Nitrate-Nitrogen, Land Use/Land Cover, and Soil Drainage Associations at Multiple Spatial Scales

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Managing non–point-source pollution of water requires knowledge of land use/land cover (LULC) influences at altering watershed scales. To gain improved understanding of relationships among LULC, soil drainage, and dissolved nitrate-N dynamics within the Calapooia River Basin in western Oregon, we selected 44 watersheds ranging in size between 3 and 33 km^2 for monthly synoptic sampling of surface water quality between October 2003 and September 2004. Seasonal associations were examined between dissolved nitrate-N and proportion of woody vegetation or poorly drained soils at differing scales (10, 20, 30, 60, 90, 150, 300 m, and entire watershed), which we defined as influence zones (IZs), surrounding stream networks. Correlations between nitrate-N and proportion woody vegetation or poorly drained soil at each IZ were analyzed for differences using the Hotelling-Williams test. We observed negative correlations (r = –0.81 to –0.94) between nitrate-N and proportion of woody vegetation during winter and spring. Poorly drained soils had positive correlations (r = 0.63–0.87) with nitrate-N. Altering the scale of analysis significantly changed correlations between nitrate-N and woody vegetation, with IZs <150 m being stronger than the watershed scale during winter. However, absolute differences in correlation values were small, indicating minimal ecological consequence for significant differences among scales. In contrast, nitrate-N correlations with poorly drained soil were stronger at the watershed scale than the 10- through 90-m IZs during winter and spring, and absolute differences were sufficient to suggest that scale is ecologically important when determining associations between dissolved nitrate-N and poorly drained soils.

With the advent of readily available land use/land cover (LULC) data sets, a number of studies have been completed to determine the relationship between LULC and nitrate-N in surface water (Allan, et al., 1997; Gove, et al., 2001; Hunsacker and Levin, 1995; Omernik et al., 1981; Rinella and Janet, 1998; Scott, et al., 2002; Tufford et al., 1998; Van Sickle, 2003). Of particular interest in the examination of basin-wide relationships between LULC and nitrate-N is the scale at which changes in land use have the greatest impact on water quality (e.g., Allan et al., 1997; Gove et al., 2001; Omernik et al., 1981). There appear to be conflicting results among studies using correlation or regression analysis at multiple spatial scales, with some concluding that large regional scales best explained variation in nitrate-N concentration (Allan et al., 1997; Compton et al., 2003; Hunsacker and Levin, 1995; Omernik et al., 1981), whereas others show that small to moderate scales provided a stronger relationship (Gove et al., 2001; Tufford et al., 1998). These discrepancies are likely a result of differences among the areas studied, resolution of data used, and analysis techniques, indicating that additional research is required to examine LULC and water quality, especially at multiple spatial scales. If a consistent scale or range of scales could be identified that provides improved prediction of dissolved nitrogen (DN) response, then further, process-oriented research within that scale or those scales could be applied to determine drivers of elevated DN concentrations in surface water in mixed–land-use basins. This kind of knowledge is also important for determining how to best manage landscapes to meet water quality standards and for participation in conservation programs designed to improve natural resources conditions.

The inconsistent results presented above suggest that in some instances near-stream conditions play less of a role in regulating nitrate-N concentrations, bringing into question the role of ri-

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Abbreviations: DEM, digital elevation model; DN, dissolved nitrogen; HW, Hotelling-Williams; LULC, land use/land cover; IZ influence zone.

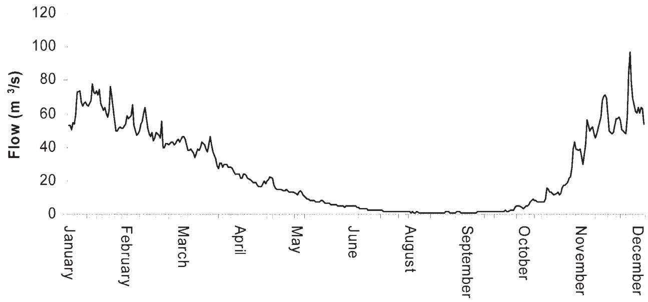

Fig. 1. Mean daily stream discharge for the Calapooia Basin, Oregon based on data collected between 1941 and 1980 (USGS, 2005).

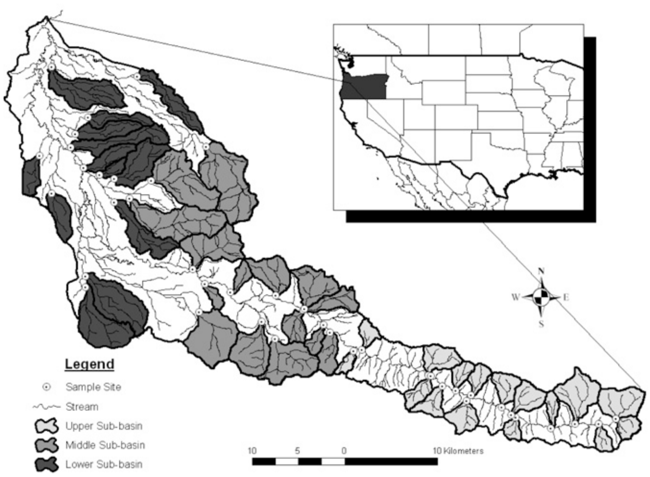

Fig. 2. Synoptic sampling locations and watershed delineation and classification (Upper, Middle, and Lower Zones) in the Calapooia Basin, Oregon.

parian areas in controlling delivery of dissolved nutrients to streams under some conditions. In numerous studies, riparian areas have been very important in controlling nutrient export to surface waters (Griffith et al., 1997; Klapproth, 2000; McKergow et al., 2003; Wigington et al., 2003). However, the effectiveness of riparian zones at removing problematic nutrients depends on a number of factors, such as hydrology, soils, and vegetation (Klapproth, 2000). In some regions, there is uncertainty as to the overall effectiveness of riparian buffers at mitigating water quality impacts, especially in heavily disturbed, intensively managed landscapes with poorly drained soils (Wigington et al., 2003, 2005).

Although protection of riparian zones for maintenance of water quality is widely promoted, there is evidence that riparian zones may not always effectively remove nitrate-N before it enters streams, especially in areas with poorly drained soils and high potential for overland flow. Disagreement abounds as to what scales of LULC have the greatest potential to affect water quality, be it at a regional scale or those in closest proximity to streams. There is also limited research available that integrates all LULC types within a watershed, a prerequisite to evaluate cumulative watershed impacts. In addition, although we were able to find examples of studies incorporating LULC and soil drainage (e.g., Mueller et al., 1997; Smith et al., 1997), we were unable to find any studies that incorporated proximity of soil drainage conditions to the stream network into relationships with nitrate-N. Additional research is required to provide a better understanding of how LULC and soil drainage affect water quality, particularly nitrate-N concentrations in surface water.

The Calapooia River, a major tributary to the Willamette River in northwestern Oregon, provides an outstanding opportunity to study nitrate-N dynamics in a multiple–land-use basin at differing scales. In 1991, the National Water Quality Assessment Program began studies in the Willamette Basin (Bonn et al., 1996) and identified the Calapooia River as having the third highest concentration of nitrate-N for all major tributaries of the Willamette River (Bonn et al., 1996). The Oregon Department of Environmental Quality has also designated Calapooia River water quality as poor, identifying nitrate-N and ammonium-N concentrations as high (Oregon Department of Environmental Quality, 1996). It was the overall objective of this study to determine if multiple spatial-scale analysis using banding techniques can identify a scale(s) in the Calapooia River Basin providing the strongest correlations between seasonal nitrate-N concentrations in surface water and LULC or soil drainage classes. These results are used to frame a discussion focusing on land management, soil properties, and riparian function. We also elucidate limitations associated with using only LULC data and soil drainage properties along with opportunities for future research that will improve our understanding of nitrate-N dynamics in multiple–land-use watersheds.

Methods

Study Area and Site Selection

The Calapooia drainage basin is located within the Willamette River Basin in northwestern Oregon. The Willamette Valley temperate marine ecoregion is characterized by mild, wet winters with low-intensity, long-duration precipitation events. Summers tend to be warm and very dry. In the central Willamette Valley at the Oregon State University climate station, annual precipitation averages 1084 mm, with peak precipitation occurring in December (196 mm) and lowest occurring in July (13 mm). The mean temperature is 11.1°C, with August being the warmest month (19°C) and January being the coolest (4.1°C).

The Calapooia River is approximately 130 km in length, and its watershed area is 966 km^2. Peak stream flow occurs during the winter months when precipitation is highest, with very low flows occurring in the summer (Fig. 1). The highest elevation in the Calapooia Basin is 1571 m, and the lowest point is 54 m. The following three zones within the Calapooia Basin have been delineated based on LULC, geology, and topography: (i) Upper Zone, (ii) Middle Zone, and (iii) Lower Zone (Fig. 2).

Steep, highly dissected hillslopes connected directly to the Calapooia River characterize the Upper Zone. The 2.4% river gradient is steepest within this zone, with numerous waterfalls. The uppermost reaches of the Calapooia River originate within the Upper Zone in the Willamette National Forest, which contains the few remaining stands of old-growth forest in the watershed. Private forestland managed primarily for timber production is the dominant land use within this zone. Basalts and tuffs from the Miocene to the Holocene are the primary geological forms (Johnson and Raines, 1995). Soils are moderately to well drained within the Upper Zone (USDA-NRCS, 1986, 1995).

The Middle Zone is described by relatively flat valley bottoms leading into steep hillslopes. The mean gradient of the Calapooia River in this zone is 0.35%, which is considerably less than the Upper Zone; however, some waterfalls are present. Intensive forest management in this zone occurs primarily on the hillslopes, away from the Calapooia River. Pastureland, small-scale agriculture, hobby farms, and home sites occur in the valley bottom along the Calapooia River. Brownsville (population, 1500) is the only major settlement in the Middle Zone, although numerous small communities occur throughout with most along the mainstem. Basalts, volcanistic rock, and balsaltic lava flows from the Miocene and Oligocene are generally found on the hillslopes (Johnson and Raines, 1995). Geology related to fluvial processes dominates the flat valley bottom, with alluvial deposits, terrace pediment, and lag gravels from the Holocene and Pleistocene adjacent to the river and lacustrine and fluvial sedimentary rocks from the Pleistocene comprising the geology between the active river channel and hillslopes (Johnson and Raines, 1995). Well drained soils are found on the hillslopes, and moderately to poorly drained soils occur on the valley bottoms (USDA-NRCS, 1986, 1995).

Flat topography and relatively low stream density during the summer dry season characterize the Lower Zone. The mean gradient of the Calapooia River in this zone is 0.11%. Grass seed farming is the predominant land use, with minor components of pasture used primarily for sheep grazing. Tangent City (population, 900), Albany (population, 41,000), and Lebanon (population, 13,000) are located in the Lower Zone. The majority of the Albany and Lebanon populations are located outside of the Calapooia Basin. Alluvial deposits from the Holocene are adjacent to the Calapooia River (Johnson and Raines, 1995). The remainder of the Lower Zone geology is comprised of lacustrine fluvial sedimentary rocks from the Pleistocene (Johnson and Raines, 1995). Soils in the Lower Zone are generally moderately to poorly drained (USDA-NRCS, 1986, 1995).

Because of the large size of the Calapooia Basin, and to ensure an adequate representation of DN dynamics within the basin, a synoptic sampling approach was used to collect water samples. Sample locations were selected at the mouth of 44 independent watersheds ranging in size from 3.1 to 32.3 km^2 (Fig. 2). The Upper, Middle, and Lower Zones have 16, 15, and 13 watersheds selected for this study, respectively. Watersheds in the Upper Zone were 100% forested. Watersheds in the Middle Zone contained at least 30% forest, and forested areas in the Lower Zone ranged from 2 to 25%. Delineation of watersheds was completed using ArcHydro (Maidment, 2003) and was based on a 30-m digital elevation model (DEM) made available by the Pacific Northwest Ecosystem Research Consortium (PNW-ERC, 1999) (http://oregonstate.edu/dept/pnw-erc/, 2005). Black-and-white, 30-cm-resolution, ortho-rectified photos taken in 2000 were used to adjust watershed boundaries to account for boundaries crossing visible streams. Boundaries requiring adjustment were more prevalent in the Lower Zone because of low relief and the relatively coarse DEM used.

Land Use/Land Cover and Soil Drainage Classification

Land use/land cover classification for the 44 independent watersheds was based primarily on the 30-m resolution Landsat PNW-ERC LULC GIS layer (PNW-ERC, 1999). This dataset was originally developed in 1992 and was last revised in 1999. Land use/land cover was separated into three major classes—Agriculture, Urban, and Woody Vegetation—to reduce variability in land management classification and to account for year-to-year changes that we would not be able to detect, especially in agricultural settings. Grass seed, row crops, orchards, nurseries, pasture, hayfields, and Christmas tree farms were included under Agriculture. The Urban classification included all built up areas, whereas Woody Vegetation contained everything from unmanaged blackberry shrubs to old-growth stands found in the Upper Zone. Preliminary analysis indicated that 30-m-resolution LULC data were inadequate in some instances for delineating woody vegetation, especially the narrow bands along the stream network in the agriculture-dominated Lower Zone. We hypothesized that this component had high potential to act as a nutrient sink; therefore, we adjusted all woody vegetation data using 30-cm-resolution, black-and-white, ortho-rectified air photos taken in the spring of 2000. In using this data set, we assumed no significant changes to woody vegetation cover between 2000 and 2004.

A combination of STATSGO (USDA-NRCS 2003a) and SSURSGO (USDA NRCS 2003b) soils as a GIS layer was used to collect soil drainage information that was available through the PNW-ERC (1999). Soil Hydrogroup class was used to describe soil drainage (Table 1) (USDA-NRCS, 1986, 1995). Soil Hydrogroup D, hereafter referred to as "poorly drained soil," was used for further analysis based on a companion study in the Calapooia Basin, which showed DN to have a strong relationship with poorly drained soil (Floyd, 2005). In addition, others have suggested that overland flow and riparian bypass are associated with poorly drained soil in the Willamette Valley (Wigington et al., 2003, 2005).

We used GIS to create influence zones (IZs) of 300, 150, 90, 60, 30, 20, and 10 m around the stream network in the 44 independent watersheds using the buffer function within the

Table 1. Soil hydrogroup class description for drainage classification in the Calapooia Basin, Oregon.

Hydrogroup	Drainage	Soil texture	Description
A	high infiltration	sand; loamy sand; sandy loam	deep soils; coarse texture mainly sands and gravels
B	moderate infiltration	silt loam; loam	deep to moderately deep soils; moderate texture
C	slow infiltration	sandy clay loam	soils with impeding layers; moderate to fine texture
D	very slow infiltration	clay loam; silty clay loam; sandy clay; silty clay; clay	high water table or shallow to impervious layer; fine texture, high clay content

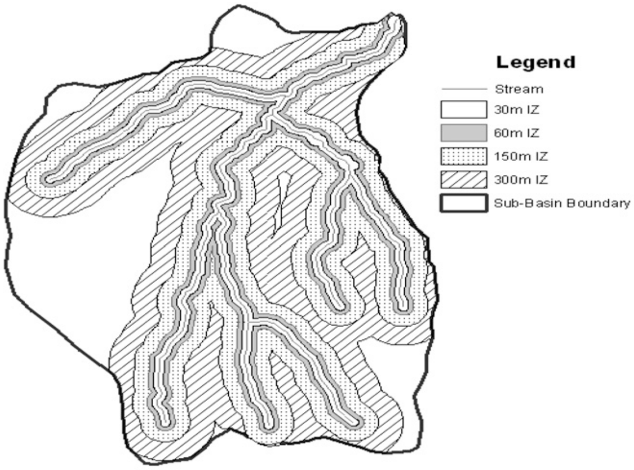

Fig. 3. Examples of influence zones (IZs) created around perennial stream networks within independent watersheds in the Calapooia Basin, Oregon. The figure does not show all IZs used for analysis.

GIS (Fig. 3). Stream coverage was provided by the Institute for a Sustainable Environment at the University of Oregon based on data supplied by the Pacific States Marine Fisheries Service (PNW-ERC, 1999). The entire watershed was also considered as an IZ. Proportion LULC classes and poorly drained soils were calculated within each IZ and for the entire watershed.

Water Sampling and Analysis

Synoptic surface water sampling began in October 2003 and ended in September 2004. We collected samples once each month in autumn, spring, and summer. Sample frequencies increased to every 2 to 3 wk during winter because of the potential increase in nitrate-N export due to higher stream flows. Sample periods occurred between precipitation events to characterize seasonal baseflow conditions. For each period, samples were collected in 250-mL hydrochloric acid–washed Nalgene bottles within a 10-h period. Nitrate-N variation within the stream water column was captured using a depth-integrated sampler. Streams >10 m in width were sampled across the width and combined on-site to account for cross-sectional variability. Efforts were made to collect samples from turbulent stream flow to ensure adequate mixing of upstream sources. Duplicate samples were collected at 10% of the sampling sites. Water samples were stored at 4°C during field transport. Field blanks containing double de-ionized water were carried on all collection trips to monitor contamination of samples during transport. Samples analyzed within 24 h of collection were stored at 4°C, and samples stored longer than 24 h were frozen.

Samples were vacuum filtered using a 0.45-μm filter before analysis. Colorimetric nitrate-N analyses were done using a Lachet analyzer (Lachet Corp., Milwaukee, WI). The minimum detection limits for the Lachet QuikChem 4200 were 0.1 mg L^{-1} for samples taken from October 2003 to February 2004 and 0.04 mg L^{-1} for samples taken for the remainder of the project.

Statistical Analyses

We used Pearson correlation analysis to determine associations between seasonal nitrate-N concentrations and LULC classes or poorly drained soils within IZs. Log-transformed nitrate-N data were used because they were not normally distributed. Seasons were delineated based on major shifts in precipitation and streamflow. Autumn samples were collected during early October 2003 to late November 2003. Winter included all samples from December 2003 through March 2004. Spring samples were collected from April through June 2004. Summer samples were collected during July through September 2004.

We calculated correlations between nitrate-N concentrations and LULC classes or poorly drained soils for all IZs in the 44 study watersheds. We were not able to collect all of the planned samples in some seasons because of inaccessible sites (high water during winter) or dry stream channels (autumn, spring, and summer). We used the Hotelling-Williams (HW) test to determine if correlations among the various IZs were significantly different ($P \le 0.05$) as described in Steiger (1980) and VanSickle (2003). The HW test takes into account the correlation of proportion LULC or poorly drained soil between IZs being compared; thus, it is a better test of model equality than using P values and correlation coefficients (Van Sickle, 2003). The HW statistic is given by Eq. [1]:

$$HW = \left(r_{IZ_A} - r_{IZ_B}\right)\sqrt{\frac{(N-1)\left(1 + r_{IZ_A vs IZ_B}\right)}{2D(N-1)/(N-3) + r_x^2\left(1 - r_{IZ_A vs IZ_B}\right)^3}} \quad [1]$$

where r_{IZ_A} and r_{IZ_B} refer to the correlations between nitrate-N concentration and proportion LULC or poorly drained soils for IZs compared, and $r_{IZ_A vs IZ_B}$ is the correlation of proportion LULC or poorly drained soils between IZs. In equation [1], $r_x = ½(r_{IZ_A} + r_{IZ_B})$ is the mean of the correlations being compared for equality. The determinant (D) from Eq. [1] is calculated using Eq. [2]:

$$D = \left(1 - r_{IZ_A}^2 - r_{IZ_B}^2 - r_{IZ_A vs IZ_B}^2\right) + 2r_{IZ_A}^2 r_{IZ_B}^2 r_{IZ_A vs IZ_B}^2 \quad [2]$$

Significant differences among correlations were determined using the HW statistic as one would use a t statistic. When a significant difference between correlations was identified, additional comparisons were made with other IZ correlations using the HW test until an insignificant difference was found. This hierarchical approach, which we refer to as "threshold analysis," was applied to identify an IZ threshold at which differences became insignificant ($P > 0.05$). Pearson correlation analysis was completed using S-Plus 6.1 (Insightful Corp., Seattle, WA). The HW test was completed using the above formulas in a spreadsheet program. Nitrate-N values below detection were set to the detection limit; we deemed this a conservative approach because provided maximum possible nutrient concentrations and allowed us to assess "maximum potential nitrate-N" scenarios. In a preliminary correlation analysis, we set the non-detects (i) to 0, (ii) to 0.5 of the detection limit, and (iii) at the detection limit. The effects of these three approaches resulted in correlation coefficients that were not significantly different among approaches (data not shown). Because we generally had a wide range of nitrate concentrations between the forest and agriculture sub-basins, setting the non-detects to the detection limit was sufficient for our analysis.

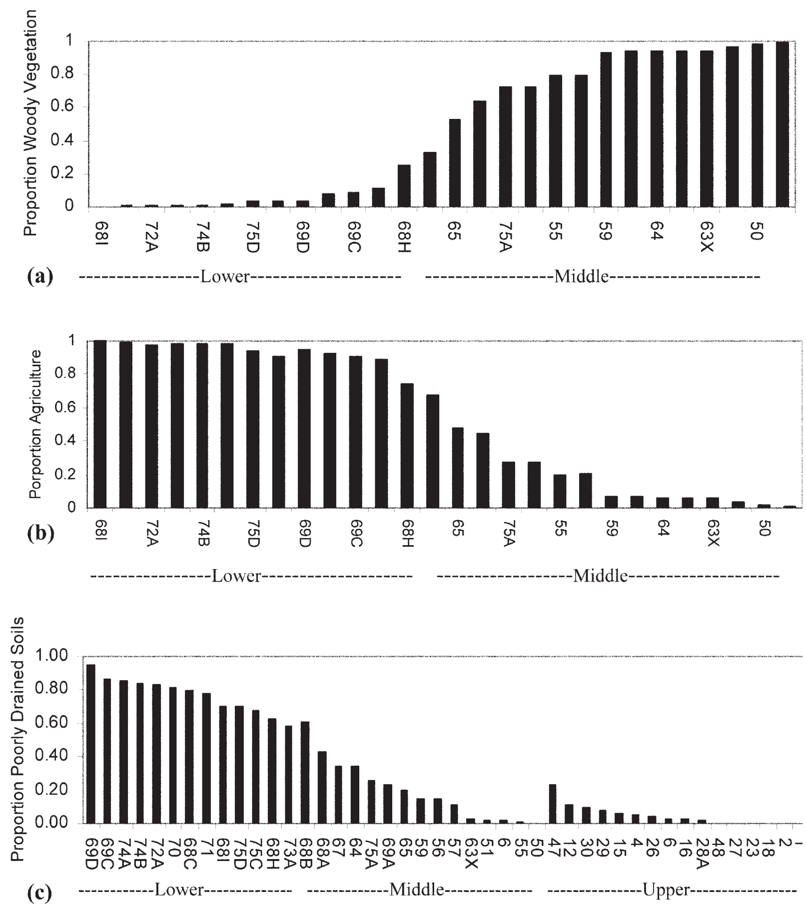

Fig. 4. Distribution of proportion land use/land cover and poorly drained soil distribution for the independent watersheds in the Calapooia Basin, Oregon. Labels on the *x* axis represent site numbers for each watershed. (a) Woody vegetation for watersheds in the lower and middle zones. Upper zones are not shown because all watersheds are 100% forested. (b) Agriculture for watersheds in the lower and middle zones. Upper zones are not shown because all watersheds are 100% forested. (c) Poorly drained soil in the Lower, Middle, and Upper zones.

Results

Distribution of Land Use/Land Cover and Poorly Drained Soil

Woody vegetation, poorly drained soils, and agriculture had proportions at the watershed level ranging from 0 to 100%, providing a relatively uniform distribution of LULC and poorly drained soils (Fig. 4). The Upper watersheds were completely forested; thus, woody vegetation within all IZs was 100%. Urban LULC was found within 13 of the 44 watersheds and was <10% total LULC within these watersheds, with only one watershed having >5% proportion urban (results not shown). In addition, all urban influences tended to be on the edges of the watershed far upstream of the sampling points; thus, the influence on nitrate-N would likely be minimal. Woody vegetation and agriculture are strongly inversely correlated (Fig. 4). For the remainder of this paper, results focus on correlations between nitrate-N and woody vegetation because of our interest in the role of woody vegetation within IZs. However, because of the strong inverse correlation between woody vegetation and agriculture LULC categories, the presence of negative correlations between woody vegetation and nitrate-N is also indicative of a very similar degree of positive correlation between agriculture and nitrate-N.

Nitrate-N

Watersheds within the Calapooia River Basin Lower Zone consistently had higher concentrations of nitrate-N than those in the Upper and Middle Zones through winter and spring (Fig. 5 and 6). Streams were dry in the Lower Zone during autumn 2003, and there were no detectable levels of nitrate-N from any of the watersheds throughout the basin. The highest concentrations of nitrate-N occurred in winter, coinciding with highest precipitation and maximum stream flows of the year. Mean winter nitrate-N concentration in the Lower Zone was 4.80 mg L^{-1}, compared with 0.11 mg L^{-1} in the Upper Zone and 0.74 mg L^{-1} in the Middle Zone (Fig. 5). Nitrate-N concentrations were lower in the spring, but the Lower Zone still had the highest mean concentration at 0.95 mg L^{-1}, in contrast to 0.07 mg L^{-1} for the Upper Zone and 0.23 mg L^{-1} for the Middle Zone (Fig. 6). During summer, most of the streams in the Lower Zone were dry, and the Middle Zone had the highest mean concentration of nitrate-N at 0.62 mg L^{-1}.

Land Use/Land Cover and Poorly Drained Soil Associations

No significant associations were found among nitrate-N and woody vegetation or poorly drained soils during the au-

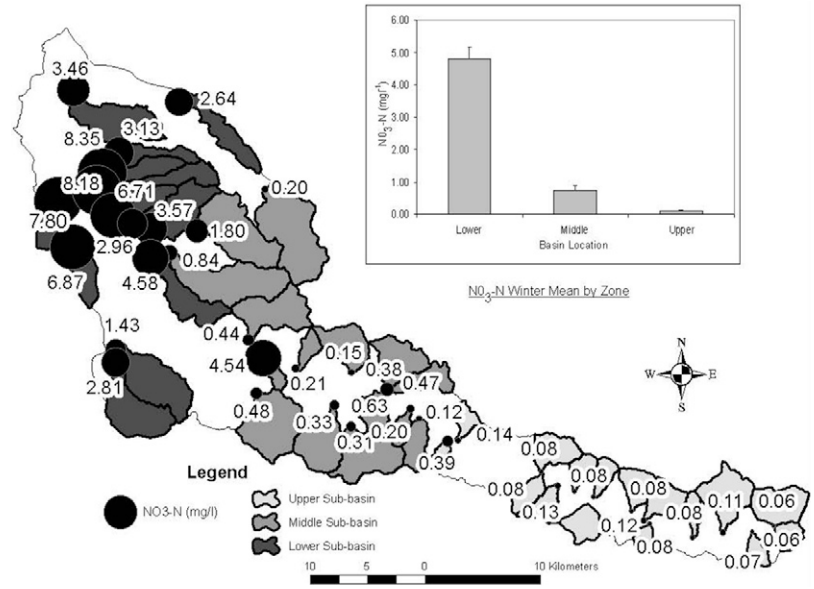

Fig. 5. Mean base flow nitrate-N concentrations in the winter 2003–2004 for watersheds in the Calapooia Basin, Oregon. Means are based on values below detection set to the detection limit. The larger the circle, the higher the nitrate-N concentration. Numbers adjacent to the circles are mean winter nitrate-N concentration. Error bars on the bar graph represent SEM.

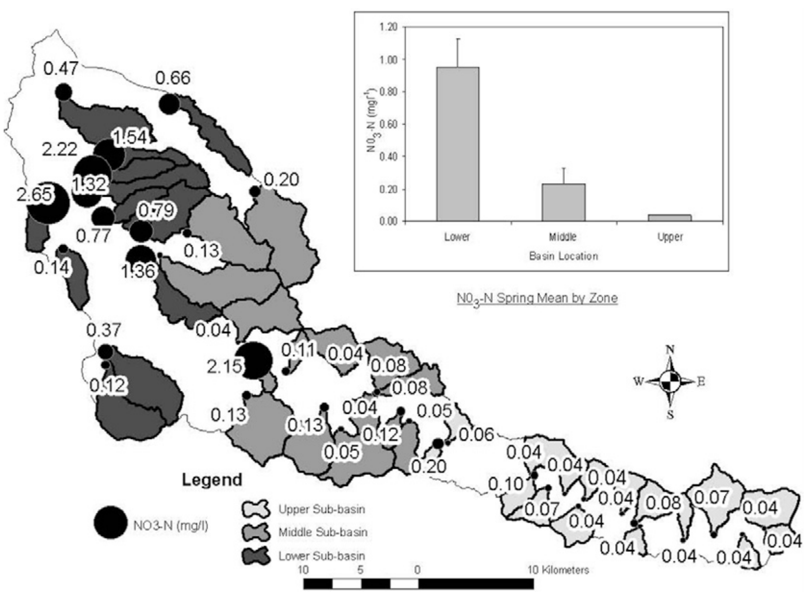

Fig. 6. Mean base flow nitrate-N concentrations in the spring 2004 for watersheds in the Calapooia Basin, Oregon. Means are based on values below detection set to the detection limit. The larger the circle, the higher the nitrate-N concentration. Numbers adjacent to the circles are mean winter nitrate-N concentration. Error bars on the bar graph represent SEM.

tumn season. There were significant correlations during the summer season, but the data were highly non-normal because of the large number of dry streams. Thus, analyses among IZs during summer were not further explored in this paper. Our results show highly significant ($P \leq 0.0001$) negative correlations ($r = -0.81$ to -0.94) between nitrate-N and the proportion of woody vegetation during winter and spring and moderate to strong correlations ($r = 0.63$–0.87) between nitrate-N and proportion of watersheds with poorly drained soils during the same seasons (Table 2). Correlations during summer and fall were not significant ($P > 0.05$). For the remainder of this section, we focus on winter and spring correlations.

Woody Vegetation Influence Zones

Relationships between nitrate-N concentrations and woody vegetation were always negative, and there were significant differences among IZs. During winter, correlations between nitrate-N concentration and the proportion of woody vegetation at 150-, 90-, and 60-m IZs ($r = -0.94$) were greater than the correlations between nitrate-N and the proportion of woody vegetation in the entire watershed IZ ($r = -0.91$) (Table 2). Although these differences were significant, correlations only differed by 0.03. There were no significant differences among the IZ correlations for nitrate and woody vegetation during spring (Table 2). Threshold analysis provided no additional significantly different correlations among IZs.

Poorly Drained Soil Influence Zones

We found significant differences among correlations between nitrate-N concentrations and poorly drained soil among IZs for the winter and spring seasons (Table 2). All correlations were positive, and differences were greater than those for nitrate–woody vegetation correlations.

Correlation between winter nitrate-N concentration and proportion of poorly drained soil within the watershed IZ (r = 0.87) was greater than correlations between nitrate-N and IZ for the 90- through 10-m IZs (r = 0.79–0.82) (Table 2). The correlation between nitrate-N concentration and proportion of poorly drained soil within the 300-m IZ (r = 0.85) was significantly stronger than correlations at the 30-, 20-, and 10-m IZs (r = 0.79 and 0.80) (Table 2). Water samples collected during the spring provided additional significant differences for correlations between nitrate-N concentration and proportion of poorly drained soil, with the correlation between nitrate-N and IZ for the watershed (r = 0.71) being stronger than correlations between nitrate-N and IZ for the 30- through 10-m IZs (r = 0.64 and 0.63) (Table 2).

Discussion

Importance of Scale

Our results show that there were significant differences among correlations developed at multiple IZs between nitrate-N concentrations and woody vegetation or poorly drained soils in the Calapooia River Basin. These scale-dependent associations agree with the literature, suggesting that scale is an important factor in this type of analysis (Allan et al., 1997; Compton et al., 2003; Fitzpatrick, et al., 2001; Gove et al., 2001; Hunsacker and Levin, 1995; Omernik et al., 1981; Perry et al., 1999; Scott et al., 2002; Tufford et al., 1998). In particular, moderate-sized scales (within 150 m of the stream), at least in terms of proportion of woody vegetation, provided stronger relationships with nitrate-N concentration than watershed-wide scales during winter. However, absolute values of these significant differences are so small among IZs for woody vegetation and nitrate-N concentrations that their ecological importance is questionable.

Differences among IZs for correlations between poorly drained soils and nitrate-N are greater than for woody vegetation associations, allowing us to suggest that scale is an ecologically important factor when considering the role of poorly drained soils. The presence of multiple significant differences among correlations between nitrate-N concentration and poorly drained soils at different IZs suggests a threshold is met where either increasing scale or decreasing scale significantly changes the associations. Gove et al. (2001) found that increasing the scale (i.e., larger IZ) used to calculate the proportion LULC in two watersheds in Washington State resulted in a stronger relationship between DN and LULC. However, once a certain scale or threshold was met, the relationships remained constant or began to weaken. We did not find a similar result when examining the woody vegetation LULC class. However, this was the case for poorly drained soils, a variable not previously examined in the literature using proximity analysis methods.

Table 2. Pearson correlation coefficients showing significant differences among correlations between nitrate-N and proportion of woody vegetation or poorly drained soil in each influence zone in the Calapooia Basin, Oregon.†

Influence zone	Nitrate-N vs. woody vegetation		Nitrate-N vs. poorly drained soil	
	Winter	Spring	Winter	Spring
Sub-basin	−0.91 b	−0.81 a	0.87 a	0.71 a
300 m	−0.93 ab	−0.83 a	0.85 ab	0.69 ab
150 m	−0.94 a	−0.83 a	0.83 abc	0.67 ab
90 m	−0.94 a	−0.83 a	0.82 bc	0.66 ab
60 m	−0.94 a	−0.83 a	0.81 bc	0.65 ab
30 m	−0.93 ab	−0.84 a	0.80 c	0.64 b
20 m	−0.93 ab	−0.84 a	0.80 c	0.64 b
10 m	−0.93 ab	−0.84 a	0.79 c	0.63 b

† Hotelling-Williams test used to identify significant differences ($p < 0.05$) between two dependent correlations sharing a variable. In each column, correlation coefficients followed by different letters are significantly different at a p value of 0.05 based on the Hotelling-Williams test.

A number of studies have suggested that regional and watershed-wide LULC proportions provided the strongest relationships with DN (Allan et al., 1997; Compton et al., 2003; Hunsacker and Levin, 1995; Omernik et al., 1981; Scott et al., 2002). Although our study shows this to be the case for poorly drained soils, it suggests that scale is not important when creating associations between nitrate-N and LULC in the Calapooia River Basin. Neither proportion of woody vegetation nor poorly drained soil within 30 m of the stream network had significantly stronger correlations than at other IZs. This finding is in agreement with other research in this area (Allan et al., 1997; Compton et al., 2003; Gove et al., 2001; Hunsacker and Levin, 1995; Lattin et al., 2004; Omernik et al., 1981; Perry et al., 1999; Scott et al., 2002; Tufford et al., 1998).

A number of authors (Allan et al., 1997; Tufford, et al., 2003) were surprised that LULC within 30 m of the stream network did not provide the strongest relationships in their studies, and they suggested that LULC data resolution, generally at 30 m or greater, was too coarse to capture the LULC variability within this zone. We used high-resolution orthophotos to accurately document LULC, specifically woody vegetation within 30 m of the stream network. Even with these higher-resolution data, relationships between DN and woody vegetation for IZs within 30 m of the stream network were not significantly greater than larger scales. This indicates that coarse-resolution datasets may not be the sole reason for these weaker relationships; rather, it may be characteristics of the LULC distribution on the landscape that were not quantified by our approach. For example, our approach assumed that woody vegetation was relatively stable on the landscape between when the airphotos were taken in 2000 and the water samples were taken in 2004. It is possible that significant changes occurred that our methods did not capture. We also quantified LULC within each IZ using a potentially coarse stream network based on a 30-m DEM. This may have missed many ephemeral streams and variable source areas, possibly masking significant changes in IZ associations.

Other research completed within the Willamette River Basin concluded that assessment of nitrate-N relationships to land use using 30-m resolution, satellite-derived LULC was comparable to relationships developed for LULC data generated using high-resolution, color-infrared airphotos (Lattin et al., 2004). This, combined with our results, implies that use of readily available satellite-derived imagery may be adequate when examining relationships between DN and LULC. However, using these methods to derive process-based hypotheses may be difficult, if not impossible, due to the many confounding variables and lack of detail in some LULC and physiographic datasets. Process-based research within the Oak Creek watershed, in a comparable geographic location as the Calapooia, showed a similar pattern of high late autumn/early winter concentrations of nitrate-N in surface water with a gradual decrease through to the spring months (Poor and McDonnell, 2007). The high concentration of nitrate-N in the late fall and early winter was attributed to application of manure in the summer months to agricultural fields. Using more detailed storm-based methods did not allow the authors to make definitive statements about practices within specific land uses due to the link between hydrology, soils, and land use. However, they argued that nitrate-N differences between major land uses was more important than background hydrological variation (Poor and McDonnell, 2007).

Land Use/Land Cover and Riparian Function

Although our dataset has limitations, valuable information can be gleaned from research such as ours. We observed that watershed-wide scales using proportion LULC did not provide the strongest relationships to dissolved nitrate-N as suggested by other research (Allan et al., 1997; Compton et al., 2003; Hunsacker and Levin, 1995; Omernik et al., 1981; Scott et al., 2002), nor did small scales (normally associated with riparian buffers) provide the strongest relationships between LULC and dissolved nitrate-N. Instead, proportion of woody vegetation provided essentially similar associations with dissolved nitrate-N at all scales. This suggests that land management should focus on woody vegetation communities at all scales to help manage nitrate-N concentrations, rather than within specific locations. However, due to the relative similarity between proportion of LULC at all IZs and the similar Pearson correlation coefficient values between nitrate-N and LULC at each scale, our results do not fully support this suggestion. Although our results for LULC are inconclusive, plot scale research completed in the Calapooia using a water balance approach showed riparian buffers to be effective at removing nitrate-N from ground water. However, the majority of nitrate-N entered the stream network as surface water that completely bypassed the riparian zone (Wigington et al., 2003).

Riparian buffers are well documented tools that are used to protect stream conditions from land management practices at a site-specific scale (Griffith et al., 1997; Klapproth, 2000; Lowrance et al., 1983, 1984; McKergow et al., 2003; Wigington et al., 2003). Our LULC dataset is limited because it provides no information about unmanaged grass that we observed in riparian areas. These riparian grass communities could be effective buffers adjacent to stream networks to reduce ground water nitrate-N concentrations (Griffith et al., 1997; Wigington et al., 2003). Much effort has been focused on retaining or restoring woody vegetation within riparian zones (e.g., Kauffman et al., 1997). Woody vegetation can provide bank stability, shade, and coarse woody debris inputs—all valuable components for wildlife habitat, maintenance of water quality, and general stream health (Gregory et al., 1991). Field observations within the Calapooia Basin indicate that unmanaged grass buffers are present in riparian zones of many streams located in the Lower Zone. Grass buffers in this basin are often associated with poorly drained soils that may be too wet to support trees. These grass buffers can be effective in reducing DN concentration through direct uptake and denitrification, especially in areas of the Willamette Basin where this type of grass is actively growing during the winter months when deciduous woody vegetation is dormant (Griffith et al., 1997; Wigington et al., 2003). Characterizing this type of LULC data may provide further insight into riparian area function in the Calapooia River Basin and may provide greater absolute differences in associations between nitrate-N and LULC among IZs.

Poorly Drained Soils and Riparian Bypass

In contrast to woody vegetation, the proportion of poorly drained soils at the watershed scale provided significantly stronger relationships with nitrate-N than IZs within 90 m of stream channels during winter and within 30 m of channels during spring. This suggests that soil properties and associated hydrology at larger scales may play a greater role in controlling surface water nitrate-N concentrations than the proportion of poorly drained soils in close proximity to the stream network. There are often different management practices associated with poorly drained soils, such as increased fertilization, that make it difficult to differentiate whether the DN concentrations are a direct result of soil drainage or a direct result of land use practices. Nevertheless, poor drainage is a dominant component of the soil and hydrologic characteristics of the Calapooia Basin. This is supported by observations of the high potential for stream expansion during winter and spring in the Calapooia Basin (Wigington et al., 2005). As the proportion of poorly drained soils increases in portions of this basin, there is a higher potential for overland flow and stream expansion. This expanded ephemeral network may result in DN entering the stream network directly, without ample opportunity for uptake or reduction. Although the associations explored within this paper are confounding, they provide information related to areas where future research can occur to separate land management practices from physical properties of the landbase.

Studies (e.g., Gold et al., 2001) have found that hydric soils are required for effective nitrate-N removal. However, surface seeps reduce this effectiveness by encouraging riparian bypass. Control of overland flow is important to minimize nutrient loss, especially during the wet winter months (Marston, 1989). The dynamic nature of stream expansion during the winter and early spring, followed by contraction during the late spring and summer in the Middle and Lower Zones of the Calapooia Basin, make it difficult to establish effective riparian buffers. In some areas, buffers around such networks would cover entire watersheds, essentially removing them from agricultural production. This is unfeasible in most areas, so other management alternatives need to be addressed to reduce nitrate-N levels in surface water, such as optimizing fertilizer rates, using proper drainage control, and selecting crops that are efficient at processing excess nitrate-N. Using a 30-m DEM does not allow for the delineation of areas that will be subjected to channel expansion, especially in the lower agriculture dominated portion of the Calapooia. Emerging technology, such as Light Detection and Ranging, may provide the large scale data resolution that will allow for better mapping of potential channel expansion and variable source areas. This could be a useful tool for research and operation planning purposes.

Ephemeral channel expansion and overland flow are not the only mechanisms for riparian bypass in the Calapooia Basin. Tile drains were documented at a number of sites in the agriculture-dominated Lower Zone of the watershed. The extent of these drains in the watershed is unknown. However, tile drains can have very high nitrate-N concentrations, often in excess of 10 mg L^{-1} (Cambardella et al., 1999; Kladivko et al., 1999; Warren, 2002). The high potential of these drains to contribute to elevated DN concentrations requires further research into their extent and their contributions to stream flow on a seasonal basis. It is likely that this type of data would significantly improve our ability to predict DN concentrations in surface water. Combining stream network expansion information with tile drain information would provide a clearer representation of DN transport mechanisms and improve our ability to assess watershed-wide water quality and riparian function.

Additional Factors Affecting Dissolved Nitrogen

Field disturbance, primarily through tillage, can promote mineralization of organic N to available inorganic N. Tillage increases aeration, provides carbon inputs, and helps to warm the soil—all factors that have the potential to increase mineralization of N. Other types of disturbance in the Calapooia Basin, especially in the Lower and Middle Zones, include burning of crop residues and the use of herbicides. During 2004 in a subset of watersheds from the Calapooia Basin, ground disturbance ranged from 26 to 74% in each watershed (Mueller-Warrant et al., 2005). This represents a wide range of conditions within these watersheds and substantial portions within some watersheds that have the potential to influence DN concentration in surface water. Most ground disturbance occurs in the late summer and autumn, creating the potential for increased mineralization before or at the onset of the wet winter months. This may result in excess inorganic N in the soil profile that can be readily transported to the stream network during the high flows associated with winter rains in the Calapooia Basin. A key component of future research will require an assessment of mineralization rates in these disturbed fields as well as transport potential to the stream network through ground- and surface-water pathways.

Stream nitrate-N concentrations can also be related to geomorphological features, which can modify the effects of management practices on nutrient concentrations (Franklin et al., 2002). Stream morphology is strongly influenced by surrounding topography and geology, as is the type of LULC. Steep mountainous catchments are far less suitable for agriculture than low-lying fluvial plains. In most instances, separating management effects from geomorphological influences can be difficult (Fitzpatrick et al., 2001). There are few instances where we can compare a specific LULC on different types of topography and soil types, especially within the same region such as the Calapooia Basin. Furthermore, hydrologic processes ultimately determine the effectiveness of riparian buffers at capturing or transforming pollutants, and these processes are not only a function LULC but are driven by physical components of the riparian zone (Baker et al., 2001). The fact that research comparing multiple-scale relationships can find no consistent scale at which LULC relationships with DN are strongest suggests that LULC effects on DN are modified by geomorphologic setting and local climatic and hydrological conditions.

Conclusions

We have observed significant differences among the associations between dissolved nitrate-N and the proportion of woody vegetation or the proportion of poorly drained soils at varying IZs in the Calapooia River Basin. Absolute changes among IZs for woody vegetation were small; thus, there is probably minimal ecological significance associated with these small differences. We have shown that relationships change seasonally, with winter having the highest concentrations of nitrate-N and the strongest relationships with proportion of woody vegetation or poorly drained soil. These findings provide potential areas of focus to perform process-oriented investigations, test alternative management scenarios, and collect additional data to use in modeling. Although our results show that proportions of poorly drained soils have strong, positive correlations with high nitrate-N concentrations, we can infer little about the causative factors involved in nitrate-N concentration in surface water of the Calapooia River Basin.

Our results indicate that spatial scale is an important factor in developing nitrate-N associations with soil drainage class but is not important with woody vegetation. The progression of research within the Calapooia River Basin and similar basins with multiple land uses will require site-specific data related to riparian function, tile drain extent, stream network expansion, and field management practices to increase our understanding of nitrate-N dynamics. This research also suggests that land management objectives that focus on reducing nitrate-N concentration in basins similar to the Calapooia must focus on all watershed-scale practices, including proper drainage, optimized fertilizer application and crop selection, maintenance/creation/restoration of nutrient sinks, and use of riparian buffers, to prevent excess nitrate-N concentration in surface water.

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