fish habitat
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A Conceptual Framework for Assessing Impacts of Roads on Aquatic Biota

ABSTRACT

Roads are pervasive in modern landscapes and adversely affect many aquatic ecosystems. Conventional environmental assessments of roads focus on construction impacts but ignore subsequent impacts. A comprehensive framework for considering all impacts of roads would enable scientists and managers to develop assessment tools that more accurately inform stakeholders and policymakers about the biological consequences of road building. We developed a two-dimensional framework to organize impacts of roads on aquatic biota. One dimension recognizes three phases of road development, each with distinctive ranges of spatial and temporal scales. The second dimension recognizes five classes of environmental impacts associated with road development. The framework is useful in evaluating the completeness of assessments and in identifying gaps in scientific knowledge. We applied the framework to a draft environmental impact statement (DEIS) for a proposed interstate highway to illustrate which road impacts are typically ignored in such assessments and how our framework can be used to enhance assessments. The DEIS largely omitted long-term, large-scale impacts from consideration. Such omissions preclude fair assessments of the desirability of roads and bias landscape-management decisions in favor of road building. Additional scientific input and changes in agency ideology are needed to reduce bias in assessments of the biological impacts of roads.

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Introduction

Roads are pervasive features of modern landscapes and have major impacts on air, land, and water quality. The United States has >6.2 million km of public roads used by >200 million vehicles (National Research Council [NRC]1997). Road corridors (road plus maintained parallel strips) cover 1% of the United States (NRC 1997) but their direct environmental impacts extend to 20% of the land surface (Forman 2000). Ecological effects extend 100 to 1,000 m (average of 300 m) on each side of four-lane roads (Forman and Deblinger 2000). These effects, which stem from both construction and use, vary considerably in type and degree among regions and among particular roads (Forman and Alexander 1998; Trombulak and Frissell 2000).

Roads strongly affect the composition and operation of surrounding ecosystems. Natural habitats such as forests, wetlands, and streams are commonly disfigured, fragmented, or contaminated because of roads (Forman and Deblinger 2000; Trombulak and Frissell 2000; Paul and Meyer 2001). Effects on biotic populations and communities can be dramatic and extensive. Major direct effects on wild animals include modified behavior, impaired movement, and mortality from collisions with vehicles (Trombulak and Frissell 2000). Forman and Deblinger (2000) estimated that effects on large mammals, birds, and amphibians typically extended to 300 m on both sides of a four-lane highway in Massachusetts. In addition, key ecological processes, including the transport of water and sediment and the dispersal of organisms, are modified by roads (Forman and Deblinger 2000; Trombulak and Frissell 2000).

Despite the increasing prominence of roads across most landscapes, their impacts on aquatic biota are not well documented. Intuitively, effects on water quality (e.g., via toxic spills and runoff), habitat quality (via sediment loading and channel modification), and habitat connectivity (via barriers to movement) may often be severe. Roads may constrain fish distribution and abundance or impair ecosystem health. Many road crossings over streams constrain movements by small fishes (Warren and Pardew 1998). Such movements are essential for individuals to complete their life cycles and for metapopulations to remain viable (Schlosser and Angermeier 1995). To the extent that roads contribute to fine-sediment loading in waterways, they are serious threats to aquatic biota (Waters 1995; Wood and Armitage 1997). Roads are known to endanger 94 species across many taxa in the United States (Czech et al. 2000) and probably contribute to local extirpation and regional endangerment of many fishes. Managers of fishes and fisheries should be keenly interested in the environmental impacts of roads, especially proposed roads.

Assessing environmental impacts of human activities on public resources is an iterative collaboration among the public, resource managers, and scientists. Roles of the public include articulating the impacts of concern (e.g., through legislation) and holding managers accountable for assessing those impacts. It is incumbent on managers (often agencies) to implement specific policies and protocols that address societal concerns. This process includes seeking out and applying the best available scientific knowledge and methods to aid in assessing impacts. Implicit in their contract with society, scientists are obligated to develop concepts and methods relevant to societal concerns and to make them available for managers to apply. All three parties must participate actively for environmental impact assessments to serve as intended in the decision-making process.

Current assessments of environmental impacts of roads are inadequate to ensure informed decision-making (Atkinson and Cairns 1992; TRB 2002). Transportation policy in the United States is attentive to stream-channel geometry and soil erosion during road construction but largely ignores many other common consequences of roads for habitat quality, ecological processes, and biota (NRC 1997). In particular, the extensive and serious impacts of post-construction maintenance and of subsequent urban development along roads typically are excluded from agency decisions about building new roads. Thus, direct, localized, or acute impacts are emphasized whereas indirect, dispersed, or chronic impacts are neglected. This bias reflects the typical application of the National Environmental Policy Act (NEPA), wherein attention is narrowly focused on species rather than ecosystems, on site-specific scale rather than regional scale, and on short-term rather than long-term environmental impacts (Southerland 1995), despite the fact that the NEPA requires all reasonably foreseeable impacts to be assessed (Council on Environmental Quality [CEQ] 1993). The mismatch between scales of assessment and impact is especially problematic for roads because there is compelling scientific evidence that long-term, large-scale impacts are the greatest threats to biota. The problem of incomplete assessments of road impacts has been apparent throughout the 14 years that one of us (PLA) has consulted with the Virginia Department of Transportation (VDOT) and the U.S. Fish and Wildlife Service regarding effects of roads on imperiled fishes in Virginia.

This problem of incomplete assessments became more obvious and captured our attention when we recently reviewed VDOT's draft environmental impact statement (DEIS; VDOT 2000) for the proposed construction of a new interstate highway (I-73) through Virginia. We judged the DEIS to be inadequate in its assessment of impacts on the federally endangered Roanoke logperch (*Percina rex*) as well as more general impacts on ecosystem integrity (Wheeler et al. 2003). We suspect that such inadequacy is typical of assessments of road impacts. Our main concern is that omission of major impacts from official environmental assessments like this one precludes a fair evaluation of the actual costs of a new road, biases landscape-management decisions toward more road-building, and thus results in multiple failures to meet goals of the Endangered Species Act and the Clean Water Act.

Aquatic scientists as well as resource management agencies are culpable for inadequate assessments of road impacts. The lack of appropriate assessment tools contributes to the inadequacy of environmental assessments of roads (TRB 2002). The CEQ (1997) has informally outlined eight general principles and many steps useful in analyses of cumulative effects of projects such as roads, but legally binding requirements and an ecological framework for organizing such analyses are lacking. The DEIS for I-73 was based on a very narrow conception of what constitutes environmental impact and of the spatiotemporal frames in which impact is assessed. Perhaps that conception would have been broader if ecologists had provided a straightforward framework to facilitate a more comprehensive assessment of road impacts on aquatic environments. For example, a more complete view might recognize that impacts: (a) occur over multiple spatial and temporal scales, which reflect the overall process of road development, and (b) can be stratified into physical, chemical, and biological categories, which differ in their relative importance at various points in the road development process. A framework incorporating these features would provide a basis for gathering a richer array of relevant information and would enable managers to readily assess the completeness of their impact assessments. Because no such framework has been developed, many impacts, especially long-term and large-scale impacts, can be easily overlooked by managers and the public.

Our goal in this article is to present a comprehensive conceptual framework for considering impacts of roads on aquatic biota. First, we introduce a simple two-dimensional matrix of impact categories to organize and evaluate the myriad aquatic impacts associated with roads. The matrix columns reflect three major phases of road development, each of which generates impacts at a distinctive range of spatiotemporal scales. The matrix rows reflect five major classes of physical, chemical, and biological impacts associated with each development phase. Based on our review of the scientific literature, we rank each of the 15 cells in the matrix (three phases x five classes) with respect to the severity of associated impacts. Next, we draw from our experience with the I-73 DEIS to illustrate general shortcomings of conventional assessments of road impacts in the context of our framework. Finally, we discuss how our framework might be used to redress some of these shortcomings. This discussion is illustrative rather than prescriptive; developing a detailed protocol or methodology to evaluate impacts of roads is beyond the scope of this article. We do not thoroughly review road impacts (see Forman and Alexander 1998, Trombulak and Frissell 2000, and Spellerberg 2002 for previous reviews), but do offer examples from the United States to illustrate types of impacts represented in the framework. Although we emphasize paved roads, we suspect that the issues we address and the conclusions we draw also apply to most unpaved roads. We expect the framework to be most useful in identifying gaps in environmental impact assessments as well as gaps in scientific understanding of impacts. Although we focus on impacts to fishes, the framework is designed to apply to all aquatic biota.

Matrix Columns: Phases of Road Development

A crucial step in assessing biotic impacts of roads is recognizing that road development is a long-term process and that roads affect environmental conditions over a broad range of spatial and temporal scales. Our review of the literature suggests three main phases of road development, each with a distinctive but cumulative suite of environmental impacts road construction, road presence, and urbanization. Each phase features a distinctive spatial and temporal frame over which aquatic biota are affected (Figure 1), although individual roads vary widely in the details of particular impacts and spatiotemporal frames. Below, we provide a brief overview of each phase and describe general patterns of environmental impacts.

Phase 1: Road Construction

Road construction is characterized by relatively small temporal and spatial frames (days to years, hundreds to hundreds of thousands of square meters, respectively; Figure 1). Environmental impacts of construction largely stem from direct, localized, and acute alterations of physical conditions, including addition of fine-sediments, channelization of streams, and disruption of groundwater flow. Soil erosion associated with construction diminishes rapidly as exposed areas are revegetated and stabilized (Ketcheson and Megahan 1996).

Construction activities can affect aquatic biota directly and indirectly. Operating machinery in shallow-water habitats can destroy nests of animals or crush sedentary individuals (e.g., mollusks). The most serious and common biotic impacts of road construction stem from the indirect effects of elevated levels of fine sediment. Excessive fine sediment interferes with breathing, feeding, reproducing, and food production for many aquatic animals (Waters 1995; Wood and Armitage 1997). Consequently, sediments generated during construction can substantially depress certain populations of invertebrates (e.g., Cline et al. 1982) and fishes (e.g., Whitney and Bailey 1959), thereby producing communities dominated by silt-tolerant species. Reducing the impact of fine sediment generated by road construction is the principal focus of mitigation measures employed by transportation agencies during construction projects (Southerland 1995). For example, the VDOT regularly imposes restrictions on the seasons during which construction can occur and authorizes translocation of sedentary animals from construction sites. However, even though effects of construction-generated sediment may extend several km beyond the construction site and persist for years after construction, large-scale and long-term effects rarely are assessed or studied (but see Wellman et al. 2000).

Phase 2: Road Presence

We view roads passing within 1 km of a water body as being ecologically "present." Of particular concern are roads that cross or have a direct hydrological connection to a water body. Road presence affects aquatic systems over similar spatial frames but larger temporal frames (decades to centuries), compared to road construction (Figure 1). The longer timeframes reflect the fact that few roads are ever restored to natural habitat. Physical impacts of road presence include intermittently recurring effects of maintenance construction (short-term effects), as well as the long-term potential for alterations in stream hydrology and geomorphology. Hydrological effects of roads at the scale of whole watersheds are scarcely studied. However, studies in the Pacific Northwest show that roads increase the magnitude and frequency of floods and debris flows, and ultimately may increase the extent of stream networks (Jones et al. 2000). Thus, many roads may be major sources of sediment throughout their existence.

In addition to physical effects of road presence, there is a suite of acute and chronic chemical effects associated with maintenance activities and vehicular traffic. Deicing salt is commonly applied to roads and eventually enters waterways, where it can dramatically alter ion concentrations (Koryak et al. 2001) or add heavy metals (Oberts 1986). During runoff events, traffic residues produce a contaminant "soup" of metals, oil, and grease, some of which accumulates in stream sediments (e.g., Van Hassel et al. 1980) or disperses into groundwater (e.g., Van Bohemen and Janssen van de Laak 2003). Sublethal effects (e.g., on behavior, growth, or reproduction) of such contaminants seem likely but are largely unknown. Toxic spills are inevitable, potentially catastrophic impacts of large roads. Most hazardous materials, of nearly all types, are transported by truck in the United States

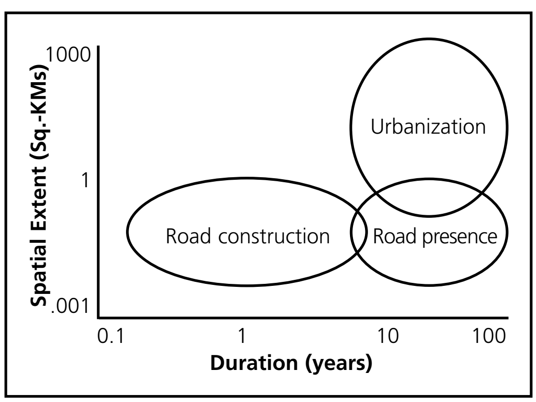

Figure 1. Temporal and spatial extent of biotic impacts due to the three main phases of road development. Road construction occurs over relatively small time and space scales, while urbanization occurs over much larger scales. Note logarithmic scaling of axes.

(Atkinson and Cairns 1992). Over 10,000 accidental releases of hazardous material occur annually on highways in the United States (USEPA 1996); many of these materials eventually reach waterways and devastate local biota.

The biological consequences of road presence are poorly documented. Several studies have shown elevated concentrations of contaminants in aquatic animals near roads (Van Hassel et al. 1980; Stemberger and Chen 1998) but effects on populations and communities are largely unexamined. Roads enhance human access to water bodies, thereby increasing the spread of non-native fishes (e.g., via authorized and unauthorized stocking), mollusks, and pathogens (Trombulak and Frissell 2000). Many roads fragment aquatic habitats at culverts, which can be significant barriers to fish movement (Warren and Pardew 1998; Wellman et al. 2000). Although poorly documented, such barriers could impair recolonization after local extinctions or reduce gene flow. The lack of extensive roadless areas in the United States makes scientific study of road impacts on biota very difficult. Nevertheless, we hypothesize that road density is correlated with increasing predominance of species tolerant to silt, metals, petroleum products, and salt. In areas with frequent toxic spills, predominant species must also be good colonizers. Unfortunately, none of these biological effects of road presence was discussed in the DEIS for I-73.

Phase 3: Urbanization

Urbanization, the final phase of road development, affects aquatic systems across large spatial and temporal frames (up to thousands of square kilometers and centuries respectively; Figure 1). Urbanization, the general transformation from rural or agricultural to residential, commercial, or industrial land use, has accelerated in recent decades and is a major contributor to contamination of surface and ground water and to modification of hydrology in the United States (USEPA 2000). Over 130,000 km of U.S. streams and rivers are impaired by urbanization, making it a leading cause of water-body impairment (USEPA 2000). Moreover, urbanization endangers at least 275 species in the United States, where it is the second-leading cause (next to non-native species) of species imperilment (Czech et al. 2000).

The relation between road building and urbanization is noteworthy in the context of road impacts on aquatic biota because it is typically ignored in official impact assessments. This omission is puzzling in NEPA-driven assessments (required for all federally funded projects), given that highway projects are one the main types of federal action that cause urban sprawl (Southerland 2004). Effects of urbanization, which may lag behind road construction for decades, are generally excluded from impact assessments despite their severe, well-documented consequences for biota. More explicit recognition of the relation between road building and urbanization and of the effects of urbanization on aquatic biota is crucial to comprehensive assessment of road impacts. Roads, especially highways, are necessary but not sufficient for economic growth (TRB 1995). Although specific effects of new highways on land development patterns are poorly understood (TRB 2002), roads unquestionably facilitate urbanization, including more road building, through their strong influence on the distribution of development (TRB 1995). Although roads are not the sole determinants of economic growth, many highways are built for the express purpose of promoting it. For example, the U.S. Congress authorized building the Appalachian Development Highway System, a 5,535-km network of major highways, to promote economic development in Appalachia. This network, which is 75% complete, has contributed substantially to the region's economic growth (Wilbur Smith Associates 1998). In rural areas, where new highways tend to be built, economic growth is tantamount to urbanization. In some mountainous areas of the eastern United States, roads and urban sprawl generally follow stream valleys (Wear and Bolstad 1998), resulting in especially severe impacts on aquatic biota.

Urbanization affects aquatic ecosystems in many ways (see Paul and Meyer 2001 for a review of effects on streams). Physical and chemical effects of urbanization include all those of road construction and road presence, but are more severe because of greater road densities, more construction, and more vehicular traffic in urban areas. For example, urbanizing watersheds can contribute 10,000 times as much fine sediment to streams as forested watersheds (Wolman and Schick 1967). Urban streams also carry higher concentrations of phosphorous and nitrogen than forested or agricultural streams (Osborne and Wiley 1988).

An additional suite of physical effects on streams emerges in urbanized watersheds in response to hydrologic changes. The proliferation of impervious surfaces fundamentally alters the timing of precipitation runoff, resulting in higher peak flows during storms and lower base flows (e.g., Wang et al. 2001). Roads are often the biggest contributor to impervious area (May et al. 1997). The increased flood frequency causes stream channels to incise (Booth 1990), which may add additional fine sediment to bottom substrates. Consequently, urban streams tend to have deep, wide, silty channels with relatively little water. Although stream channels may naturally adjust to the altered hydrology, such adjustments may take several decades following urbanization (Henshaw and Booth 2000).

Habitat quality in urban streams is often further reduced by active removal of instream woody debris and riparian vegetation. Woody debris is crucial in providing cover for fishes and substrate for invertebrates, and as an agent of pool formation. Vegetation along streams is a key source of organic matter, including wood, which supports food webs and biotic production. Riparian vegetation buffers streams from inputs of contaminants and fluctuations in temperature and flow (May et al. 1997). Riparian vegetation and large woody debris also help stabilize stream banks and channels.

The physical and chemical changes associated with urbanization strongly influence aquatic biota. Fish abundance often decreases as urbanization increases (Weaver and Garman 1994; Wang et al. 2000). Populations that persist in urban ecosystems must be tolerant to all the insults associated with road construction and presence, as well as to extreme variation in water flow, temperature, and food availability. Consequently, macroinvertebrate and fish communities in urbanized watersheds commonly exhibit low species and functional diversity (Weaver and Garman 1994; Kemp and Spotila 1997). Anadromous fishes are especially sensitive to urbanization (Limburg and Schmidt 1990). Although specific mechanisms are not well understood, biotic impacts are detectable quite early in the urbanization process. Tolerant macroinvertebrate and fish species quickly replace sensitive species as impervious surfaces cover 5–15% of a watershed's area. Biotic communities often change little after impervious land cover exceeds 20% of a watershed (Booth and Jackson 1997; Wang et al. 2000; but see Morley and Karr 2002 for a biotic response when impervious land cover exceeds 50%). Thus, unlike most agricultural land cover, small amounts of urban land cover, especially near streams, can severely impair biota (Wang et al. 2001). Additional study is needed to sort out the relative importance of physical versus chemical effects as the primary drivers of biological changes during urbanization.

Viewing road development in three progressive phases provides a simple framework for organizing the broad range of spatial and temporal scales over which biota are affected by roads. The three phases can serve as one dimension in categorizing the types of impacts that resource managers might need to assess. Each phase is associated with a distinctive suite of physical, chemical, and biotic effects; some effects in each phase are often severe. Ecologically organized categories for these effects would complement the phases of road development and serve as a second dimension in a framework for assessing road impacts. We suggest five such categories in the next section.

Matrix Rows: Classes of Factors Affecting Biota

For environmental impact assessments to be useful in public decisions, the assessors must clearly address the environmental concerns of society. These concerns are articulated in cornerstone pieces of federal legislation such as the Clean Water Act, which explicitly mandates the protection of aquatic biological integrity. This mandate provides an appropriate, well-established foundation for assessing impacts of roads on aquatic biota, where impacts are departures from the range of natural conditions for a given region. Important strengths of the integrity concept are that it applies to multiple levels of biotic organization (e.g., individual, population, community) and a wide range of spatiotemporal scales (Angermeier and Karr 1994). Incorporating biological integrity into assessments of road impacts will yield assessments that are more comprehensive and public decisions that are more informed.

The major determinants of biological integrity in aquatic ecosystems are commonly represented as five classes of factors: habitat structure, water chemistry, flow regime, energy source, and biotic interactions (Angermeier and Karr 1994; Karr and Chu 1998). Habitat structure encompasses physical features such as water depth, current velocity, and substrate composition, which form the habitat matrix in which aquatic organisms live. Water chemistry comprises parameters such as pH, dissolved oxygen, and contaminant concentrations. Flow regime refers to temporal patterns in the availability of water, especially seasonal and annual variability. Energy source encompasses aspects of size, abundance, and nutritional quality of food particles. Biotic interactions include competition, predation, and parasitism. These five classes provide an ecological framework for organizing the long lists of specific physical, chemical, and biological effects of roads. Moreover, based on our review of the scientific literature, we hypothesize that roads differentially and predictably influence classes of factors throughout the process of road development. To illustrate, we briefly summarize below typical trends in how these classes of factors are affected in a water body near to and downstream of a four-lane highway during the three phases of road development.

The primary impacts of road construction are linked to earth-moving, which directly alters stream channel morphology and indirectly accelerates fine-sediment loading by exposing soils to erosion. These alterations are manifest as shifts in descriptors of habitat structure such as channel depth, pool-to-riffle ratio, percent fines in substrates, and cover availability (Figure 2). Effects on the other four classes of factors are typically minor and localized.

Effects on habitat structure decrease somewhat during the road presence phase but effects on water chemistry and flow regime increase substantially (Figure 2). Changes in water chemistry commonly associated with contaminants from roads include elevated concentrations of salt, metals, and petroleum products. Toxic spills from trucks could cause catastrophic changes in various water-chemistry parameters. The extensive impervious surface of a highway would increase the frequency and magnitude of floods. If these increases were large, habitat structure (e.g., channel depth, percent fines) could be affected. Although effects on energy source and biotic interactions are not expected to be large, they may become apparent during the road presence phase. Removal of riparian trees and shrubs, which often begins during road construction, may reduce the availability of coarse particulate organic matter and the ratio of allochthonous-to-autochthonous production. Introduced non-native species could cause shifts in the distribution, abundance, or size of native species.

Road impacts generally increase in severity and scope throughout the road development process. Urbanization strongly affects all aspects of aquatic ecosystems (Figure 2) and undermines biotic integrity more severely than the other phases of road development. Moreover, because the ecological effects of urbanization extend well beyond the immediate vicinity of roads, this is the phase most likely to threaten entire aquatic populations and community-types. Habitat evaluations in urbanized waterbodies are likely to reveal reduced spatial complexity, increased embeddedness of substrates, and unstable streambanks. A wide assortment of contaminants, including oil, metals, and pesticides, may impair quality of water and sediment. The hydrology of urban watersheds is likely to feature frequent and severe floods and low-flows, with reduced recharge of groundwater. Urban waters are typically eutrophic with simple food webs. The resulting biotic communities usually support higher proportions of non-native species and of native ecological generalists, all of which must be tolerant of poor water quality and frequent disturbance.

Applying the Conceptual Framework

Collectively, the three phases of road development and five classes of ecological factors form a tractable framework for organizing impacts of roads on aquatic biota. The framework can be depicted as a 15-cell matrix, where each cell's relative importance reflects the magnitude of expected effects shown in Figure 2. For simplicity, we assigned one of two ranks (high versus low impact) to each cell (Figure 3). These ranks provide a basis for prioritizing attention to monitoring, mitigation, or restoration efforts, as might be needed to meet the goals of the Clean

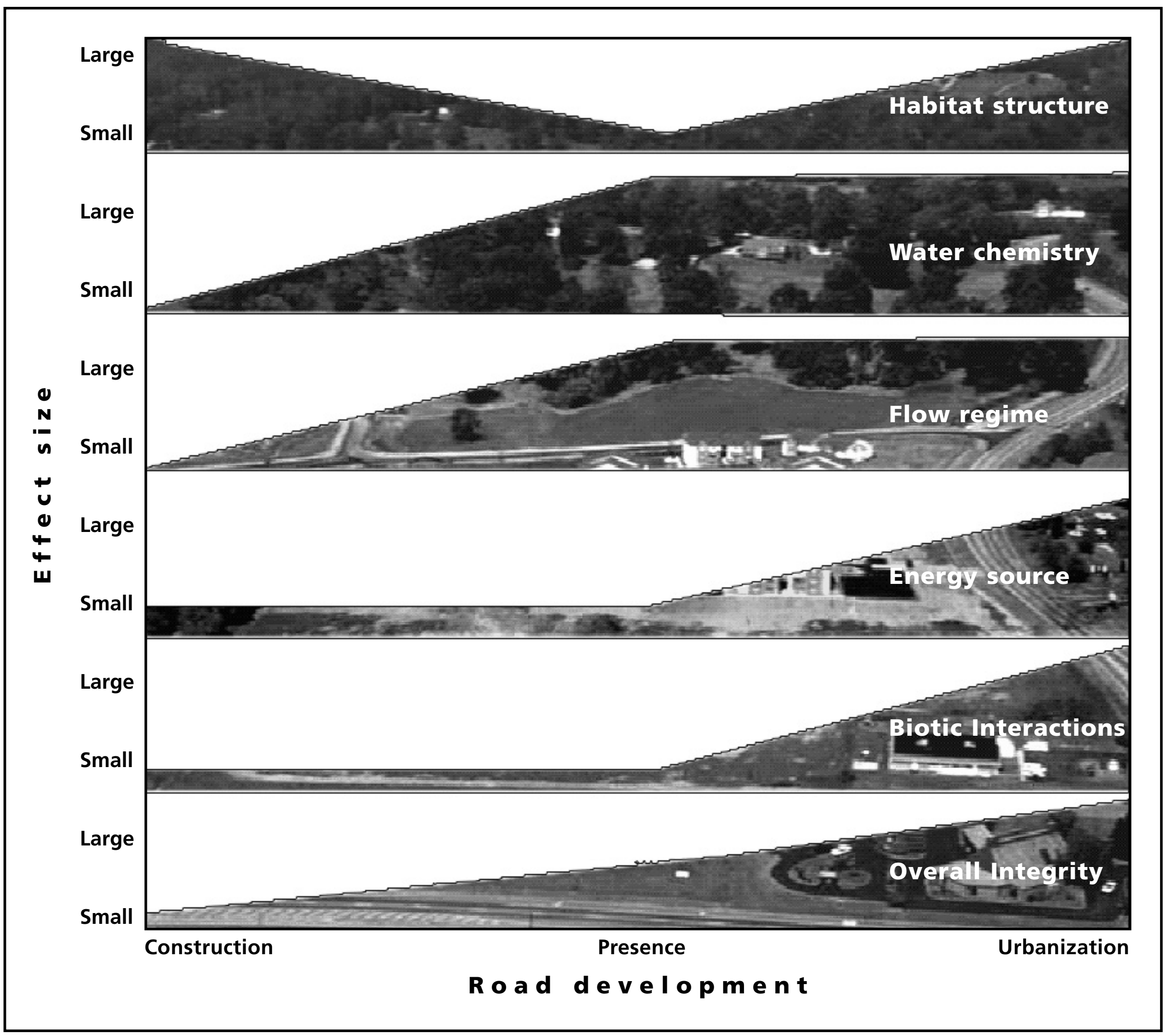

Figure 2. Hypothesized size of effects of road development on five classes of factors that determine biotic integrity of aquatic ecosystems. The size of overall effects on biotic integrity also is shown.

Water Act or the Endangered Species Act. For example, protecting a stream's biological integrity or imperiled species would dictate paying more attention to the impacts of road presence or urbanization than to the impacts of road construction, and more attention to impacts on habitat structure, water chemistry, and flow regime than to impacts on energy source and biotic interactions (Figure 3).

Cell ranks are effectively working hypotheses based on best available scientific information. Our cell ranks (Figure 3) reflect our collective best guesses, and warrant additional rigorous evaluation. Ideally, sound scientific information would support the ranks in every cell. In reality, the information available for cells will vary widely in how confidently it can be applied to a given road, and may come from studies of the road in question, studies of other roads, and expert opinion. The science that informs some cells (perhaps most) will necessarily be uncertain and come from inferences based on weights of evidence (Holling and Allen 2002) rather than from readily interpreted experimental studies. In any case, compiling the information relevant to each cell for each assessment is crucial to the general utility of this framework and to the cost-effective protection of aquatic biota. Despite the uncertainty of some of the information supporting cell ranks, we believe that impact assessments based on such a framework would provide a much broader knowledge base for informing decision-makers and stakeholders about the biological consequences of building roads than do conventional assessments.

We view our matrix as one of many tools that can be used to conceptualize and analyze environmental effects of roads (CEQ 1997). We expect it to be especially useful in scoping ecological consequences and in gauging the thoroughness of a given impact assessment. The I-73 DEIS that we reviewed appeared seriously incomplete because the impacts associated with only 2 of the 15 cells (and only 1 of the 8 high-impact cells) were addressed (Figure 3). A more appropriate assessment would have reviewed the scientific literature on the effects of roads on (a) Roanoke logperch (and closely related species), (b) biotic integrity of streams generally, and (c) other key resources (e.g., wetlands), then discussed those effects in the context of all 15 cells in our matrix. The DEIS discussed impacts on habitat structure and water chemistry during road construction but neglected all other impacts. This pattern is especially troubling because the I-73 DEIS appeared to follow standard Federal Highway Administration (FHA) guidelines for such documents. We suspect that most assessments of environmental impacts of roads are similarly superficial. In fact, there are several reasons to expect the I-73 DEIS to be more comprehensive than most. For example, the huge social, economic, and environmental costs of a new interstate and the potential impacts on federally endangered species should provide strong incentives for a thorough assessment. Given that the U.S. Environmental Protection Agency recently lauded the VDOT as "a model of environmental leadership" (VDOT 2003), VDOT's investment in environmental assessments seems well within the range of what is expected of a road management agency. The sharp contrast between the scope of an impact assessment based on our framework (i.e., with all 15 cells addressed) and the scope of an actual assessment for a proposed interstate suggests that current standards for environmental management by road agencies are too low to ensure protection of aquatic biota.

The inadequacies we observed in the I-73 DEIS reflect failures by both managers and scientists. The authors of the DEIS based their assessment of impact primarily on unpublished reports rather than on peer-reviewed literature, and on a narrow conception of what constitutes environmental impact. However, the scientific literature does not provide a useful framework for conducting comprehensive assessments of road impacts on aquatic environments. Consequently, many impacts can be overlooked easily by managers and stakeholders. Current approaches to environmental management recognize the need for explicit analysis at multiple spatial and temporal scales and for making the scale at which management occurs commensurate with the scale of human impact: (Fausch et al. 2002). The severity and extent of road impacts warrant assessments more complete than those traditionally conducted, including more attention to large-scale and long-term effects. Adopting our framework could help road managers develop more comprehensive assessments of road impacts on aquatic biota. For example, assessments might be structured so that each cell in our matrix is addressed in its own section of text.

Our framework may also be useful in identifying important gaps in the scientific knowledge germane to road impacts. Even if managers did adopt our impact matrix to organize their assessments, the scientific literature pertinent to some cells would be disconcertingly sparse, especially for post-construction impacts and biotic interactions. Thus, ecologists need to do a better job of calling attention to the importance of road impacts for aquatic biota by conducting and publishing studies that demonstrate impacts at individual, population, and community levels of organization. Our review of the literature identified several gaps in scientific knowledge that cut across cells in our impact matrix and warrant additional study (Table 1). The ranks (high versus low) assigned to the cells in our matrix are effectively hypotheses about the magnitude of vari-

Figure 3. Hypothetical matrix of road impacts that could be used to scope potential impacts or to evaluate completeness of impact assessments. Cells are ranked as high (H) or low (L) likelihood of significant impacts occurring. Assigned ranks would be based on region-specific conditions. The two cells addressed in the I-73 draft environmental impact statement are indicated by bold letters.

	Construction	Presence	Urbanization
Habitat structure	**H**	L	H
Water chemistry	**L**	H	H
Flow regime	L	H	H
Energy source	L	L	H
Biotic interactions	L	L	H

ous impacts. A major goal of the science related to road impacts, including research and monitoring, should be to distinguish confidently between high- and low-impact cells. Generating the relevant knowledge will require scientists and managers to take fuller advantage of rural areas where additional road-building is imminent and to create areas where road removal is politically feasible. Both scenarios could provide valuable experimental opportunities to learn about biotic responses to roads. Other opportunities to build scientific knowledge could come from experimental studies of the efficacy of the many protective and restorative measures available to agencies. In all cases, knowledge of long-term and/or large-scale relations would be especially valuable. However, building reliable knowledge will require a much greater fiscal and philosophical commitment to scientific assessment of road impacts than is currently in force.

Socio-political Constraints

We observed a major discrepancy between the greatest threats posed by I-73 and the focus of its DEIS. In particular, threats to Roanoke logperch and ecosystem health stemmed primarily from long-term, large-scale effects, especially those due to urbanization, but the DEIS addressed only certain short-term, small-scale effects of road construction. This discrepancy reflects the range of interpretations available for what constitutes biological threat in the context of official impact assessments and underscores the inadequacy of conventional interpretations for protecting aquatic biota. Interpretations of "threat" have important consequences for how legislation is implemented. For example, under Section 7 of the Endangered Species Act habitat impairment associated with roads is usually considered "incidental take" (unintended harm). Incidental take during road construction is minimized via time-of-year restrictions and implementation of various "best management practices," but incidental take during the more harmful post-construction phases of road development typically is not addressed. A more comprehensive interpretation of threat and management of the associated incidental take would enable more effective conservation of imperiled species. However, the process of defining threat and impact for regulatory purposes is driven more by politics than by science.

The narrow focus maintained by state and federal agencies on short-term, small-scale impacts reflects a broader fundamental problem with the implementation of environmental policy in the United States. Several federal laws, including the Federal-Aid Highway Acts, the Intermodal Surface Transportation Efficiency Act, and the Transportation Equity Act for the 21st Century, call for systematic consideration of social, economic, and environmental impacts of roads and for more public engagement in transportation planning (TRB 2002). States have much flexibility in satisfying these mandates but traditionally have given environmental concerns less weight than short-term economic and political priorities in highway-planning decisions (Atkinson and Cairns 1992). The NEPA requires agencies that use federal funds for road-building to develop EISs that consider all reasonably foreseeable environmental effects, including direct and indirect effects (FHA 2002). Because little formal federal oversight has been provided (e.g., by the CEQ), agencies independently have developed protocols for analyzing cumulative effects of roads (CEQ 1997). Unfortunately, a consistent pattern is that "road impacts" have been constrained to mean "road construction impacts" in the context of NEPA implementation. Effects of road construction are viewed as direct effects, whereas effects of road presence and urbanization, although quite foreseeable, are relegated to indirect (or secondary) effects. Thus, agencies generally abrogate their responsibilities to address environmental consequences beyond the actual building of roads.

Although many experts agree that environmental assessments of new highways should include direct, indirect, and cumulative effects (Atkinson and Cairns 1992; FHA 2002; TRB 2002), progress in making such assessments standard practice has been dismayingly slow. Knowledge of many indirect effects of roads has existed for decades and guidelines for considering these effects in assessments have been available for more than ten years, but agency protocols for explicitly addressing indirect effects in impact assessments remain largely undeveloped and these effects rarely influence project decisions (FHA 1992). Also, the CEQ has not yet promulgated legally binding guidance to protect against cumulative effects or the loss of biodiversity

Table 1. Key topics needing additional scientific study relevant to assessments of road impacts on individuals, populations, and communities of aquatic biota.

1. Role of road-crossings in impairing movement/dispersal by individuals.
2. Role of roads in facilitating spread of non-native individuals via human vectors.
3. Relative importance of the three road-development phases in influencing population dynamics.
4. Contribution of roads to local extinction and regional imperilment of populations.
5. Type, magnitude, and direction of shifts in functional composition (e.g., trophic or reproductive traits) of communities in response to roads.
6. Influence of zoogeographical and regional contexts on impacts of roads.
7. Interactions (synergistic and antagonistic) between impacts of roads and impacts of other anthropogenic activities.
8. Effectiveness of protective and restorative measures in preventing/reducing impacts of roads.
9. Timeframes for recovery of biota following mitigation of road impacts.
10. Biotic responses to road removal.

associated with road development (CEQ 1993, FHA 2002). Thus, current assessment tools do not incorporate the best available science and are inadequate to ensure informed decisions on highway planning (TRB 2002), as illustrated by our analysis of the I-73 DEIS (Figure 3). Additional research on the environmental effects of roads and on protocols for assessing those effects has some potential to improve the information value of conventional impact assessments. However, we suspect that agencies' lack of commitment to environmental concerns rather than a lack of scientific knowledge currently limits effectiveness of assessments of road impacts. Agency commitment to protecting aquatic biota reflects the mores of society at large. Public agencies will provide real protection to aquatic biota only when the public holds those agencies accountable for the continual decline in biological integrity and in the many ecological services that intact biota provide to society.

Conclusions

Roads have major impacts on aquatic biota but these impacts traditionally have been grossly underassessed. Ignoring long-term, large-scale environmental impacts of roads, which are often severe and foreseeable, clearly fails to fulfill the intent of key federal legislation on environmental protection. The public has not held road-building agencies accountable for meeting its mandate to fully assess road impacts. Rectifying this problem requires fundamental changes in how road impacts are defined, measured, and incorporated into policy decisions. In particular, the spatial and temporal extent of assessments must be expanded to match the scales over which the most serious biological impacts of road development are manifest.

Aquatic science should play a more prominent role in assessing road impacts. Investment by transportation agencies in research on environmental consequences of roads has been too small relative to the extent and severity of impacts (TRB 2002). Many effects of roads on aquatic biota are poorly studied, especially over large spatial and temporal scales. Agencies also need to do a better job of finding, disseminating, and using the scientific knowledge that is already available. Important sources of relevant scientific knowledge include scientists themselves, scientific literature, and other agencies involved in environmental issues. Although the impacts of a particular road on nearby areas are not precisely predictable, we present a conceptual framework to help managers organize the many common impacts of roads on aquatic biota.

The purpose of an environmental impact assessment is to describe the likely consequences of a human action so that society can make an informed decision about its desirability (i.e., cost versus benefit). Lack of attention to long-term, large-scale impacts (i.e., major costs), as is common in assessments of roads, precludes fair assessments of desirability. Thus, decisions are biased in favor of more road building, which contributes to the continued, unsustainable urbanization of landscapes. Because remediation of most road impacts is infeasible, efforts to protect aquatic ecosystems are best applied to changing the decision-making processes that precede road building rather than to fixing the damage caused by roads while and after they are built. Indirect and cumulative effects of a road on environmental quality should be considered explicitly in the planning stages, especially if the road's purpose includes spurring economic development (FHA 1992). More complete assessments of the real environmental costs of roads would likely result in less road building and slower rates of urban sprawl. Our conceptual framework is designed to facilitate development of complete assessments of the biological impacts of roads.

Given the tremendous social, economic, and environmental costs of new roads, especially highways, we believe that more thorough approaches to assessing biotic impacts are long overdue. The proliferation of roads (and their attendant impacts) now occurring in the United States is not an inevitable condition of modern society, but a policy outcome. Road policy can be changed. Agency ideology, not scientific knowledge, is the main factor limiting the completeness of environmental assessments. Although scientists should continue to generate new knowledge and tools relevant to assessing road impacts, the main breakthrough needed is in societal commitment to protecting intact biota and fully functional ecosystems. It remains up to the agencies and the publics they serve to muster the political will to reinvent road policy.

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