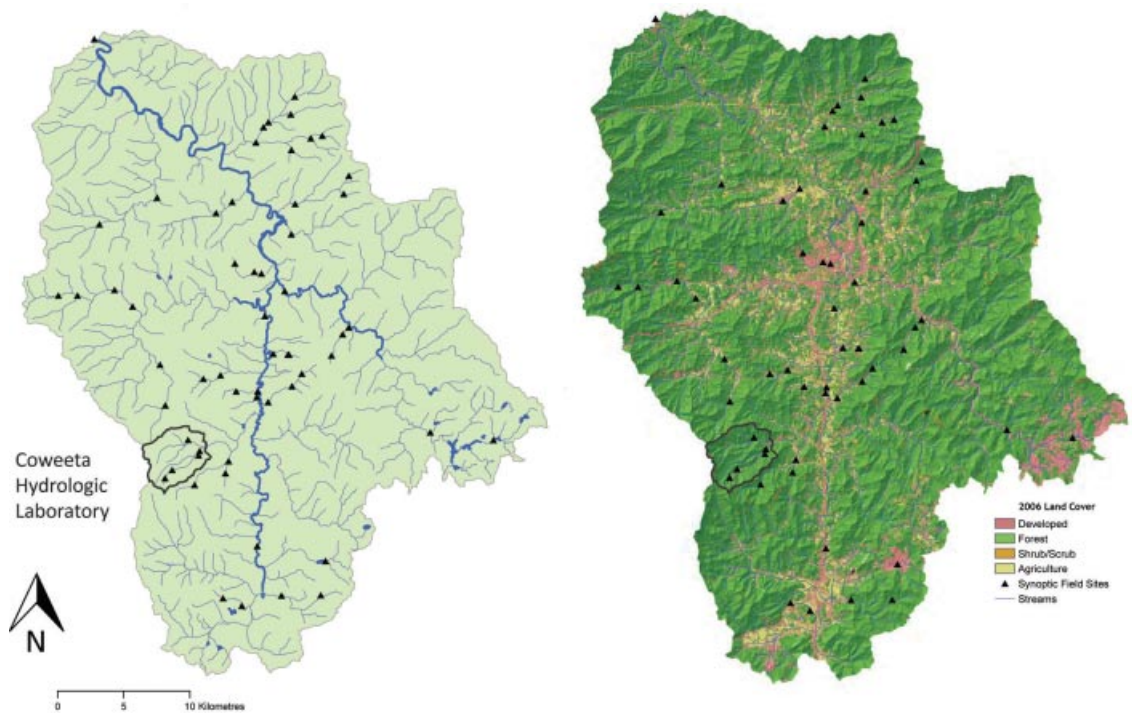
Plate 13 Land cover, stream network and sampling sites in the Upper Little Tennessee River Basin. This basin is located in Macon and Swain counties, North Carolina, and Rabun County, Georgia, USA.

Plate 14 Freshwater pearl mussels on the bed of a river in Scotland. ©Sue Scott/Scottish Natural Heritage.