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REGIONAL CHARACTERISTICS OF NUTRIENT CONCENTRATIONS IN STREAMS AND THEIR APPLICATION TO NUTRIENT CRITERIA DEVELOPMENT[1]

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ABSTRACT: In order to establish meaningful nutrient criteria, consideration must be given to the spatial variations in geographic phenomena that cause or reflect differences in nutrient concentrations in streams. Regional differences in stream nutrient concentrations were illustrated using stream data collected from 928 nonpoint-source watersheds distributed throughout the country and sampled as part of the U.S. EPA National Eutrophication Survey (NES). Spatial patterns in the differences were compared and found to correspond with an a priori regional classification system based on regional patterns in landscape attributes associated with variation in nutrient concentrations. The classification consists of 14 regions composed of aggregations of the 84 U.S. EPA Level III Ecoregions. The primary distinguishing characteristics of each region and the factors associated with variability in water quality characteristics are presented. The use of the NES and many other extant monitoring data sets to develop regional reference conditions for nutrient concentrations in streams is discouraged on the basis of sample representation. The necessity that all sites used in such an effort be regionally representative and consistently screened for least possible impact is emphasized. These sampling issues are rigorously addressed by the U.S. EPA Environmental Monitoring and Assessment Program (EMAP). A case-study, using EMAP data collected from the Central and Eastern Forested Uplands, demonstrates how regional reference conditions and draft nutrient criteria could be developed.
(KEY TERMS: nutrient criteria; ecoregions; water management; reference streams; regionalization; total phosphorus; total nitrogen.)

INTRODUCTION

Human and non-human landscape characteristics relating to nutrient concentrations in streams vary regionally. Understanding the nature of these variations is necessary for the development of nutrient criteria in surface waters. Quite simply, expectations should not be the same in different parts of the country where geographic phenomena, such as soils, vegetation, climate, and geology, cause nutrient concentrations to be different. Patterns in past and existing land use are also commonly related to these regional differences (Omernik *et al.,* 2000; Bryce *et al.,* 1999).

Partitioning land into regions based on the combinations of geographic phenomena associated with regional differences in stream nutrient concentration levels can be a powerful classification tool for criteria development. Accounting for the fundamental regional sources of variability between streams focuses inquiry into defining and explaining variability within relatively homogeneous areas; for example, factors associated with nutrient concentration levels in streams in the mountainous West are different than those in the Great Plains, and the factors in both of these regions are markedly different than those associated with variations in nutrient concentration levels in the Eastern Coastal Plains. Identifying these general regions within which combinations of the factors associated with variation in nutrient levels are likely to be different clarifies the process of defining desired water quality conditions and impaired waters. This regional framework, when used in conjunction with watershed-specific studies of ecological response to nutrient enrichment, can help in developing appropriate nutrient criteria and methods for restoration.

Our purposes in writing this paper were to show the broad scale differences that exist in stream

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nutrient concentrations and discuss the mosaics of landscape factors that are associated with them and to demonstrate the utility of ecoregionalization in describing these spatial differences and developing regional nutrient criteria. Stream data from a national stream sampling program (Omernik, 1977) were used to evaluate how 14 regions, developed for the National Nutrient Strategy (U.S. EPA, 1998a), describe spatial differences in nutrient concentration levels in streams. We discuss the inadequacies of these and other extant data for actually setting nutrient criteria and provide direction for collecting data to develop better regional characterizations than are possible with extant sets. Finally, we provide an example of how regional nutrient criteria could be developed using data from an Environmental Monitoring and Assessment Program (EMAP) survey of small streams in the Mid-Atlantic Highlands (Herlihy *et al.*, 2001).

Fourteen regions have been delineated in which there are broad scale similarities in ecosystems as well as in human and non-human related factors associated with nutrient concentrations in streams (U.S. EPA, 1998a; Figure 1). These 14 regions comprise aggregations of U.S. EPA Level III Ecoregions (Omernik, 1987; U.S. EPA, 1998b). Patterns in the spatial coincidence of characteristics including geology, soils, land use, geomorphology, and vegetation that are associated with geographic patterns in ecosystems, ecoregions, as well as these 14 aggregated ecoregions, are also spatially correlated with general patterns in nutrient concentrations in streams. It should be noted that while the Aggregated Level III Ecoregions are roughly the same level of detail as Level II Ecoregions described previously (CEC, 1997; Omernik, 1995b), the Aggregated Level III Ecoregions are a new and different aggregation due to the narrower focus of the framework on landscape factors associated with nutrient concentrations in streams.

Single-purpose regionalizations, illustrating spatial patterns based on a particular water constituent, can and have been implemented (e.g., alkalinity regions, Omernik and Powers, 1983; lake phosphorus regions, Rohm *et al.*, 1995; and regions for individual nutrient species in streams, Omernik, 1977). General-purpose ecoregionalizations differ from single-purpose regionalizations in that they generally correspond with the broad-scale patterns in not one, but many, water quality characteristics. A general-purpose ecoregionalization, such as the 14 Aggregated Level III Ecoregions, provides a spatial framework that can be utilized for studying a variety of water resource issues at a national scale and may facilitate the integration of assessment, research, and management activities among resource management agencies and programs with different responsibilities for the same geographic areas. These 14 regions provide a common framework that could be used by investigators working in subdisciplines such as nutrient- and biological-criteria development, and nonpoint source and best management practice assessment to share information, integrate their strategies, and generalize results.

Level III Ecoregions (Omernik, 1987; U.S. EPA, 1998b) have been compared with other systems of land classification for stream management (Brown and Brown, 1994; Omernik and Bailey, 1997; Griffith *et al.*, 1999) and are being used to assist in establishing reference conditions and monitoring water quality in a number of states including Arkansas (Rohm *et al.*, 1987; Giese *et al.*, 1987), Ohio (Larsen *et al.*, 1986, 1988; Rankin *et al.*, 1997), Minnesota (Heiskary *et al.*, 1987), Iowa (IDNR, 1994), and Tennessee (Harrison, in review). The ecoregion framework is also hierarchical and may be further subdivided to fit the needs of State/Tribal scientists and resource managers for greater resolution and predictive power (Griffith *et al.*, 1994a, 1994b, 1997; Woods *et al.*, 1996, 1998; Clarke and Bryce, 1997; Bryce *et al.*, 1998; Pater *et al.*, 1998).

Characterizing the factors associated with variation within ecological regions, and the extent to which they might respond to the application of water quality regulations, can be useful for developing realistically attainable criteria. For example, within the Mostly Glaciated Dairy region, which contains a mixture of nutrient-poor and nutrient-rich soils and land uses, as well as a relatively high concentration of dairy operations, expectations of total nitrogen concentrations in streams may be varied and associated with factors such as animal unit density and the percentage of the watershed in agricultural use. In contrast, in the adjacent Cornbelt and Northern Great Plains, the soils are generally moist and uniformly fertile, and the land is primarily in cropland agriculture. Livestock rearing in this region is dominated by beef cattle and hog farming, rather than dairy farming. Hence, stream systems in this region may exhibit more uniform and higher concentrations of total nitrogen and may not be as responsive to the same nutrient management techniques as systems in the adjacent region.

DESCRIPTION OF REGIONS

Each of the 14 regions is distinctly different. The primary distinguishing characteristics of each region, as well as factors associated with variability and potential degradation of water quality are briefly described below. The materials used to describe the

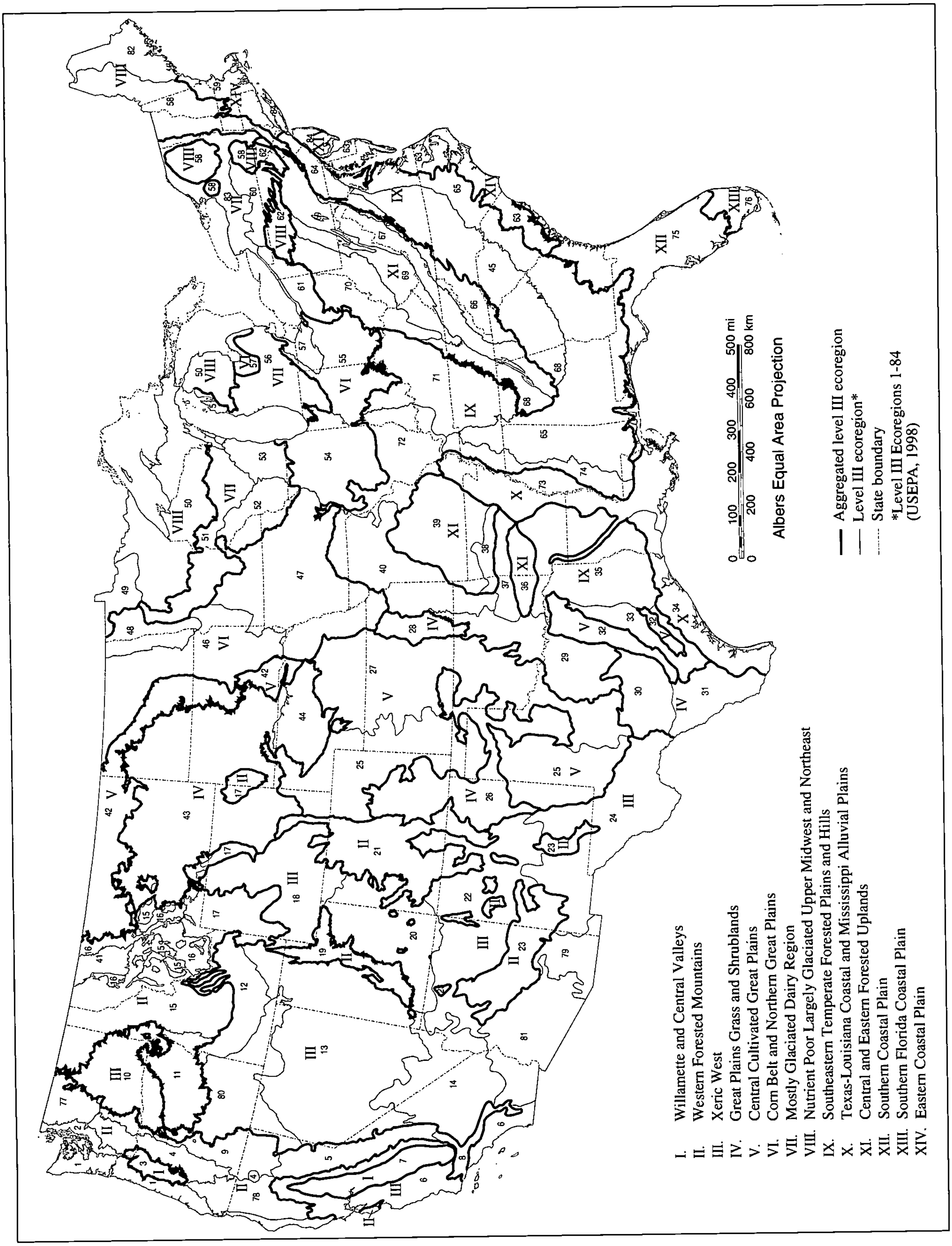

Figure 1. Aggregations of Level III Ecoregions (U.S. EPA, 1998a). The fourteen regions comprise aggregations of the 84 U.S. EPA Level III Ecoregions (U.S. EPA, 1998b) and represent areas in which there are broad scale similarities in ecosystems as well as in human and non-human related factors associated with nutrient concentrations in streams.

characteristics and factors vary in importance and scale from one area to the next.

The Willamette and Central Valleys Region (Region I)

The Willamette and Central Valleys region (Figure 1) is composed of broad, arable, western valleys that are drier, flatter, and much more densely populated than the neighboring Western Forested Mountains. Soils are typically nutrient-rich and naturally more fertile than those of the adjacent regions. They support mostly cropland agriculture.

The Willamette Valley is the most important agricultural area in Oregon and grows a wide range of primarily unirrigated crops including vegetables, berries, grapes, nursery stock, grass seed, Christmas trees, hay, and grain; pastureland is also common. Precipitation is concentrated in the fall, winter, and spring months; summers are dry and, correspondingly, summer streamflow is relatively low. The Willamette Valley is the home to most of Oregon's rapidly growing population and industrial base. Urbanization, fertilizer use, industrialization, irrigation return flows, nearby logging, and livestock rearing have affected surficial water quality. Dissolved phosphorus in some streams is rising due to human activities such as increased agricultural use of phosphorus fertilizer, greater runoff from suburban-urban areas, and more discharge from municipal sewage treatment plants.

The Central Valley of California is composed of the intensively farmed Sacramento and San Joaquin valleys. More than 90 percent of the Central Valley is in farms and ranches; urban or suburban areas have been rapidly expanding but occupy less than 5 percent of the Central Valley. Nearly half of the region consists of cropland growing sugar beets, vegetables, grains, rice, almonds, walnuts, alfalfa, citrus, pasture, cotton, and cantaloupes. About three-fourths of the cropland is irrigated. Stream flow is limited over much of the area during the summer and water for crops often comes from stream diversions, wells, canals, and reservoirs. Environmental concerns in the region include high salinity concentrations due to evaporation and reuse of irrigation water, high phosphorus and nitrogen concentrations in streams from nonpoint sources, groundwater contamination from heavy use of agricultural chemicals, lowering of the groundwater table due to overpumping, and wildlife habitat loss due to urban sprawl.

The Western Forested Mountains (Region II)

Region II includes most of the great mountain ranges that are located west of the Great Plains. This large, disjunct region is characterized by forests, high relief terrain, steep slopes, perennial streams, a general lack of cropland agriculture, and much lower anthropogenic inputs of nitrogen and phosphorus from artificial fertilizers than neighboring, more agricultural regions. The highest mountains are wetter and colder than lower elevations and are often snow-covered during the winter months; they can be glacially modified and lake-studded. Overall, Region II receives far more precipitation than the lower regions that surround it. However, within Region II, rainshadow influences are common and precipitation varies with elevation and latitude. Alpine vegetation grows in the highest areas, coniferous forests dominate the high areas, mixed deciduous and coniferous stands with a grass understory are found at the lower elevations, and shrubs and grasses are common at the lowest elevations.

Dominant land uses in Region II are logging, recreation, grazing, and mining. Logging can increase erosion and contribute large amounts of sediment to streams. Grazing can contribute significant amounts of nitrogen, phosphorus, and sediment to surface waters. Locally, mining activities have contributed suspended sediments, acidic drainage, and toxic trace elements such as arsenic, cadmium, copper, lead, manganese, and zinc to surface waters. Cropland agriculture is uncommon except within some mountain valleys and a part of the lowlands surrounding Puget Sound.

The Xeric West (Region III)

The Xeric West is composed of unforested basins, alluvial fans, plateaus, buttes, and scattered mountains. Region III is drier than surrounding regions and naturally occurring water is scarce in nearly all places. Its climate is subject to large year-to-year, seasonal, and diurnal variations. Perennial streams are rare and those that occur typically originate outside the region in the higher, wetter, more rugged Western Forested Mountains (Region II). Vegetation is mostly desertic with areas of woodland occurring only locally in wetter locations. Most of the area is uncultivated and used for range. However, irrigated agriculture occurs where water is available and soils are suitable. In parts of the region, ground water overdraft has lowered the water table causing diminished spring flow/streamflow, salt water intrusion (in coastal areas), and ground subsidence. Rivers that are heavily used for irrigation have high concentrations of dissolved solids, nitrite plus nitrate, and salinity that can increase downstream due to the effects of irrigation return flow and evaporation. Areas of high human population density occur along with associated water quality problems including elevated levels of fecal coliform bacteria, nitrite plus nitrate, phosphorus, sulfate, and dissolved solids.

The Great Plains Grass and Shrublands (Region IV)

Region IV is composed of disjunct, grassy, rolling high plains, hills, plateaus, buttes, stabilized sand dunes, and badlands. Region IV is drier than the adjoining portions of Regions II, V, and VI. Both intermittent and ephemeral streams are common; perennial streams also occur but generally originate outside the region in the Western Forested Mountains (Region II). Low and erratic precipitation, limited opportunities for irrigation, and nutrient-poor soils limit arability. Today, most of Region IV is rangeland and cropland is much less common than in Regions V and VI. Cattle feedlots occur throughout the region but their density is far less than in Region V.

Throughout Region IV, measured nitrogen and phosphorus levels in streams are generally much lower than in regions dominated by cropland agriculture or urban-suburban development. Locally, however, industries, coal mining, oil production, cropland, livestock operations, and municipalities have affected stream quality. Rock and soil types have also influenced water quality within Region IV. High sulfate concentrations in stream water occur over broad areas and are the product of soil leaching. High suspended sediment concentrations in stream water are found in steep, sparsely vegetated watersheds composed of highly erodible sediments and in many flatter areas characterized by colloidal sediments.

The Central Cultivated Great Plains (Region V)

Region V is comprised of nearly level, rolling, and irregular plains. Northernmost parts were once glaciated and contain hummocky moraines that are studded with wetlands. Region V is semiarid and was originally grassland. Today, more than half is dryland farmed, about a third is rangeland, and most of the remainder is used for irrigated farming. Region V contains the major winter wheat growing area of the United States. Spring wheat is grown in northern areas. Both wheat and feedlots are far more common than in Regions II, III, IV, VI, or IX. Perennial streams are uncommon; they fluctuate widely in flow from year to year due to the region's erratic rainfall. Intermittent and ephemeral streams are common in the drier, western portions and/or where irrigation has lowered the water table.

Agricultural runoff and irrigation return flows have affected regional water quality. Upward trends in nitrite plus nitrate levels in rivers have mirrored increasing nitrogen fertilizer use. Irrigation return flows have increased the concentrations of sodium, sulfate, chloride, and dissolved solids in base flows. Runoff from feedlots is a significant regional water quality problem; nondisinfected runoff from livestock confinement areas has significantly elevated fecal coliform bacteria and nitrite plus nitrate concentrations in rivers. Overall, however, potential loss of nitrogen and phosphate fertilizer and pesticide from farm fields is much lower than in Region VI. Some urban areas in Region V especially in Texas and Colorado have been growing rapidly and, consequently, a great deal of agricultural land has been recently converted to urban and industrial uses. Discharges from municipalities and industries have caused elevated concentrations of nitrate and phosphorus in streams. Such increased nutrient loading has caused a corresponding increase in the eutrophication rates of some downstream lakes and reservoirs.

The Corn Belt and Northern Great Plains (Region VI)

The rolling plains and flat lake beds of Region VI are dominated by extensive, highly productive, cropland. Moist, fertile soils are characteristic and are generally more nutrient-rich than those of Regions IV, VII, VIII, and IX. Perennial streams, lakes, and concentrations of seasonal wetlands occur. Corn, soybean, and livestock farming is common and feedlots occur. Many urban, suburban, and industrial areas are also found in Region VI. This land-use mosaic differs from the rangeland of Region IV; the winter wheat, grain sorghum, and feedlots of Region V; the dairying and silage corn of Region VII; and the forest, cropland, and pastureland of Region IX.

Present-day land use and the region's nutrient-rich soils significantly influence surface and subsurface water quality. Elevated concentrations of nitrate and phosphorus are significant water quality problems in many basins and are a byproduct of nutrient-rich agricultural runoff and wastewater treatment effluent; dissolved oxygen depletion occurs in sluggish, warm rivers that have high nutrient levels. Pesticides are widely used on cropland in the Corn Belt and Northern Great Plains (Region VI) and have contaminated surface waters. High concentrations of suspended sediment are found in many streams, especially those in flat, agricultural areas with clayey soils and artificial drainage. Fecal coliform bacteria levels in streams have been elevated by feedlots, municipal wastewater effluent, urban runoff, and livestock operations. Lakes occur especially in the northern part of the region; they are used for fishing and recreation and are important wildlife habitat. Those that are found in Region VI range from mildly eutrophic to hypereutrophic. Eutrophic conditions are also found in southwestern portions of Lake Michigan and Lake Erie.

Mostly Glaciated Dairy Region (Region VII)

Region VII has a short growing season and is dominated by forests, dairy operations, and livestock farming. It was mostly glaciated and includes flat lake plains, rolling till plains, hummocky stagnation moraines, hills, and low mountains. Many wetlands and lakes occur.

Soil, climate, vegetation, land use, and surficial water characteristics are transitional between those of Region VIII and those of regions to the south. Overall, it is not as flat nor as cropland-dominated as the Corn Belt and Northern Great Plains (Region VI) and not as lake-studded nor as forest-dominated as Region VIII. The Mostly Glaciated Dairy Region (Region VII) has a mix of nutrient-rich and nutrient-poor soils that contrast with the mostly fertile soils of Region VI and the relatively thin, nutrient-poor soils of Region VIII.

Surficial water characteristics are also transitional between more northerly and more southerly regions and have been affected by land use. Many lakes are found in Region VII; their median total phosphorus concentration is less than half of Region VI's and about twice that of Region VIII's median concentration. Livestock, cropland agriculture, and urban areas have contributed nutrients and fecal coliform bacteria to streams. Total nitrogen and total phosphorus concentrations from nonpoint sources are usually above the levels found in Region VIII but below those measured in the Corn Belt and Northern Great Plains (Region VI).

The Nutrient Poor, Largely Glaciated Upper Midwest and Northeast (Region VIII)

Region VIII is characterized by extensive forests, nutrient-poor soils, a short growing season, limited cropland, and many marshes, swamps, lakes, and streams. Less cropland and fewer people occur here than in neighboring regions; related nutrient problems in surface waters are also less. Water quality issues center around the effects of acid precipitation, logging, lake recreation, and near-lake septic systems.

Perennial streams are common and are often fed by water stored in the glacial deposits that overlie noncalcareous bedrock. Streams typically have low concentrations of alkalinity, sulfate, chloride, and dissolved solids due, partly, to the insolubility of the bedrock. Levels of fecal coliform, total nitrogen, total phosphorus, and suspended sediment are also generally low; stream concentrations of these constituents are typically much less than in nearby, more developed regions.

Many oligotrophic and mesotrophic lakes occur in Region VIII. Total phosphorus concentrations are generally much lower, and Secchi disk transparencies are much higher, than in the lakes of the Corn Belt and Northern Great Plains (Region VI). Acid precipitation caused by airborne emissions from upwind industrialized regions is a major water quality problem in the eastern portion of Region VIII and can threaten fish survival in weakly buffered glacial lakes.

The Southeastern Temperate Forested Plains and Hills (Region IX)

Region IX is composed of irregular plains and hills. Originally the Southeastern Temperate Forested Plains and Hills (Region IX) was mostly forested in contrast to the Central Cultivated Great Plains (Region V); areas of savannah and grassland also occurred. Today, Region IX is a mosaic of forest, cropland, and pasture. Major poultry and aquaculture operations occur locally. The Southeastern Temperate Forested Plains and Hills (Region IX) is not as arable as the Central Cultivated Great Plains (Region V) or the Corn Belt and Northern Great Plains (Region VI). However, there is much more cropland than in the more rugged Central and Eastern Forested Uplands (Region XI). Lateritic soils are common and are a contrast to the soils of the surrounding regions. Areas of depleted soils are found in parts of the region.

Stream quality in the Southeastern Temperate Forested Plains and Hills (Region IX) has been significantly affected by urban, suburban, and industrial development as well as by poultry, livestock, silviculture, and aquaculture operations. Downstream of sewage treatment plants, poultry farms, and hog operations, nutrient levels can be very high and pose a substantial eutrophication threat to surface waters. Silviculture, agriculture, and urban development have impacted suspended sediment levels in streams especially where soils are highly erodible. Increased acidity and sediment loads from coal mining have degraded water quality and affected aquatic biota in several areas including southern Iowa, northern Missouri, and eastern Pennsylvania.

The Texas-Louisiana Coastal and Mississippi Alluvial Plains (Region X)

Region X is nearly level and is composed of alluvial plains in the Mississippi River Valley and coastal plains along the Gulf of Mexico. It is well known for producing large amounts of cotton, rice, and soybeans and has concentrations of industrial and urban activity. The Mississippi alluvial plain has nutrient-rich soils, a favorable climate, and is one of the most important cash crop areas in the United States; soils in the more irregular Southeastern Temperate Forested Plains and Hills (Region IX) are not as naturally fertile. The coastal plain is dominated by range, pasture, marshy wildlife habitat, woodland, cropland, and both recreational and urban development. A higher percentage of the land is in cropland than in bordering regions. Wet soils are common and must be artificially drained to be farmed. The wettest areas that are not artificially drained remain in forests and wetlands and are important wildlife habitat. Urban and industrial areas are found in the region and population is increasing.

Urbanization, industrial activity, and agricultural runoff have affected the region's water quality. Total phosphorus, total ammonia, and nitrite plus nitrate concentrations are often high in rivers, streams, and ditches due to extensive fertilizer use and discharge from municipal sewage treatment plants. Dissolved oxygen depletion has occurred in some sluggish, warm rivers affected by nutrient-laden agricultural runoff. Turbidity is a problem in channelized areas. Pesticide residues are found in the surface waters. Industrial activity has released contaminants including heavy metals to surface waters.

The Central and Eastern Forested Uplands (Region XI)

The Central and Eastern Forested Uplands is disjunct and comprises most of the unglaciated, forested low mountains and upland plateaus in the central and eastern United States. It is underlain primarily by sedimentary and metasedimentary rocks and is characterized by forests, high relief terrain, steep slopes, and high gradient streams. Region XI is higher and more rugged than the neighboring Regions VI, VII, IX, and X. Streams are generally faster moving and clearer than the lower gradient streams of surrounding regions. Lakes are far less common than in cooler, glaciated areas such as Region VIII. Dominant land uses in the Central and Eastern Forested Uplands (Region XI) are logging, recreation, and grazing. The erosion hazard can be severe on steep slopes if the soil or vegetation is disturbed by logging or road building. Land slides and sheet flow have contributed sediments to streams which, in turn, have affected benthic habitat, turbidity, hydrology, stream temperature, and stream biota. Coal mining is locally common. It has contributed dissolved solids, suspended sediment, and acidic drainage to streams which have, in turn, impacted fish and aquatic invertebrates. Cropland agriculture and urban activity are generally less common than in nearby, lower and less-rugged regions; related water quality issues such as nutrient runoff to streams is also less. Nevertheless, in Region XI, there are a few urban areas as well as scattered croplands such as in the Great Valley. Major poultry and aquaculture operations are found in Region XI along with associated inputs of nutrients.

The Southern Coastal Plain (Region XII)

The hot, low-lying Southern Coastal Plain contains concentrations of swamps, marshes, and lakes. The region is nearly level; it has more lakes than the neighboring Southeastern Temperate Forested Plains and Hills (Region IX) or the Southern Florida Coastal Plain (Region XIII), and it is flatter than Region IX. It is underlain by limestone and has a sandy mantle of varying thickness. Sand hills reach over 200 feet elevation and are nutrient-poor. Karst topography occurs and is particularly extensive in North Central and Northwestern Florida. Thousands of lakes dot the region and have varying trophic states. Woodlands, forests, citrus orchards, vegetable farming, and pastures dominate most of the region. Locally, urban and suburban areas are common and have grown rapidly in the last 50 years. Surficial water quality has been significantly affected by human activity including urban development, industry, agriculture, silviculture, water management activity, and mining. Stream nutrient levels have been increased by runoff from sewage treatment plants, weathered rock, phosphate mines, fertilizer plants, citrus orchards, and other farms. Dissolved oxygen concentrations have been lowered by the effects of nutrient enrichment. Suspended sediment has been added to streams by agriculture and logging.

The Southern Florida Coastal Plain (Region XIII)

The Southern Florida Coastal Plain is nearly level and subtropical to tropical. It is characterized by wildlife-rich fresh water marshes, wet prairies, sloughs, swamps, and coastal wetlands; only about 10 percent is used as cropland. Canals, ditches, and broad, poorly-defined stream channels are common. Lakes are generally rare but one large, shallow, regulated lake is found in the region, Lake Okeechobee; it links the waters of the Kissimmee Basin to the Everglades. Elevations are low and range from sea level to less than 50 feet; the overall flatness of the region is broken only by hummocks, limestone ridges, beach ridges, and dunes. Poorly- and very poorly-drained, organic soils, peat, and muck are common and overlie carbonate-rich bedrock. Most of the Southern Florida Coastal Plain (Region XIII) has been set aside as parks, game refuges, water conservation areas, and Indian reservations. However, extensive areas have also been urbanized or drained for agriculture, resulting in the widespread alteration of hydrological and biological systems, depletion of peat deposits, and reduction of regional water quality. Streams draining developed areas have higher nutrient concentrations than those flowing through undeveloped areas. Lake Okeechobee, one of the largest lakes in the United States, by area, has been significantly impacted by agricultural runoff. Cattle and dairy farms have contributed a large amount of phosphorus to the lake and the Everglades Agricultural Area has pumped nitrogen-rich water into the lake to control flooding. During the 1970s, lake concentrations of phosphorus and nitrogen more than doubled and bottom sediments accumulated a massive quantity of phosphorus. By the mid-1980s, large algal blooms had occurred. State and federal governments have since intervened and both nitrogen and phosphorus inputs have been greatly reduced.

The Eastern Coastal Plain (Region XIV)

The Eastern Coastal Plain extends from Maine to Georgia and is a lowland dominated by woodland, urban areas, or marshland; less than 20 percent of the area is used as cropland and pastureland. Broad, nearly flat to depressional areas occur and have poorer drainage than neighboring regions. Nutrient-poor soils and glacial deposits typically mantle metamorphic and igneous bedrock in the northern portion of the Eastern Coastal Plain (Region XIV). The central and southern portions are underlain by sedimentary rock and are dominated by poorly-drained soils, swampy or marshy areas, and meandering, low gradient streams, many of which are tidally influenced. Urban, suburban, rural residential, commercial, and industrial areas occupy a large and growing percentage of the region; such large human population concentrations are absent from Region VIII. Some of the biggest cities in the United States are scattered throughout the Eastern Coastal Plain (Region XIV) and have locally replaced the native woodland.

Stream quality in the Eastern Coastal Plain (Region XIV) has been significantly affected by urban, suburban, and industrial development as well as by poultry, livestock, and aquaculture operations. In Connecticut, stream bottom sediments have been contaminated by metals, organic compounds, and solid residuals from textile and paper mills. In Delaware, high levels of enterococcal bacteria and total nitrate concentrations occur and are the result of increasing population, wastewater discharge, and runoff from fertilized cropland, poultry operations, and urban areas. In Maine, dioxin from pulp and paper processing effluent and bacteria in untreated sewer overflows continue to be serious problems in some reaches. In Massachusetts, bacterial contamination and low dissolved oxygen concentrations persist. Throughout most of New Jersey, nutrient and fecal bacteria concentrations continue to exceed state water quality criteria. In the southern portion of Region XIV, urban areas are far fewer than in the north and related stream water quality issues are also less. However, locally in the south, there are a large and growing number of intensive turkey, hog, and chicken operations along with associated water quality problems.

UTILITY OF ECOREGIONS FOR CHARACTERIZING PATTERNS IN NUTRIENTS

The utility of the ecoregionalization in describing meaningful variations in nutrient concentrations can be illustrated using a consistently sampled extant set of nutrient data. As part of the National Eutrophication Survey (NES), lakes with eutrophication or potential eutrophication issues, primarily from sewage treatment within the watershed, were identified throughout the U.S. A set of 928 stream sites in tributaries draining into or near these lakes were selected for sampling, to assess background levels of nutrients attributable to nonpoint sources (Omernik, 1977). They tended to be clustered around "lake areas" in parts of the country with natural lakes (Regions VII and VIII), but there was some geographic spread due to the inclusion of reservoirs, which are widely scattered throughout the U.S. The average watershed size was 42.2 km^2 and 91 percent of the watersheds were less than 100 km^2 in size. The sampled streams were selected from an initial pool of approximately 5,000 NES streams, based on the fact that they contained no discernible point-source impacts and drained watersheds generally typical of those in the area. It should be noted that although information from reports, maps, and aerial photos on the watersheds upstream of the sampling sites was analyzed to determine the absence of point sources, the watersheds were not screened in the field for other human impacts. Hence, even though without apparent point sources, these watersheds may not be truly indicative of minimal non-point impact from humans. Including watersheds in which best management practices (BMPs) are not fully implemented can result in underestimating the best nutrient conditions attainable. The data are also slightly dated. For these reasons, we do not suggest using them to actually develop regional criteria.

The extent, consistency, and quality of sampling in the NES has no functional contemporary equivalent, however, and the NES data can serve a unique role in helping to describe how well ecoregionalization effectively partitions trends in regional nutrient concentration levels in streams. Sampling methodology, frequency, and analysis were standardized for each sampling site (U.S. EPA, 1975). Grab samples were collected, preserved with mercuric chloride, and sent to the U.S. EPA National Environmental Research Center-Corvallis for laboratory analysis using adaptations of standard automated procedures (U.S. EPA, 1971). Total phosphorus was analyzed by persulfate oxidation followed by single reagent colorimetric determination of antimony-phosphomolybdate complex; analytical precision was equal to ± 0.005 mg/l. Kjeldahl nitrogen was analyzed by acid digestion followed by alkaline phenol hypochlorite reaction for ammonia; precision was ± 0.10 mg/l. Nitrite-nitrate nitrogen was analyzed by cadmium reduction followed by diazotization of sulfanilamide by nitrite coupled with N-(1-naphthyl)-ethylene diamine; overall precision was ± 0.01 mg/l. Standards were run every 120 samples. Every eighth sample was replicated, every twentieth sample was spiked, and blind samples were sent through the system to check analysts and equipment. Calculations, analytical accuracy and precision were electronically monitored. Sampling occurred at regular monthly intervals throughout the entire year, resulting in an average of 11.7 samples per site, ensuring the accuracy of mean annual concentration values of total phosphorus and total nitrogen (Kjeldahl nitrogen + nitrite + nitrate). The geographic scope of the sampling process precluded timing site-specific sampling to assess nutrient loading during individual stormflow events.

Separate single-purpose regionalizations (maps) were developed from the NES stream data to illustrate spatial patterns in total phosphorus and in total nitrogen (Figures 2 and 3, from Omernik, 1977). These maps were compiled by analyzing patterns on color-coded dot maps of mean annual nutrient concentration values in combination with maps of related landscape characteristics. Spatial differences in concentration appeared to correspond most strongly with map units depicted in Anderson's Major Land Use map (USGS, 1970). Hence, many of the boundaries on the maps of phosphorus and nitrogen concentrations in streams attributable to nonpoint sources follow map units on the Anderson land use map. Associations among spatial patterns in total phosphorus and total nitrogen values, and land use and other landscape characteristics varied regionally; however, both single-purpose total phosphorus and total nitrogen maps were drawn to incorporate these differences.

While the sampling coverage and landscape information used in the single-purpose regionalizations were generally good, some variability existed. Areas of the total nitrogen and total phosphorus maps were subjectively graded based on: the density of sampling data, the strength of association between patterns in the nutrient data and mapped landscape information, and the reliability of the mapped landscape information (Insets on Figures 2 and 3). In areas where large numbers of streams were uniformly monitored and the reliability of mapped landscape information or associations with landscape characteristics were obvious, reliability was described as "good." In areas of limited sample coverage or where a tight coupling of patterns in nutrients with mapped local characteristics was not evident, reliability was classified as "poor." This was particularly true in xeric areas of the west where water often originates from a different region and its quality is strongly influenced by irrigation return flows. Areas with adequate numbers of samples and some association between reliably mapped landscaped characteristics and nutrient patterns were designated as "fair" (Omernik, 1977).

Regional patterns of total phosphorus were found to be somewhat different than those of total nitrogen (Figures 2 and 3). In general, the spatial association of nitrogen concentrations in streams with differences in the percent of land in agriculture and forest was found to be somewhat stronger and more consistent than that regarding phosphorus, which in places appeared to be more closely associated with natural phenomena such as surface soil pH (Omernik, 1977). The map of total phosphorus concentrations based on mean annualized NES data showed phosphorus concentrations in streams to be generally higher in the western part of the U.S. than in the eastern part.

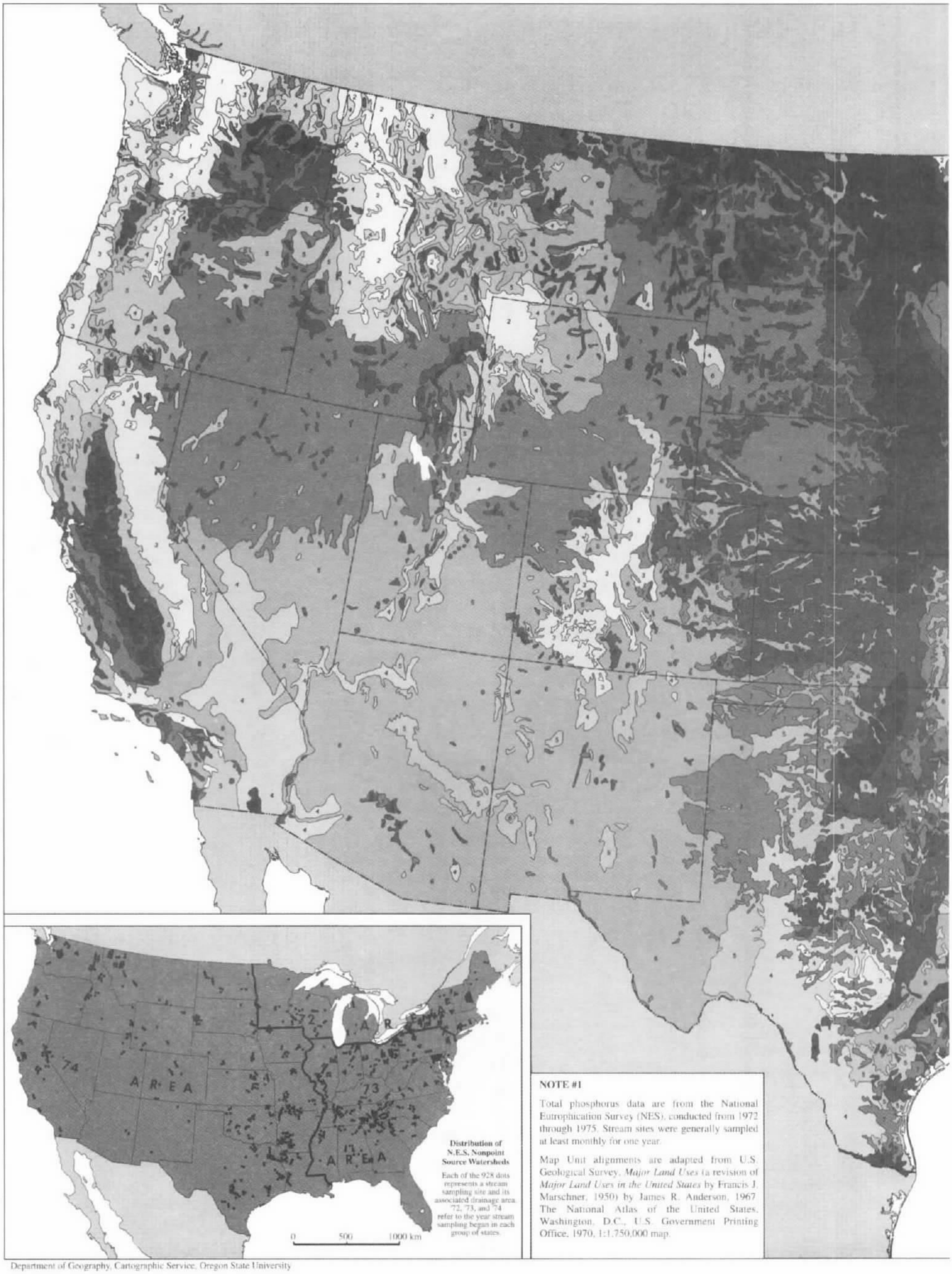

Figure 2. Total Phosphorus Concentrations in Streams From Nonpoint Sources (from Omernik, 1977). Grey tones represent the central tendency of total phosphorus concentrations in streams without point sources, based on data from 928 sampling sites with watersheds containing only non-point sources and the associations of these data to general land use and other geographic characteristics.

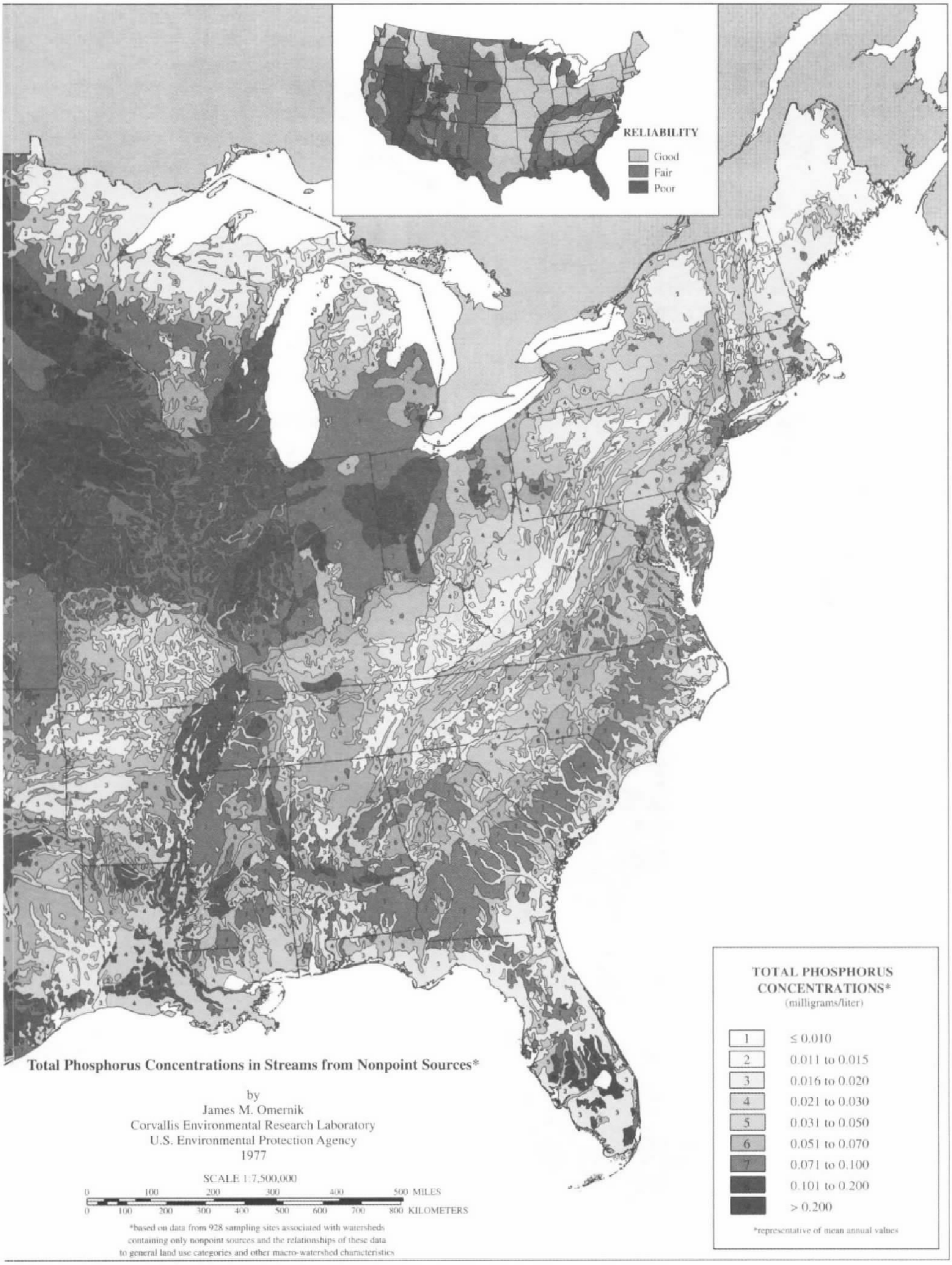

Figure 2. Total Phosphorus Concentrations in Streams From Nonpoint Sources (from Omernik, 1977) (cont'd.). Grey tones represent the central tendency of total phosphorus concentrations in streams without point sources, based on data from 928 sampling sites with watersheds containing only non-point sources and the associations of these data to general land use and other geographic characteristics.

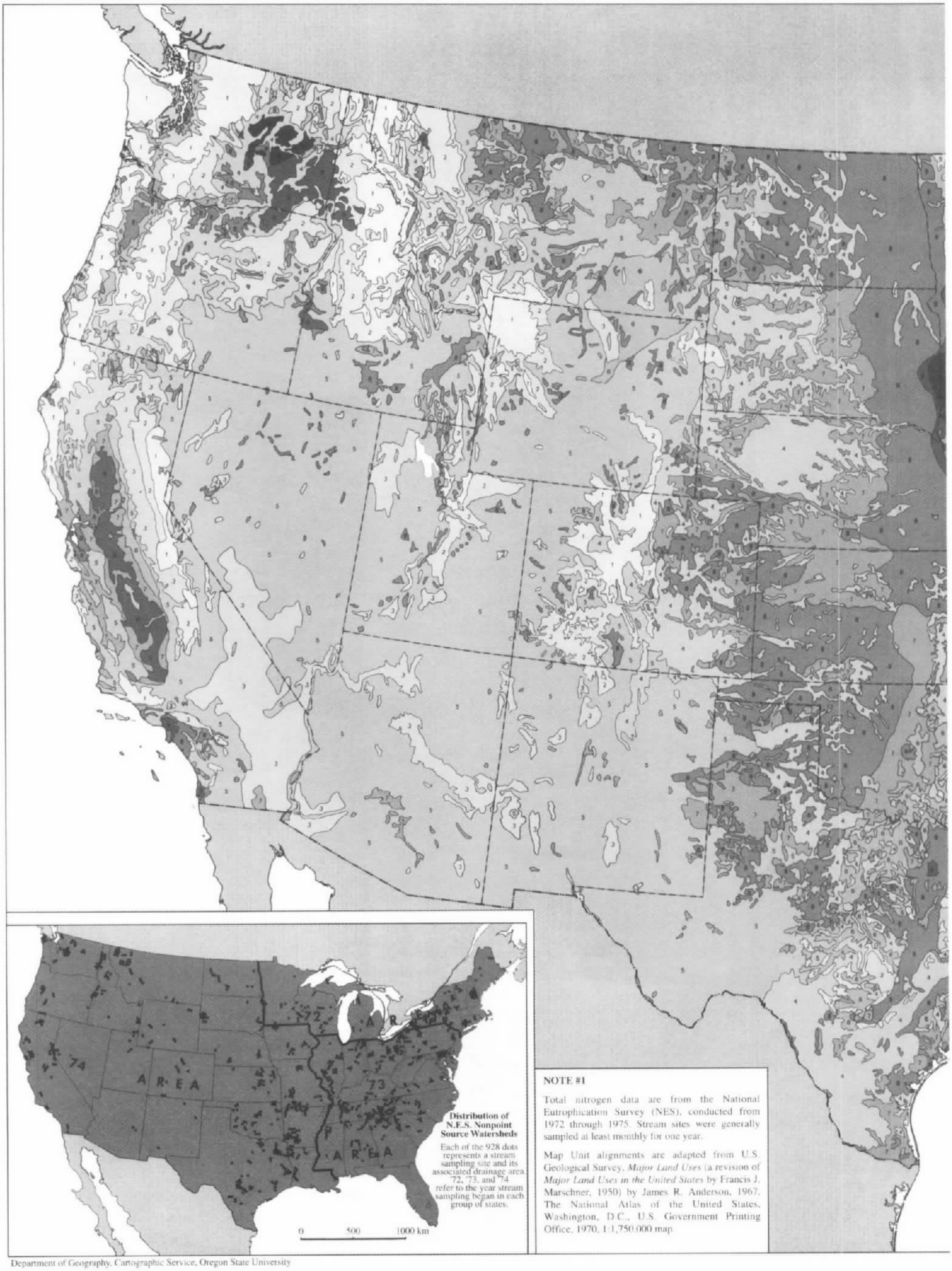

Figure 3. Total Nitrogen Concentrations in Streams From Nonpoint Sources (from Omernik, 1977). Grey tones represent the central tendency of total nitrogen concentrations in streams without point sources, based on data from 928 sampling sites with watersheds containing only nonpoint sources and the associations of these data to general land use and other geographic characteristics.

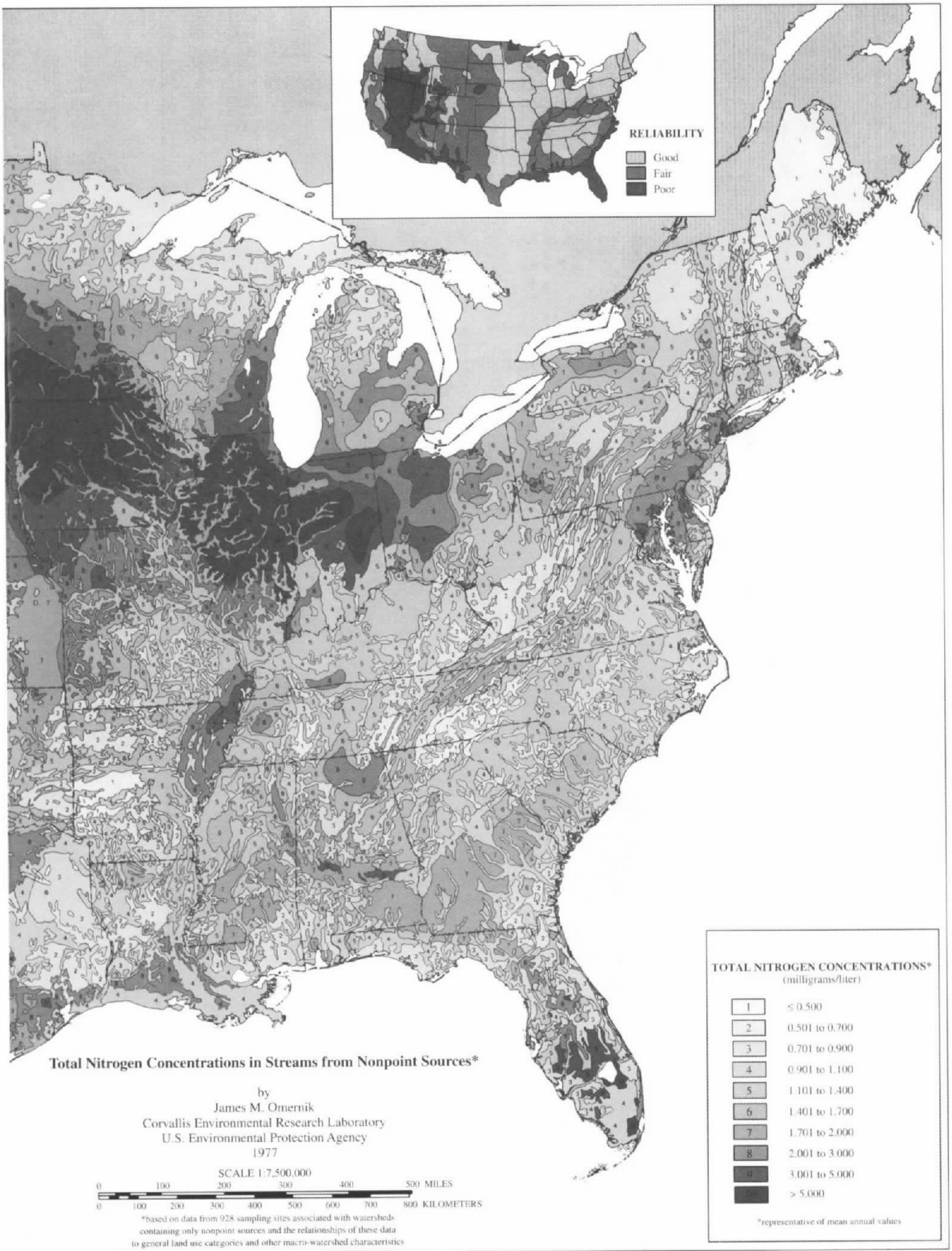

Figure 3. Total Nitrogen Concentrations in Streams From Nonpoint Sources (from Omernik, 1977) (cont'd.). Grey tones represent the central tendency of total nitrogen concentrations in streams without point sources, based on data from 928 sampling sites with watersheds containing only nonpoint sources and the associations of these data to general land use and other geographic characteristics.

The study showed a similar pattern for orthophosphorus and the trend was most pronounced in forested watersheds (Omernik, 1977). Conversely, mean annual total nitrogen concentrations were higher in streams in the eastern portion of the country than in the west, with the highest concentrations occurring in the Cornbelt from Iowa and Southwestern Minnesota to Central Ohio (Figure 3).

Both organic and inorganic species of nitrogen were evaluated for the NES and a thorough characterization of each watershed was included. Analysis showed that speciation of nitrogen was important in describing and understanding patterns of nitrogen concentration in streams (Omernik, 1977). While the difference between total nitrogen concentrations in the east and west was slight in predominantly forested watersheds, it was accentuated in predominantly agricultural watersheds. The NES study also found that, in areas of similar land use, mean annual concentrations of inorganic nitrogen in streams were much higher in the east (particularly the northeast) than in the central or western portions of the U.S. The disproportionately high percentages of inorganic nitrogen in the northeast appear to be associated with the regional pattern of higher atmospheric contributions of nitrogen (Omernik, 1977). Although there were large differences in total nitrogen concentration between individual streams, the percent of total nitrogen that was in inorganic form was found to vary considerably with the percentage of watershed in agriculture or forest. This varied from generally less than 20 percent inorganic N in watersheds with greater than 90 percent forest to over 80 percent inorganic N in watersheds with at least 90 percent agricultural land.

Evaluating total nitrogen concentrations over various regions and landscape types allows the testing of assumptions that have emerged in smaller scale or other data sets. For example, a study finding stream concentrations of total nitrogen to be inversely related to stream size in areas of similar land use in Northeastern Iowa (Bachmann *et al.,* 1991) could not be verified elsewhere.

Patterns of both mean annual total phosphorus and mean annual total nitrogen concentrations in streams, while different, tend to coincide with the boundaries of the Aggregated Level III Ecoregions (Figure 1). These general-purpose regions can be effectively used to describe differences in patterns of total nutrient concentrations in streams (Figures 4 and 5). Total phosphorus and total nitrogen concentrations in streams generally differ from one aggregated region to another in terms of their median values and distribution of values (Figures 4 and 5). The regions with the highest total phosphorus concentrations, the fertile irrigated cropland valleys in the west (Region I), and Regions V and VI (Figure 4), subsume the areas of highest phosphorus concentrations on the single-purpose phosphorus map (Figure 2). These are also the major regions of the United States within which the percentage of land in cropland and the amount of commercial fertilization is the highest (Figures 6 and 7). Regions to the east show substantially lower concentrations of total phosphorus in streams, with the lowest values observed in streams in the north (Region VIII) followed by streams in the Central and Eastern Forested Uplands (Region XI). Regions of the west generally exhibit higher total phosphorus concentrations than those in the east.

The aggregated ecoregions with the highest concentrations of total nitrogen, Regions V and VI (Figure 5), correspond to those areas showing the highest nitrogen concentrations on the single-purpose nitrogen map (Figure 3). Region VI encompasses virtually all of the areas mapped as > 5.00 mg/l on the single-purpose nitrogen map and consists chiefly of these and some areas represented by the next two lower nitrogen classes. Region V, however, encompasses a mosaic of values primarily ranging from < 1.4 to 3.0 mg/l, and its slightly lower and more heterogeneous nature is reflected in the distribution of values displayed on the aggregated ecoregion map (Figure 5). Region V, like Region VI, is in mostly cropland agriculture and is heavily fertilized. However, Region V is less humid and has a different combination of principle crops (wheat, sorghum, and corn, rather than corn and soybeans). Streams in regions to the east show lower concentrations of total nitrogen but concentrations are higher and more diverse than in streams in the Western Forested Mountains (Region II).

Several aggregated ecoregions do not contain sufficient NES non-point source sampling sites from which to extrapolate reliable distributions. In these areas, mosaics from the single-purpose regionalization (Omernik, 1977) and carefully screened data from other sources could be used to make qualified estimates.

DEVELOPMENT OF REGIONAL CRITERIA

A necessary component of the regional criteria development process is the ability to characterize the range of nutrient conditions in minimally impacted streams that drain regionally representative watersheds. These conditions can serve as a reference for what could be expected in the region where minimal impact is present. We have defined and described regions with respect to relative homogeneity in the geographic factors which affect nutrient status and processing on a national scale (Figure 1). We have further indicated that these regions correspond with patterns in total phosphorus and total nitrogen values sampled across the country as part of the NES non-point source project. Although the NES data are dated and may not consist of the most regionally representative nor least impacted sites, they were selected and sampled in a consistent manner nationwide. Using this *albeit* imperfect data set, we have shown that total phosphorus and total nitrogen concentration levels in streams and the distributions of levels vary from one part of the country to another, and these differences generally coincide with the regional boundaries (Figures 4 and 5).

Aggregated Level III Ecoregions still incorporate too much variability and represent too coarse a scale for setting nutrient criteria using this type of survey data alone. A fuller characterization of the variability and representativeness of nutrient conditions (both concentrations and responses), and factors impacting them, is needed for refining criteria. Such information can be used for developing regional reference expectations and providing a context for complementary approaches and more site-specific study results. Representative data about the type, frequency, and degree of impacts in the region also aid in identifying specific water quality needs and goals.

A sampling strategy that rigorously addresses both the issues of sample representativeness and impact in collecting data from streams and lakes over large regions has been developed and executed by the U. S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP). EMAP employs a statistical survey design and each site sampled is representative of a portion of the 'target population' of aquatic resources in a region from which the sample is drawn (Herlihy *et al.*, 2001; Larsen and Christie, 1993; Larsen *et al.*, 1994, 1995). Sample data can be extrapolated to the entire target population through statistical inference to derive a quantitative measure of representativeness.

EMAP's aim is to describe the distribution of conditions (e.g., nutrient concentrations) found across the wide range of aquatic ecosystems in a region. The representative distributions can then be examined for correspondence with information about disturbances by various human uses of the landscape (e.g., point sources in the watersheds, certain agricultural land uses, mining, etc.) to characterize types, distributions and degrees of impact within a region. 'Filtering out' sample sites known to be disturbed by identified uses (rather than implied by degraded response) produces a subset of sites representing regional reference conditions.

Within-region variability may also be addressed by further dividing the regions into smaller subregions. Ecological regions can portray ecosystem patterns at a variety of scales (Bailey, 1995; Omernik, 1995a). For example, U.S. EPA Level III Ecoregions have been subdivided into Level IV Ecoregions circumscribing relatively homogeneous landscape areas at a finer scale (Griffith *et al.*, 1994a, 1994b; Woods *et al.*, 1996, 1998; Clarke and Bryce, 1997; Bryce *et al.*, 1998; and Pater *et al.*, 1998). Bryce *et al.* (1999) have shown how these Level IV subdivisions in the Appalachian Highlands account for physical differences in the landscape, some of which result in different types, and intensity of human use and disturbance.

Data collected from filtered EMAP-type reference sites describes the reference distribution of each region. However, for some areas it may be necessary to supplement data representing regional reference conditions with additional individually selected sites, particularly in regions where minimally impacted sites are not represented with great frequency in the statistical sample. For example, confined cattle and hog feeding operations and poultry operations are so numerous throughout much of the Western Corn Belt Plains (central part of Region VI, Figure 1) and Central Great Plains (eastern part of Region V, Figure 1) that locating watersheds in these regions that are free of these impacts would require considerable additional filtering of mapped information followed by aerial reconnaissance. Hughes *et al.* (1986), Gallant *et al.* (1989), Hughes (1995), and Omernik (1995a) have outlined a general procedure for selecting regional reference sites that could be used to supplement the reference sites from the survey design.

Appropriately characterizing the reference conditions within a region clarifies the process of setting criteria by identifying a range of values that can be expected in the best (i.e., least impacted) situations. Following a similar approach to the one EMAP used for biocriteria, a critical threshold can be selected from the reference distribution (e.g., the 75th percentile) and used as a criterion. Values greater than the criterion have a high probability of falling outside the reference distribution; that is, values exceeding the criterion are greater than values typically found in the least disturbed sites in the region. Because a statistical survey design has been employed, it is possible to estimate what percentage of the target population falls above the established criterion; and, if variability or deviation from reference conditions is examined for spatial pattern, it may reveal association with identifiable landscape characteristics at a finer scale. This additional information may be useful for focusing further research on how to improve nutrient status within the region. Improvement can be quantitatively assessed against regional benchmarks; and, because of the general-purpose nature of the ecoregionalization, consistently sampled data from regional reference sites can be readily adapted for use

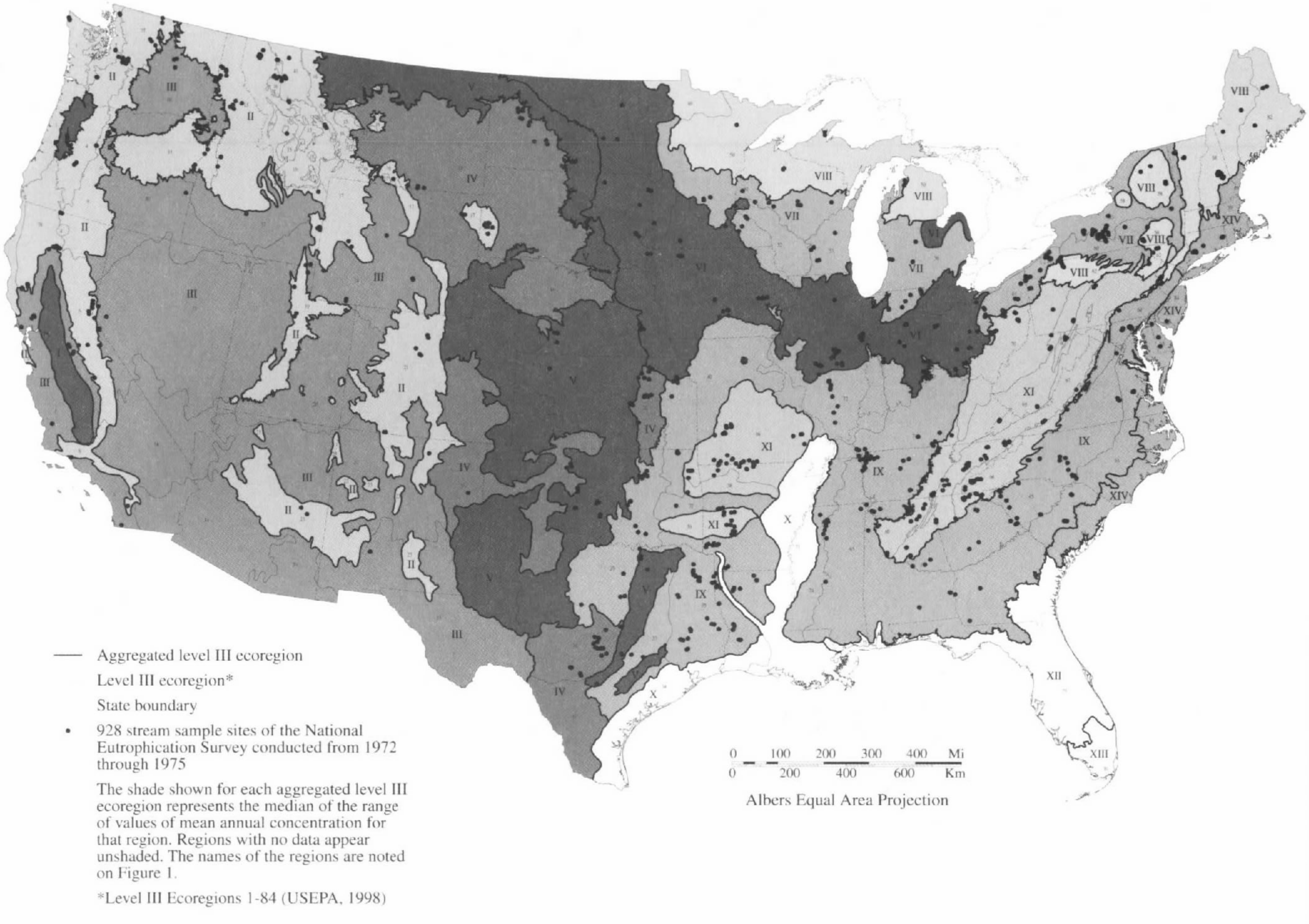

Figure 4. Total Phosphorus Concentrations in Streams in Aggregated Level III Ecoregions. Regions are shaded with the grey tone representing the median value of mean annual total phosphorus concentration for that region, based on 928 total sampling sites. Histograms (below) show the distribution of mean annual concentrations of total phosphorus occurring in each region based on the sampling sites in that region.

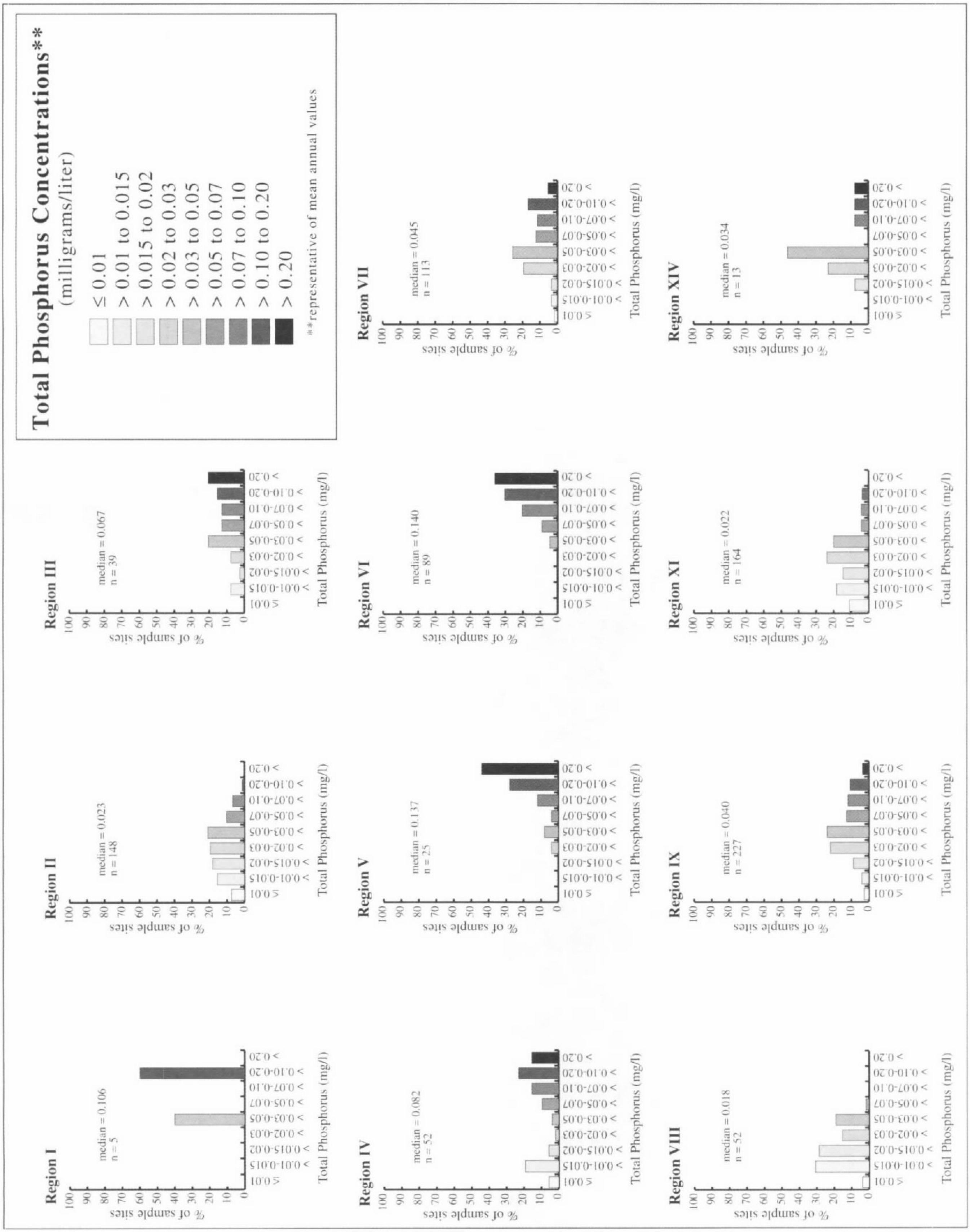

Figure 4. Total Phosphorus Concentrations in Streams in Aggregated Level III Ecoregions (cont'd.)

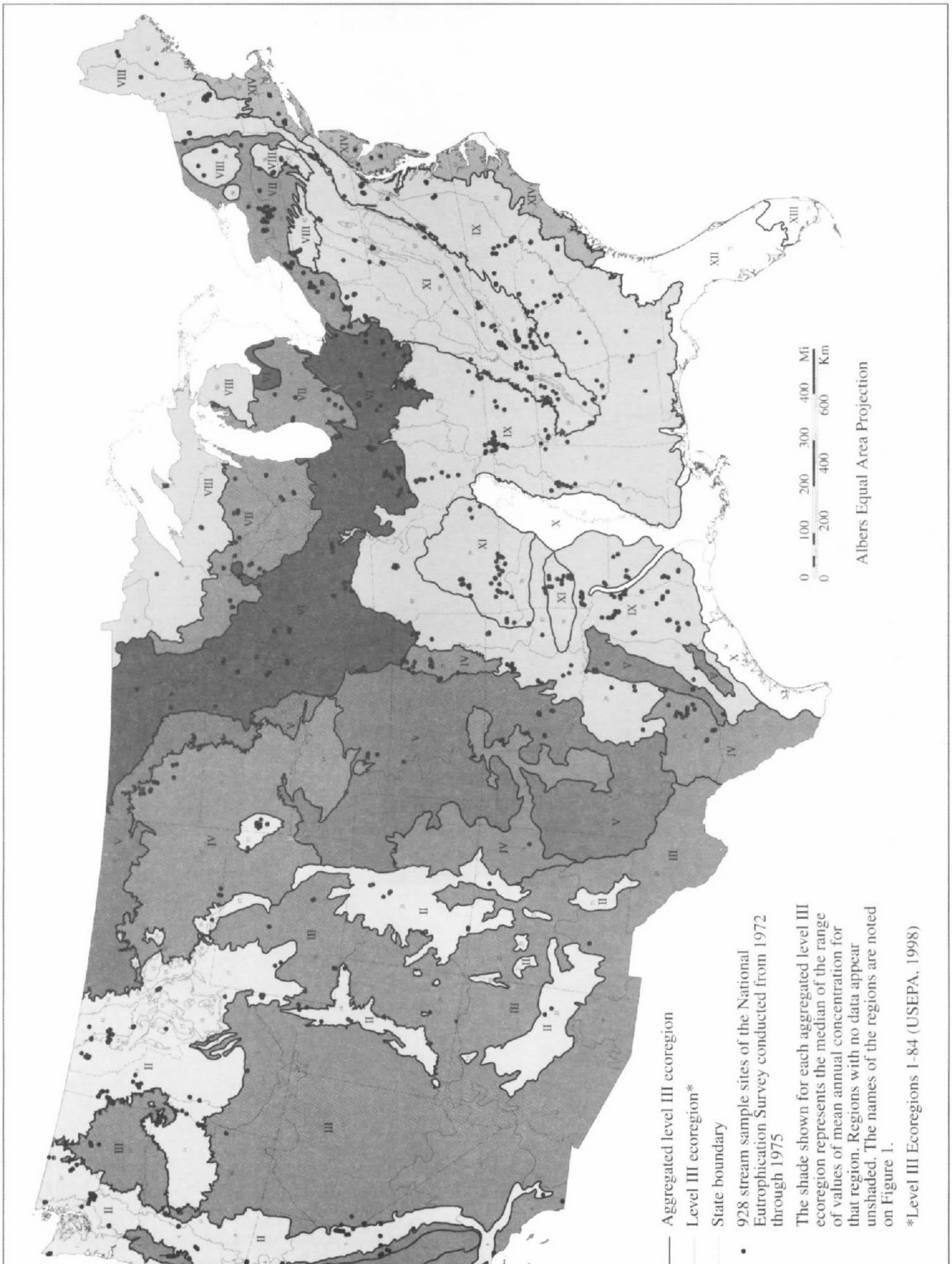

Figure 5. Total Nitrogen Concentrations in Streams in Aggregated Level III Ecoregions. Regions are shaded with the grey tone representing the median value of mean annual total nitrogen concentration for that region, based on 928 total sampling sites. Histograms (below) show the distribution of mean annual concentrations of total nitrogen occurring in each region based on the sampling sites in that region.

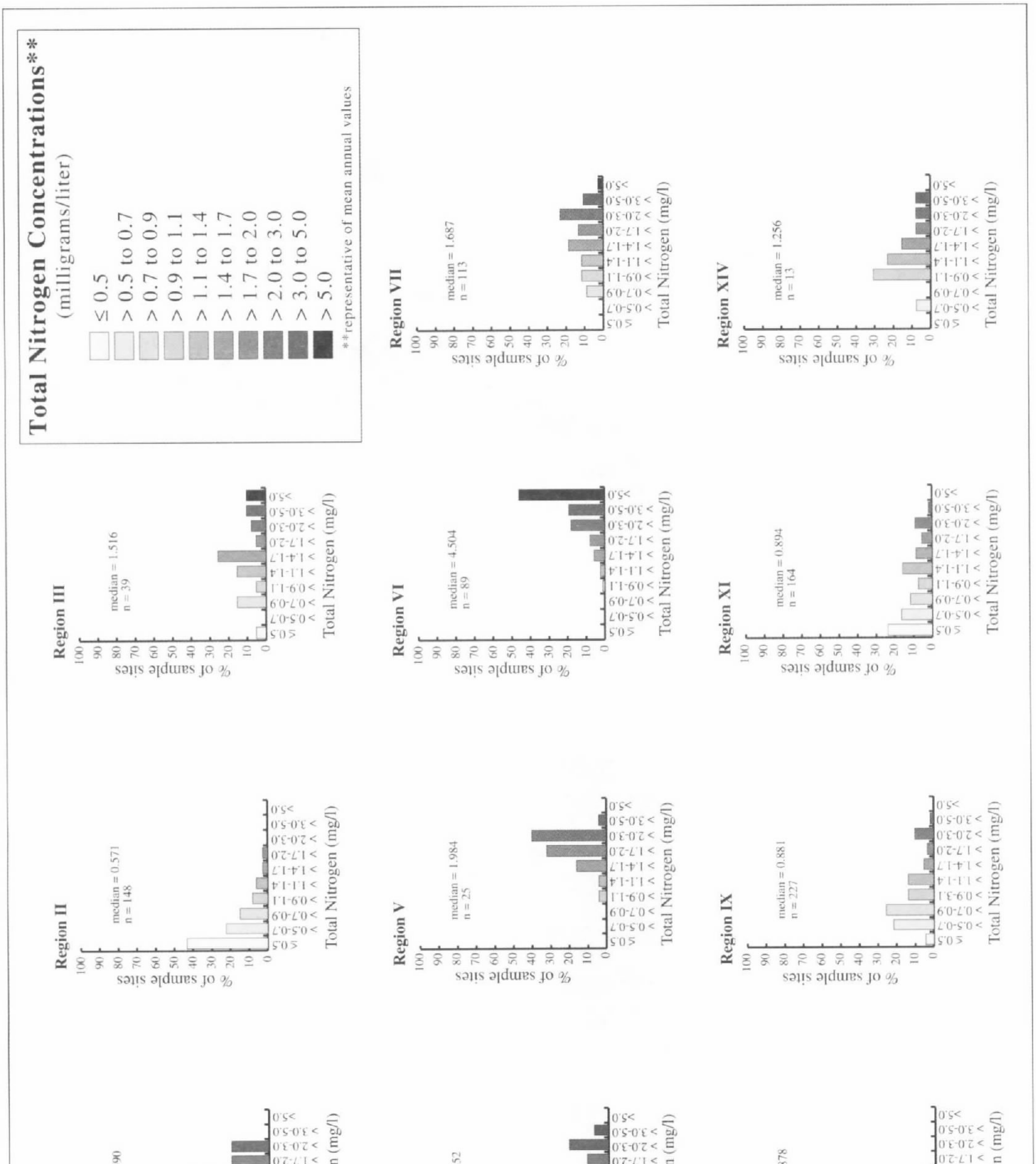

Figure 5. Total Nitrogen Concentrations in Streams in Aggregated Level III Ecoregions (cont'd.).

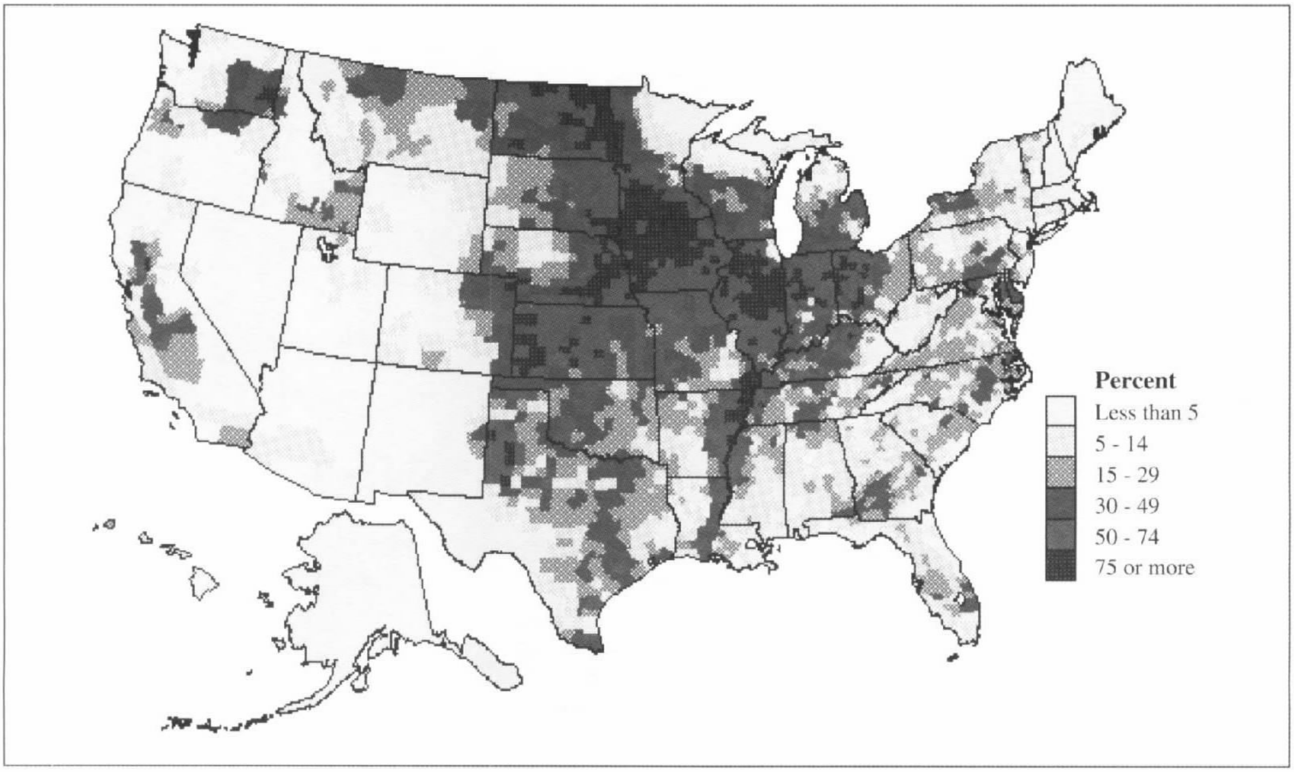

Figure 6. Total Cropland as Percent of Land Area: 1997 (from 1997 Agricultural Atlas of the United States, USDA, 1997).

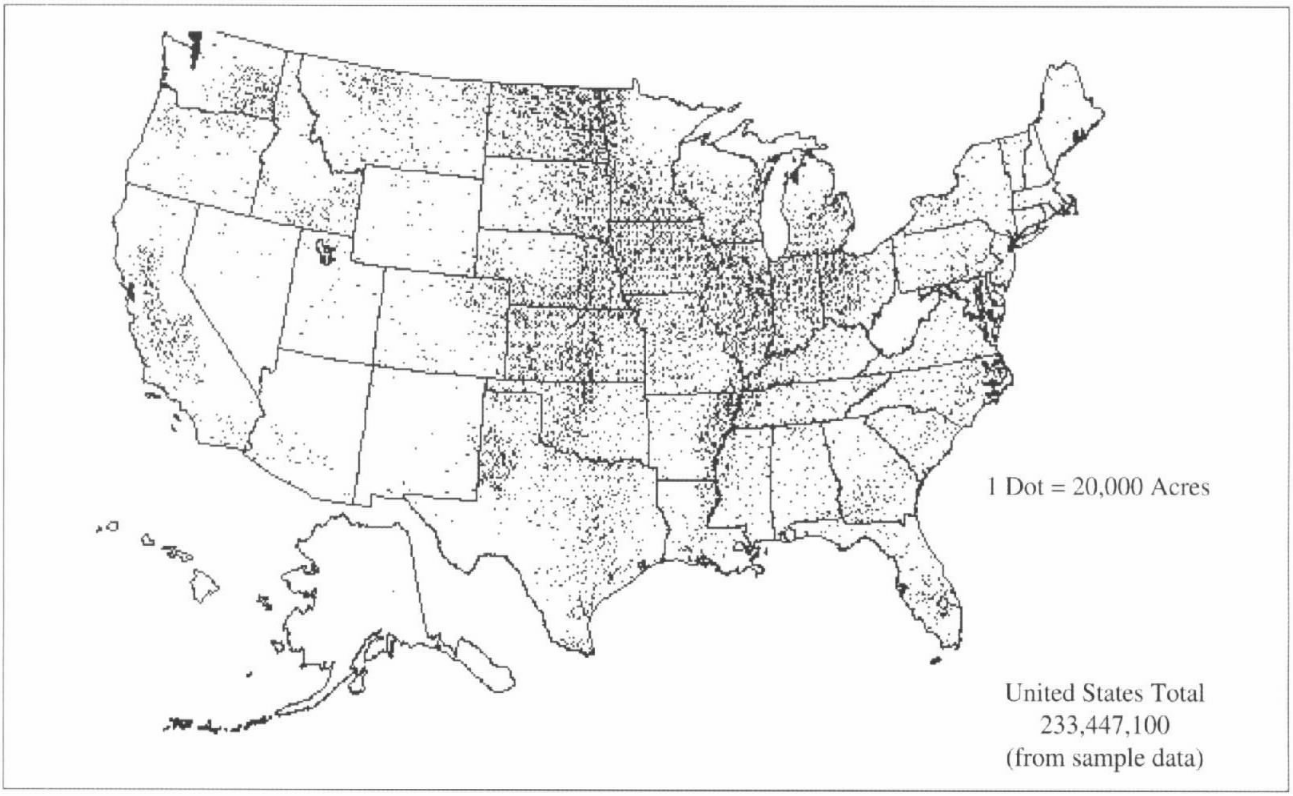

Figure 7. Acres on Which Commercial Fertilizer Was Used: 1997 (from 1997 Agricultural Atlas of the United States, USDA, 1997).

in assessment and trend analysis for a variety of water resource issues on a national scale.

USE OF EXTANT MONITORING DATA

In the absence of sampling efforts of the type presented, it is often suggested that water quality data, collected and stored as part of routine monitoring and required reporting, be grouped by region and used to establish criteria. The weakness in this approach lies in the fact that there is no explicit rationale for extrapolating from the available data to characterize the total population of streams in a region; sampling has not been exhaustive, random, regionally representative, or spatially consistent. Often, sampling by regulatory agencies is event-related and limited in duration or constituents measured. High levels of effort and funding are centered on sampling, analyzing, and electronically storing nutrient data from streams across the country annually. While most monitoring sites and methodologies are carefully chosen and accurately expedited they are often not consistent with one another (Mayio and Grubbs, 1993). When extant data are retrieved and pooled for analysis the inconsistencies can cause problems in defining what the pooled sample data represent. Minor differences in site selection criteria, sampling frequency, and methodology between data sets call into question conclusions made by pooling the data; the "samples" may no longer be accurate if the target population is not the same.

Most sites, where stream nutrient concentrations have been monitored, are not at all regionally representative, albeit often for valid reasons. Publicly important streams and rivers, often large in size and drainage area and in relatively close proximity to urban areas, are most commonly targeted for intense or routine monitoring and reporting. The difficulty with using data from streams and rivers with large watersheds to represent ambient conditions is that they often cover differing types of landscapes and may include urban/industrial and diverse nonpoint sources of pollution. A sample from such a stream or river may "integrate" the sum of polluting impacts in the associated watershed, but it should not be construed to represent the quality of all component parts of the entire watershed. In order for a stream sample to be truly representative of the land it drains, the size of the watershed from which it is drawn must be consistent with the scale of spatial homogeneity in the characteristics that affect water quality. If diverse types of land and pollutant impacts are integrated, the actual spatial association of the water quality with the land that it drains is masked (Omernik and Powers, 1983). Atypically pristine, endangered or noticeably problematic streams and rivers, and those with an extensive historical legacy are also often understandably included in monitoring programs. Pooling these different types of data, without express information about the sampling rationale, degree of impact, and types of landscape in the watershed does not result in an appropriate basis for developing realistically attainable and protective nutrient criteria.

Attempts have been made to address these issues and provide consistent national sampling coverage in recent years (e.g., Clark *et al.,* 2000). Unfortunately, to date, the number of sites included has never approached the extent and density of coverage, nor the degree of regional representativeness included in the NES. The relatively small sample sizes and particular design objectives limit the effectiveness of extrapolating the results of these studies to streams throughout the nation. The problem can be compounded if inappropriate units, such as drainage basins in which the sampling sites lie, are used to extrapolate general nutrient levels without regard to regional differences in the combination of landscape factors influencing the nutrient levels (Griffith *et al.,* 1999).

It seems clear that a consistently sampled set of regional reference data, selected with an explicit sampling design, such as that employed by EMAP, would be the most desirable foundation from which to develop regional nutrient criteria. At the very least, extant data from reporting agencies that are used should be screened by individuals knowledgeable about the water resources in the area. Any data pooled for use must be validated as regionally representative, minimally impacted, and contain information about the watershed. There should also be a minimum of difference in sampling and analysis frequency and methodology and it should be tabulated to document the degree of consistency in the pooled data.

CASE STUDY EXAMPLE

We use data from an EMAP survey of small streams in the Mid-Atlantic Highlands to illustrate how these data might be used to develop nutrient criteria. Sampling occurred in late spring (May to June) 1993 to 1996, during spring baseflow (i.e., after snowmelt and before leaf-out) and storms were explicitly avoided. The target population consisted of all small (98 percent of watersheds were less than 100 km^2 in size) streams in the upland portions of the Mid-Atlantic (Herlihy *et al.,* 2001). The extrapolated results for the stream population in a large portion of Region XI (i.e., all of Region XI north of North

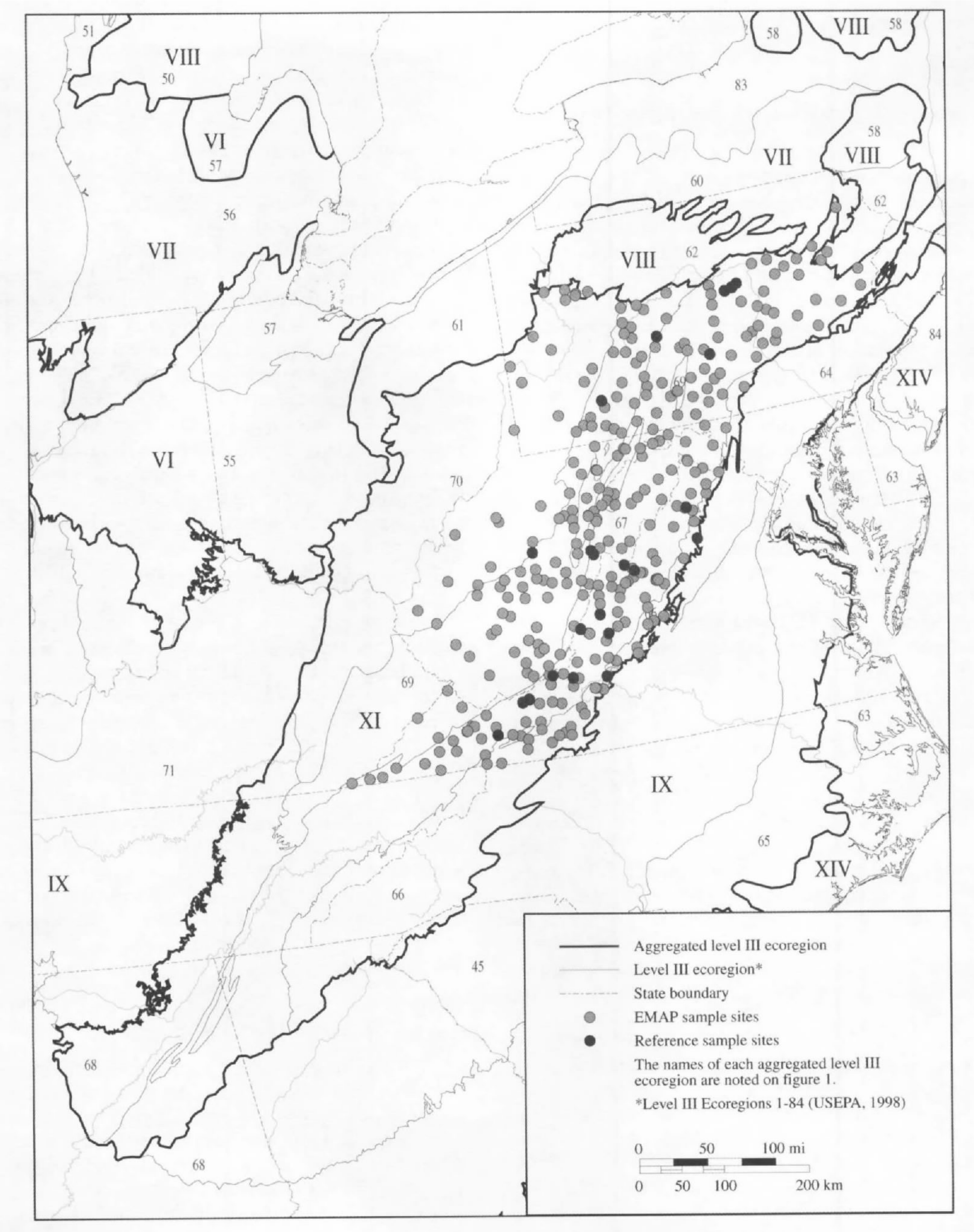

Figure 8. EMAP and Reference Sites in Region XI of Aggregated Level III Ecoregions.

Carolina and Tennessee, excluding Ohio and Kentucky, Figure 8) are shown in Figure 9. For the stream population as a whole, total nitrogen concentrations ranged from near 0 to over 3,000 µg/L (median = 480 µg/L), while total phosphorus concentrations ranged from near 0 to over 100 µg/L (median = 18 µg/L). Other variables relevant to nutrient enrichment, such as algal biomass and composition, chlorophyll concentration, and dissolved oxygen concentration could be characterized similarly (Dodds and Welch, 2000).

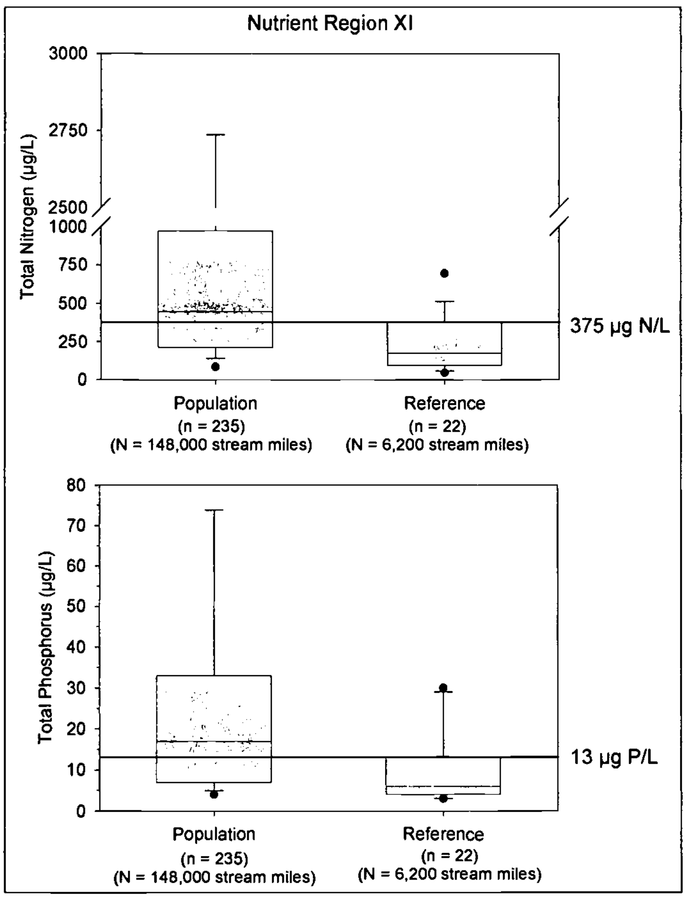

Figure 9. Box and Whisker Plots of Total Nitrogen and Total Phosphorus Distributions for the Population of Small Streams in the Studied Portion of Region XI (left box) and a Smaller Set of Reference Sites (right box). Height of boxes show 25th to 75th percentile values in each distribution; error bars show 5th and 95th percentiles. Solid horizontal lines indicate the 75th percentile values for the reference distributions as examples of nutrient criteria values.

Also shown in Figure 9 are the results of 'filtering' the EMAP data to exclude sites with known (and quantified) impacts related to nutrient enrichment. For this exercise, we have excluded watersheds with more than 5 percent agricultural landuse, more than 1 percent urban landuse, all watersheds with point sources, as well as all streams with riparian livestock grazing (based on Rapid Bioassessment Protocol values > 18; Plafkin *et al.,* 1989), elevated rates of sedimentation (RBP score > 15), mine drainage, or acidification problems (sulfate > 400 µeq/L or ANC < 50 µeq/L). This filtering results in a small dataset of sites considered to be in reference condition (the least impacted of sites available in 1993 to 1996). Because the number of least-impacted sites sampled as part of EMAP's probability survey was so small (n = 17), we have supplemented their information from five hand-picked reference sites that pass the same set of filters as the EMAP sites. Data from a total of 22 reference sites in Region XI were used to describe reference distributions for both total nitrogen and total phosphorus in Figure 9. The reference distributions range from near 0 to 750 µg/L (total nitrogen) and near 0 to 30 µg/L (total phosphorus).

The reference distributions illustrated in Figure 9 may be used to set nutrient criteria. In several biocriteria exercises, EMAP has used the 75th percentile of the reference distribution as a criterion discriminating between degraded sites and those close to reference condition. In the case of Region XI, EMAP reference distributions, including five hand-picked sites, suggest a criterion of 375 µg/L for total nitrogen and 13 µg/L for total phosphorus. An additional advantage of using EMAP-type data in this criteria development is that we can then estimate the magnitude of the nutrient enrichment problem in the region by calculating the proportion of streams that have nutrient concentrations exceeding the criteria. In the EMAP case study portion of Region XI, 57 percent of the stream length of first through third order streams represented on 1:100,000 USGS maps (or 84,000 stream miles) exceed the example nitrogen criterion of 375 µg/L; 58 percent of the stream length in Region XI (or 86,000 stream miles) exceed the example phosphorus criterion of 13 µg/L.

A key step in this nutrient criteria development exercise is the setting of thresholds for identifying reference sites. Our choices in this example (e.g., excluding watersheds with more than 5 percent of agricultural landuse or 1 percent of urban landuse, etc.) may be different than those required in other regions and may seem unacceptably restrictive to some managers in the Region. Our goal here is to demonstrate that once these thresholds are agreed upon, the availability of data like those collected in EMAP allow managers to make informed decisions about nutrient criteria based on consistently-sampled data from across a nutrient region using a verifiable process of reference site selection and the description of reference nutrient distributions.

SUMMARY

The method we have presented and demonstrated for developing regional nutrient criteria combines the concepts of natural regional variation in nutrient concentrations in streams with a rigorous sampling design to characterize within-region variability. We have used broad regions defined by landscape characteristics within which nutrient concentrations in streams are more similar than when compared with adjacent areas. This framework of Aggregated Level III Ecoregions effectively describes variation in total phosphorus and total nitrogen concentrations in streams using an extant national data set. The sampling strategy in the case-study example was designed so that existing variability within a region can be representatively characterized using statistical inference. The result is a statistically sound picture of the range and frequency of ambient conditions within the region. It also enables the characterization of representative types and extents of impacts to streams within the region.

Developing appropriate nutrient criteria requires an understanding of the regional potentials for nutrient concentrations under conditions of minimal impact. Using a representative sampling design, such as that used in EMAP, and "filtering" out sites known to be disturbed by various human uses of the landscape produces a set of representative regional reference sites. Sampling these reference sites for parameters such as total phosphorus and total nitrogen then yields a distribution of reference conditions for the region which can be used as a measure of regional potentials for the purposes of assessing nutrient status and developing criteria. Acknowledging and defining natural regional differences in nutrient levels and sampling consistently nationwide, using a representative sampling design, and setting criteria relative to ranges of least disturbed, regionally representative reference conditions helps to clarify water quality needs and realistically attainable goals for protection and improvement of nutrient status in rivers and streams throughout the country.

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