Impacts of New Highways and Subsequent Landscape Urbanization on Stream Habitat and Biota

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New highways are pervasive, permanent threats to stream ecosystems because of their short- and long-term physical, chemical, and biological impacts. Unfortunately, standard environmental impact statements (EISs) and environmental assessments (EAs) focus narrowly on the initial direct impacts of construction and ignore other long-term indirect impacts. More thorough consideration of highway impacts, and, ultimately, better land use decisions may be facilitated by conceptualizing highway development in three stages: initial highway construction, highway presence, and resultant landscape urbanization. Highway construction is characterized by physical and chemical disturbances, which generally subside through time. In contrast, highway presence and landscape urbanization are characterized by biological impacts that are temporally persistent. Although the impacts of highway presence and landscape urbanization are of similar natures, the impacts are of a greater magnitude and more widespread in the urbanization phase. Our review reveals that the landscape urbanization stage is clearly the greatest threat to stream habitat and biota, as stream ecosystems are sensitive to even low levels (<10%) of watershed urban development. Although highway construction is ongoing, pervasive, and has severe biological consequences, we found few published investigations of its impacts on streams. Researchers know little about the occurrence, loading rates, and biotic responses to specific contaminants in highway runoff. This is needed to understand how highways are affecting fish populations via contaminates in runoff and how highway networks alter natural regimes (e.g., streamflow, temperature). Urbanization research topics that may yield especially useful results include: (a) the relative importance and biological effects of specific components of urban development—e.g., commercial or residential; (b) the occurrence under which runoff is generated; and (c) the efficacy of mitigation measures—e.g., stormwater removal or treatment and forested buffers.

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Introduction
Due to their large surface area, high traffic volume, and potential to induce urban development, the construction of large (-2 to -5 lane) paved roads (herein defined as highways), are often detrimental to local ecosystems. Stream ecosystems are particularly sensitive to the construction of new highways due to characteristics of the fluvial environment and biota. Downstream transport of water and "sediment" spreads chemical and fine sediment pollution causing the ecological impacts of highways to extend farther in aquatic than in terrestrial environments (Fennessy and Alexander, 1998). Aqeous fauna often have a more difficult time avoiding spreading impacts than terrestrial fauna because their movements are generally confined to the narrow linear geometry of the stream channel. In addition, highways and urban development alter the hydraulic connection of streams to their watersheds, fundamentally altering processes, form, habitat, and ultimately contribute to biotic integrity (Wang et al., 2001; 2003).

Angermeyer et al. (2004) conceptualized the extent and nature of highway impacts on streams in three successive stages: initial highway construction, highway presence, and eventual landscape urbanization (Table 1). Because this framework reflects the spatial and temporal dimensions of impacts, it is useful for organizing, describing, and evaluating the environmental concerns of new highways. The initial phase, highway construction, includes all the short-term impacts from the construction process. These impacts are generally physical, temporary (i.e., outside through time), and local. The second phase, highway presence, encompasses secondary impacts that are chemically generated from the physical presence of the highway including chemical pollutants from automobiles and traffic channel "throughway". These chemical and physical impacts are regional and occur as long as the highway exists. Finally, landscape urbanization integrates the impacts from general economic development and "result" in various of chemical and physical impacts that are widespread and chronic. Previous reviews have focused on single phases of highway impacts (Atkinson and Cairns, 1990; Little and Mayet, 1993; Forman and Alexander, 1998; Trombaak and Frissell, 2000; Forman and Debinski, 2000; Paul and Mayet, 2001) but not clearly described or considered the inherent connectivity of the nature and values of the impacts.

Table 1
Conceptual framework for primary physical-chemical impacts of highway construction. The scale and nature of primary environmental impacts change from the direct effects of highway construction to the secondary and indirect associated with the presence of a highway and urban development and impacts through time. All physico-chemical impacts have important consequences for stream biota but the degree of peer-reviewed investigation differs among stages.

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The predictability of the three successive stages of new highway construction are seldom considered simultaneously in environmental assessments. The National Environmental Policy Act (NEPA), the Council on Environmental Quality (CEQ), and various state environmental laws (CEQ, 1997) require state and federal transportation agencies to consider the significance of anticipated impacts in environmental assessments (EAs) or prepare environmental impact statements (EISs) when significant impacts are anticipated. However, these assessments generally focus almost exclusively on short-term, localized impacts and ignore the long-term secondary and cumulative impacts (Spalding and Smit, 1993; McColl and Holtman, 1995; Burris and Carter, 1997; Cooper and Carter, 1997; Angermeyer et al., 2000) that are often primary concern of the government agencies and civilian stakeholders reviewing these documents (e.g., NWCRC and NCDPR, 2002). Although European countries are more rigorously apply ecologic principles to transportation projects than the United States (Forman and Alexander, 1998), inadequate assessment of cumulative impacts is a global problem (Cooper and Shoate, 2002).

Evaluations of the thoroughness of EISs and EAs are often limited due to a lack of published summaries of the impacts that may be expected from proposed projects. For example, evaluations of EISs and EAs have searched for the assessments for key words or concepts rather than assessing how meaningful and thoroughly preferable impacts were considered (e.g., Burris and Carter, 1997; Cooper and Carter, 1997). New review of the extent and nature of impacts from new highways that considers the stages and changing impacts identified by Angermeyer et al. (2004) will assist reviewers of EISs and EAs in explicitly linking these successive stages, a step often ignored in assessment-presented highway projects. Our review summarizes investigations that will help environmental and fisheries scientists consider potential impacts of proposed highway projects in multiple dimensions, but are otherwise unavailable in field offices, and are widely across academic disciplines. In addition EISs, EAs, and previous reviews often make asertions based on unpublished government reviews which suffer the major inadequacies of "grey" literature (Collente, 1990). In contrast, we rely almost exclusively on published, peer-reviewed studies.

The purpose of this article is to review the impacts of new highways through undevolved land. Although not the focus of this review, much of the information presented may be relevant to more common highway improvements, such as lane additions and surface upgrades. We focus on studies conducted in the United States, but some relevant international research is included to supplement sparsely researched topics. Following our conceptual framework (Table 1), we synthesize the scientific knowledge on physical, chemical, and biological responses of streams during 1) highway construction, 2) highway presence, and 3) watershed urbanization. The ultimate goals of this review are to provide information that will improve the ability of transportation planners to prepare more thorough, meaningful, and science-based EISs and EAs, and to spur research in subject areas where rigorous studies are lacking but information is needed for comprehensive impact assessment of new highways.

Highway Construction
Highway construction can be highly destructive to stream habitat and biota. Impacts on streams are primarily acute, local, and physical in nature (Table 1). Highway construction primarily degrades stream habitat locally but some of these impacts may transport down-stream. In contrast to impacts of highway presence and landscape urbanization, many construction impacts may be temporary and streams can recover if not recurrently disturbed. In this section, we review literature assessing these acute impacts (e.g., sedimentation). Other
Highway Construction and Physical Habitat

As with any earth-moving activity, the greatest threat of highway construction to streams is fine sediment pollution, which can cause a variety of problems for resident biota, including direct mortality, reduced food base, and a reduction in the food base (reviewed in Waters, 1995). Fine sediment pollution originates as bare soil erodes into streams, usually after exposure to precipitation or flowing water. Streams impacted by highway construction accumulate (Clarke and Scruton, 1997) and transport (Weber and Reed, 1976) many times more sediment than undisturbed streams. Although a variety of erosion control procedures are available and often legally required, they are seldom evaluated for their effectiveness (but see Gross (1999), Neuk et al. (2003a, 2003b)) and have a risk of failure seldom considered in published investigations or environmental impact statements. A Pennsylvania study found that, even in the presence of sediment control techniques, streams impacted by highway construction carried 5 to 12 times more fine sediment than a control stream (Weber and Reed, 1976). The suspended solids load of a Ontario stream increased from an average of 2.7 mg/l to 352.0 mg/l during the initial "clearing phase" and peaked at 1,390 mg/l (Jones) highway construction (Barton, 1977). In addition, Barton (1977) observed a 10-fold increase in fine sediment deposition following a highway construction channelization project. The stream sediment loads approached preconstruction levels near the completion of the construction. Increases in suspended sediment are detectable for long distances (kms) downstream of construction sites (Wolman et al., 2000). These sediments deposit in downstream pools, riffles, and impoundments (Duck, 1983; Brookes, 1986).

Highway construction can result in a variety of other sediment studies physical habitat degradations by encroaching into floodplains and disrupting riparian areas. Heavy equipment accessing the stream may incidentally damage (Hubbard et al., 1990) or purposefully remove (Stout and Coburn, 1989) riparian vegetation during highway construction. Riparian vegetation is a critical component of stream waterbodies and performs many important functions for streams (see Urbanization). Streams near highways are often channelized and the initial effect of heavy equipment modifying the stream channel may alter the dynamic equilibrium of the waterway and result in rapid channel reorganization, all of which can lead to additional sedimentation and erosion downstream.

Highway Construction and Stream Chemistry

We find no studies documenting chemical impacts of highway construction on streams. However, the use of heavy machinery in and around streams likely causes some chemical pollution. In addition, many highway construction materials are highly toxic to aquatic biota. For example, industrial waste materials and byproducts such as shredded tires, ashes, mining wastes, municipal sludge, and wood wastes may be used in highway construction (Eldin, 2002). These materials release heavy metals and hydrocarbons which are toxic to water fleas Daphnia magna and algae Selenastrum capricornutum (Eldin, 2002). The toxicity of these materials may be reduced when in contact with soil, and during typical construction these toxicants are unlikely to reach detrimental levels in streams. Nevertheless, the proximity of toxic materials to streams increases the chances of accidental spills and releases.

Biological Effects of Highway Construction

The impact of highway construction on stream fishes and macroinvertebrates is rarely studied. Similar to other anthropogenic landscape changes, highway construction is difficult to research for several reasons. Highway construction consists of many individual impacts that occur concurrently; thus, specific causal mechanisms are difficult to establish. An additional obstacle to research is that construction timespans are often unpredictable, and construction often takes longer than the tenure of a typical graduate student. In addition, highway construction prevents statistical, well-controlled study designs (e.g., treatments are difficult to replicate and meaningful controls difficult to establish).

We found only a few studies investigating the effects of highway construction on stream fishes and macroinvertebrates. However, fine sediment pollution occurs from a variety of anthropogenic sources and is widely studied outside the context of highway construction. The effect of fine sediments on stream biota has been recognized for decades (Ellis, 1936) and is the subject of many previous reviews (Chater, 1969; Brown, 1985; Ryan, 1991; Waters 1995; Wood and Armsteg, 1997; Henley et al., 2000). In addition, to studies that directly focus on highway construction, this section includes more general investigations of the effect of fine sediment on stream biota.

Fine sediment pollution from highway construction can immediately alter macroinvertebrate and fish communities (Barton, 1977). Reductions in the abundance and diversity of macroinvertebrates may depend on the timing and duration of construction impacts (Chine et al., 1982). Stout and Coburn (1989) found an absence of macroinvertebrate shredders in pools below highway construction. Fine sediment from highway construction may result in reduced macroinvertebrate diversity and density (Lenat et al., 1981). Highway construction immediately reduce the overall abundance of stream fishes by over 50% (Whitney and Bailey, 1959; Barton, 1977). Taylor and Roff (1986) reported that the abundance of bottom-feeding fishes is initially reduced, but recovers after fine sediment deposition rates decline. Fish and invertebrate communities begin recovering after the fine sediment loads are reduced and deposits wash downstream, but full recovery may require years (Taylor and Roff, 1986).

Fine sediment pollution degrades stream biotic communities through a variety of mechanisms. Stream periphyton and macrophytes are shaded, suffocated, and shaded by fine sediment (Waters, 1995). Fine sediment loads impact macroinvertebrates by inducing catastrophic shifts (Carp et al., 1986), damaging individual's respiratory structures (Lembry, 1982), and reducing habitat by clogging interstitial spaces in streambeds (Lenat et al., 1981). Fine sediment can also choke the gills of fishes and reduce the quality of their habitats for foraging by impairing visibility and reducing prey abundance (Barton, 1985). It is possible that construction interferes with a variety of feeding strategies; Berkman and Raben (1978) found that fine sediment deposition reduced populations of both imperturbable and lethargic freshwater fishes. In addition, fine sediment suspended in the water can lower reproductive success of fishes (Burkhead and Jelks, 2001). For example, egg survival of some species depends on substrate that is permeable to water flow (Kondol et al., 2001).

Highway Presence

Although highway construction can be highly detrimental to stream habitat and biota, construction sites are sparse compared to the land covered and increasingly affected by existing highways. Currently in the United States, there are 6.3 million km of public roads, 60% of which are paved with a surface area of about 50,000 km². At present,
20% of the United States' land area is directly affected by road presence (Iverson, 2000), and 50% is within 82m of a road (Ritters and Wickham, 2003). In contrast to the localized, temporary effects of highway construction, the extensive effects of highway presence are persistently generated by highways with direct hydraulic connections to streams (Table 1).

Highways and Physical Habitat

Although plethora of highway runoff can substantially affect stream channels, we found no studies of its impact on physical stream habitat. However, many investigators have examined the impacts of logging roads (see Gascuel et al., 2001). Although unaltered forest roads are not the subject of this review and differ from paved highways in many aspects, they are similar in that their impervious surfaces collect stormwater and route runoff into streams. Collecting and routing runoff to streams increases the imperviousness and frequency of stream flooding (King and Tennyson, 1984; Jones and Ginn, 1996). These runoff changes are also characteristic of urban areas and cause a variety of physical changes to stream channels, such as channel widening and downcutting (see Urbanization section). However, because paved roads are only minor components of the total impervious surfaces of an urban watershed, the presence of a single highway in a watershed likely results in less changes to flow regimes and, ultimately, less severe changes to physical stream habitat than urban development.

Streams near highways are often channelized during construction. However, unlike many construction impacts such as fine sediment pollution, this modification has continual long-term consequences for physical stream habitat. Channelization increases channel slope, reduces base flows, increases peak flows, alters substrate composition, and so on. Floodplain loss has been noted (Hartig et al., 1997). In addition, channelization reduces the habitat diversity and characteristics of natural streams by replacing coarse substrates with fine substrates, reducing depth and velocity heterogeneity, creating more linear flows, removing cover, and eliminating natural pools and riffles (Peterson and Atwood, 2004). If engineered properly, bridges may cause minimal impacts on the physical stream channel; however, through channelization or poor construction practices, bridges can destabilize stream channels. Although culverts are generally more detrimental to stream habitat and biota, they are often installed as a cheaper alternative to spanning structures. The presence of culverts destabilizes stream channels by interrupting the downstream transport of woody debris, sediment, substrate, and water. Although few quantitative studies of the impact of culverts on physical stream habitat are available, Gubin (2003) provided a qualitative overview. Unlike dynamic natural stream channels, culverts are rigid and unaccommodating to changes in channel morphology. In addition, the stream channel is often widened above the culvert, creating increased velocities and forming a trap or sump. Although downstream sediment flow is reduced above the culvert, it continues or accelerates below the culvert causing channel downcutting and resulting in an "oxygenation" drop, even if initial construction is done to protect the pipe at stream level. Typically, culverts are sized to accommodate rare flood flows but are too small to allow passage of woody debris. Accumulations of woody debris near the culvert can start downstream areas of this important component of stream habitat (see Urbanization section) and may plug the culvert, causing failure of road fill during floods and increasing the risk of catastrophic debris torrents.

Highways and Stream Chemistry

Highway surfaces collect a variety of chemical pollutants from automobile traffic and are disproportionately contributors to overall pollutant loads. For example, public highways cover 8% of Rhode Island, but produce 16% of the state’s oil and grease pollution, and 77% of the state’s zinc pollution (Hoffman et al., 1985). These pollutants are mobilized by runoff water and transported to streams where they accumulate in sediments and biota and spread downstream, resulting in chronic and widespread effects. This runoff represents an important, but relatively unnoticed, component of stream pollution (Wu et al., 1998).

Traffic residue adds a variety of metals to highway runoff, including iron, zinc, lead, cadmium, nickel, copper, and chromium. Tires contain up to 18% zinc by weight (Hedley and Lockley, 1975) and are a significant source of zinc in the environment (Davis et al., 2001). Brake pad dust contributes copper (Davis et al., 2001). These metals accumulate in roadside dust (Lehman et al., 1992), soil (Goldsmith et al., 1993), and stream sediments (Van Hasselt et al., 1976; Mabry et al., 1995). The concentrations of metals in stream sediments are positively correlated with the volume of traffic (Van Hasselt et al., 1988; Callender and Rice, 2000), although differences in stream flow (drained or undrained (Mabry et al., 1995)), suggesting that pollution will be most severe when large highways are drained by small streams.

Highway surfaces also accumulate petroleum from automobile traffic. Motor oil accumulates from crankcase drippings, washes off the highway surface, and accumulates in sediment in streams (Borrman et al., 1985). Until the Clean Air Act of 1970 phased out leaded gasoline, lead was the most widespread metal pollutant from automobile traffic. Unleaded gasoline permits the use of catalytic converters, which convert gaseous exhaust pollutants such as carbon monoxide, nitrogen oxides, and hydrocarbons to less toxic chemicals such as carbon dioxide, nitrogen, and water. Exhaust systems by platinum group elements (PGEs), including platinum, palladium, and rhodium, which are emitted on highway surfaces during operation. Since the introduction of catalytic converters, PGEs have become a new source of sediment pollution. Concentrations of PGEs in stream sediments (Brench and Morrison, 1997) and streams are common impurities in PGE catalysts and may also be deposited on highways (Rausch et al., 2004). Concentrations of PGEs in roadside soils and traffic volumes are increasing to such a degree that their recovery (i.e., mining roadside soil) may become economically viable (Ely et al., 2001).

In areas that undergo winter weather, deicing salt is another widespread, but little studied, chemical pollutant of streams. Salt is spread in highways in anticipation of and during snow and ice accumulation, from where it directly enters into streams or is stored in the soil. A study in Pennsylvania found 20- to 30-fold increases in a stream's conductivity during winter thaw (Kenyok et al., 2001). Although high concentrations harmful to fish are considered rare (Transportation Research Board, 1991), few studies have addressed the effects of these "shock loads" of salt on stream biota. Kiviat et al. (2001) observed differences in temperature, ionic strength, and host condition in organisms receiving shock loads of deicing salt. Furthermore, deicing salt may be contaminated by metals and nutrients. Phosphorous, lead, and zinc were found in highway deicing salt and anti-skid sand (in Minnesota (Overtv, 1986) and iron, nickel, lead, zinc, and copper in deicing salt in England (Hedley and Lockley, 1975). Road salt that does not run off directly into streams may still cause chronic problems through slow release into adjacent soils, chlorination of raw and salt have a no-effect residence time of at least 2 years (Mason et al., 1996).

Another concern associated with the presence of a highway is the inevitability of toxic chemical spills. In 1982, hazardous materials materials made up more than 5% of all domestic freight shipments (List and Akkewitz, 1986). Almost all types of hazardous wastes and 62% of all hazardous materials (by weight) are moved by truck (Akkewitz et al., 1989; Atkinson and Cifrus, 1992). Unfortunately, accidental releases during shipping are not infrequent.
Moyle (1976) compared channelized and unchannelized sections of a California stream and found the biomass of fish and invertebrates in channelized locations was less than one-third of that in unchannelized locations. He also found differences in fish and macroinvertebrate species composition between channelized and unchannelized areas. Channelization may reduce the recruitment and production of fishes by eliminating nursery habitat. For example, removal of gradually sloping streambanks increases the area of unstable habitat with velocities greater than the swimming speeds of age-0 fishes (Copp, 1991; Kett; Scheidegger and Bain, 1955; Mann and Bass, 1989; Mejía; and Tonkin, 1990). Moyle (1976) compared channelized and unchannelized sections of a California stream and found the biomass of fish and invertebrates in channelized locations was less than one-third of that in unchannelized locations. He also found differences in fish and macroinvertebrate species composition between channelized and unchannelized areas. Channelization may reduce the recruitment and production of fishes by eliminating nursery habitat. For example, removal of gradually sloping streambanks increases the area of unstable habitat with velocities greater than the swimming speeds of age-0 fishes (Copp, 1991; Kett; Scheidegger and Bain, 1955; Mann and Bass, 1989; Mejía; and Tonkin, 1990).

Culverts are a feature of highway pavement that can have a variety of negative impacts on stream biota. Culverts provide poor internal habitat due to low-bottom complexity and uniformly high-flow velocities inside culverts provide poor habitat (Swarbrick and Ebeler, 1990), but most importantly, they are notorious fish movement barriers. The effects of highway crossings on stream fish movement depend on the swimming speed and behavior of individual species (Tiedt et al., 1999). Fish passage is obstructed by high current velocities and shallow depths inside culverts, as well as vertical steps at the culvert outflow (Baker and Van Tuzika, 1990). In addition, concrete box culverts may develop internal gravel bars (Wettman et al., 2000) that impede fish movement. Warren and Andow (1990) found that overall fish movement in salmon habitats was an order of magnitude lower through culverts than through other crossing types or natural channel in small, warmwater Arkansas streams. Culverts throughout a tributary network may reduce 90% of species richness that require spawning migrations, such as salmon Oncorhynchus kisutch, by preventing adults from reaching spawning habitat (Beecham et al., 1994). Barriers can isolate populations, resulting in reduced genetic diversity and increased probability of extinction due to demographic instability and impeded recolonization. Most investigations of fish movement barriers have focused on economically important fishes with known migration patterns; for example, Belford and Gould (1989) determined combinations of water velocity and culvert length that prevented passage by brook trout Salvelinus fontinalis, rainbow trout Oncorhynchus mykiss, and brown trout Salmo trutta. However, entire fish communities are vulnerable to highway crossing movement barriers (Jackson, 2003) and the importance of movement and movement barriers to anadromous fishes and fish communities is poorly understood. In one of the few published studies for a nonmigratory species, Schaefer et al. (2003) found that a variety of culvert types significantly decreased the probability of movement of the Federally threatened leopard darter Percina pantherina between habitat patches. Although culverts present a variety of obstacles to fish movement, engineers designing passable culverts may narrowly focus on the effects of singular parameters such as vertical outflow depth or current velocity (e.g., Holand et al., 2001) and not consider the cumulative effects of multiple passage inhibiting features.

Urbanization

Urbanization is difficult to define, as the meaning of "urban" varies across disciplines (Paul and Meyer, 2001). We modify the definition by Kemp and Spotsill (1992) and define urbanization as development in a watershed, such as building construction, that changes land use typical of rural areas (e.g., farming, grazing) to uses more typical of residential and industrial areas (e.g., retail, suburban residential areas, plants and factories). This definition describes the general process of watershed-altered development that is characteristic of the urban landscape and the focus of this review.
The construction of new highways is the "quintessential public sector investment" by which government attempts to encourage economic growth in rural areas (Chaudhry and Thompson, 2000). At the state level, new highways are ineffective at increasing economic activity (Evans and Karras, 1994; Holtz-Eakin, 1994; Danenberg and Partridge, 1997), but they effectively redistribute economic activities among locales. New highways reduce traditional rural economic activities of nearby counties such as agriculture, but enhance and concentrate urban economic activities such as manufacturing and retail in the county the highway intersects (Raphael and Innes, 1994). Similarly, precipitation falling on impervious surfaces without direct hydraulic connections to streams (Schueler, 1994; Wang et al., 2001, 2003), capture precipitation and route it quickly into storm sewers and gutters and, ultimately, into streams (Hollis, 1973). Similarity, precipitation falling on impervious facades without direct hydraulic connections to streams may reach streams quickly at overland flow (Horton, 1945; Leopold, 1973). Thus, urbanization fundamentally alters the delivery of water to streams (Booth, 1991).

These changes in precipitation delivery alter stream flow regimes. As a watershed urbanizes, peak flow volume from precipitation events increase (Hollis, 1975; Beaud and Chang, 1979; Neller, 1988; Booth, 1990; Clark and Petersen, 2001), thereby increasing the frequency of bankfull flows (Leopold, 1973; Hollis, 1975; Arnold et al., 1982; Moscisc and Montgomery, 1997). Even low levels of growing increase the magnitude of frequent flows (mean annual flow, for example, 2-year flows of the watershed can increase the peak discharge of the mean annual flood by an order of magnitude (Hollis, 1975). Thus, discharge rates that previously occurred once every 2 years may double in frequency following watershed development (Hartges et al., 1992). A later study concluded that these relationships were consistent for interstate streams nationally (Hartgen and Kim, 1998). Hartgen et al. (1992) described the general requirements, stages, and potential paths of interbasin development, and all potential paths that interbasin construction leads to the conversion of forest and agricultural areas to commercial or residential development. Improvements to existing highways, such as lane additions, also increase development activity along the highway corridor (Cervero, 2003).

Other studies have documented land use change induced by the presence of nearby highways. Although these studies do not address the construction of new highways, they provide insight into the impact of increasing development at points other than existing highways. Bradshaw and Mulier (1990) mentioned the conversion of farmland to urban areas in California, describing highways between cities as "magnets for decentralized growth." The southern Appalachian Mountains, near to low highways to were more likely to experience urban change than states in the Midwest. The relationship between new highways and urban development is intuitive, predictable, and often a declared political goal. Few investigators have examined this association. Indeed, this connection is a contentious issue for transportation planners. The reason new highways do not result in urban development, although apparently ubiquitous among transportation planners, is not well-supported by published studies. The "failure" to yield failed to produce any peer-reviewed examples relating a positive relation between highway construction and urban development (but see Hartgen 2003a, 2003b).

A stream's physical habitat and chemical environment are largely products of its watershed. Thus, as a watershed urbanizes, changes occur in stream habitat, water chemistry, and ultimately biota. Similar to the presence of a hydraulically connected highway, urban development continually affects stream chemical and chronic impacts (Table 1), but at greater magnitudes. Runoff from urban areas contains all the chemical pollutants from automobile traffic as well as those from urban sources. In addition, urbanization drastically alters how a watershed produces stream flows, resulting in many changes in physical habitat.

Undeveloped waterbodies are characterized by land surfaces that are pervious to precipitation. Rain falling in undeveloped waterbodies infiltrates the soil and reaches streams slowly as subsurface flow. The urban landscape, however, is characterized by rooftops, asphalt, compacted soils, and other highly impervious surfaces (Schueler, 1994; 1995). These impervious surfaces produce direct hydraulic connections to streams (Schueler, 1994; Wang et al., 2001, 2003), capture precipitation and route it quickly into storm sewers and gutters and, ultimately, into streams (Hollis, 1973). Similarly, precipitation falling on impervious facades without direct hydraulic connections to streams may reach streams quickly at overland flow (Horton, 1945; Leopold, 1973). Thus, urbanization fundamentally alters the delivery of water to streams (Booth, 1991).

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Undeveloped waterbodies are characterized by land surfaces that are pervious to precipitation. Rain falling in undeveloped waterbodies infiltrates the soil and reaches streams slowly as subsurface flow. The urban landscape, however, is characterized by rooftops, asphalt, compacted soils, and other highly impervious surfaces (Schueler, 1994; 1995). These impervious surfaces produce direct hydraulic connections to streams (Schueler, 1994; Wang et al., 2001, 2003), capture precipitation and route it quickly into storm sewers and gutters and, ultimately, into streams (Hollis, 1973). Similarly, precipitation falling on impervious facades without direct hydraulic connections to streams may reach streams quickly at overland flow (Horton, 1945; Leopold, 1973). Thus, urbanization fundamentally alters the delivery of water to streams (Booth, 1991).

These changes in precipitation delivery alter stream flow regimes. As a watershed urbanizes, peak flow volume from precipitation events increase (Hollis, 1975; Beaud and Chang, 1979; Neller, 1988; Booth, 1990; Clark and Petersen, 2001), thereby increasing the frequency of bankfull flows (Leopold, 1973; Hollis, 1975; Arnold et al., 1982; Moscisc and Montgomery, 1997). Even low levels of growing increase the magnitude of frequent flows (mean annual flow, for example, 2-year flows of the watershed can increase the peak discharge of the mean annual flood by an order of magnitude (Hollis, 1975). Thus, discharge rates that previously occurred once every 2 years may double in frequency following watershed development (Hartges et al., 1992). A later study concluded that these relationships were consistent for interstate streams nationally (Hartgen and Kim, 1998). Hartgen et al. (1992) described the general requirements, stages, and potential paths of interbasin development, and all potential paths that interbasin construction leads to the conversion of forest and agricultural areas to commercial or residential development. Improvements to existing highways, such as lane additions, also increase development activity along the highway corridor (Cervero, 2003).

Other studies have documented land use change induced by the presence of nearby highways. Although these studies do not address the construction of new highways, they provide insight into the impact of increasing development at points other than existing highways. Bradshaw and Mulier (1990) mentioned the conversion of farmland to urban areas in California, describing highways between cities as "magnets for decentralized growth." The southern Appalachian Mountains, near to low highways to were more likely to experience urban change than states in the Midwest. The relationship between new highways and urban development is intuitive, predictable, and often a declared political goal. Few investigators have examined this association. Indeed, this connection is a contentious issue for transportation planners. The reason new highways do not result in urban development, although apparently ubiquitous among transportation planners, is not well-supported by published studies. The "failure" to yield failed to produce any peer-reviewed examples relating a positive relation between highway construction and urban development (but see Hartgen 2003a, 2003b).

A stream’s physical habitat and chemical environment are largely products of its watershed. Thus, as a watershed urbanizes, changes occur in stream habitat, water chemistry, and ultimately biota. Similar to the presence of a hydraulically connected highway, urban development continually affects stream chemical and chronic impacts (Table 1), but at greater magnitudes. Runoff from urban areas contains all the chemical pollutants from automobile traffic as well as those from urban sources. In addition, urbanization drastically alters how a watershed produces stream flows, resulting in many changes in physical habitat.
may be balanced by rapid loading of fine debris during the initial phases of urbanization. For example, Vollenweider (1967) hypothesized that high sediment loads from the construction Phase of urbanization could temporarily clog and constrict stream channels, a phenomenon later observed by Leopold (1973).

When the extent of urbanization is in a watershed, stabilized, stream channel enlargement may cease, and the channel banks may restabilize. In addition, as the rate of urban development declines, fine-sediment loading may be greatly reduced as construction sites soils are stabilized via revegetation or pavement, and prior deposits may be removed by scouring during subsequent flooding (Wolman, 1967; Clark and Wilcock, 2000; Finkenbine et al., 2000). However, the process of bank erosion, downcutting, and channel adjustment may continue for several decades, and some streams never stabilize (Hendrix and Booth, 2005).

Urbanization typically results in loss of streamside riparian vegetation as areas near streams are cleared. The degree of riparian disturbance varies with type of urban land. For example, Tobiati (1997) found the land used for transportation, schools, and industry had more intact riparian areas than residential, commercial, and recreational land. Riparian vegetation is a critical component of the watershed (reviewed by Kerr and Schlosser, 1978; Gregory et al., 1991; Naimon and Décarie, 1997; Passy and Arbington, 2003), and although they cover a small percentage of the watershed, riparian areas are disproportionately important for stream health. Recent riparian areas absorb and filter out metals, fine sediment, and nutrients from overland runoff (Castelle et al., 1994) and generally mitigate the physical and chemical effects of urbanization (May et al., 1997). Riparian vegetation stabilizes streambanks and reduces bank erosion (Whipple et al., 1981; Breson and Despin, 1995; Finkenbine et al., 2000), and helps moderate urban stream temperatures (Pellati et al., 1997).

Urban vegetation comprises leaved, woody, and other organic debris to streams. The biota of small (< 4th order) streams, such as those generally associated with urban areas (Raney and Hubei, 1984), depend upon leaves and organic inputs as their energy base (Vannote et al., 1980). In riparian areas, there is an important component of stream channels because it stabilizes stream banks (Keller and Swanson, 1979; Booth, 1991; Gregory et al., 1991; Finkenbine et al., 2000), creates pools (Keller and Swanson, 1979; Larson et al., 2001), and provides habitat for microinvertebrates (Beske et al., 1985) and fish (Angermeier and Karr, 1984; Flebbe and Deltolf, 1995). In urban areas, recruitment of woody debris declines as development removes floodplain trees and instream abundance is typically reduced by intentional debris removal (Larson et al., 2001).

Stream water temperature is a major determinant of the distribution and abundance of aquatic biota and is primarily regulated at two spatial scales, the riparian and the watershed. Riparian vegetation shelters streams from warming by absorbing or reflecting sunlight before it reaches the water. THUS, loss of riparian vegetation contributes to the warming of urban streams (Hartman et al., 1985; Leffiane et al., 1997). At the watershed scale, impervious surfaces, especially parking lots, collect and heat runoff water before it reaches streams. For example, Vann et al. (2000) developed a computer model to predict runoff temperature and observed that a parking lot produced runoff 5.9°C warmer than summer rainfall. The maximum daily water temperature in Wisconsin and Minnesota streams increase by 0.25°C with every 1% increase in the impervious area of the watershed (Wang et al., 2003). In addition, increases in average water temperature, urban streams exhibit increased thermal variability (Moglen et al., 2004).

Urbanization and Water Chemistry

Urban runoff contains a variety of chemical pollutants including petroleum, metals, and nutrients. Rivers and streams receive the majority of urban runoff (Baker and Huber, 1984) and chemical pollutants are often stored in stream sediments. House et al. (1995) reviewed the contents and impacts of urban runoff on receiving waters. Oil and grease enter urban runoff from a variety of sources including deliberate dumping, automobile engine emissions, and chemical spills; however, the majority originates from automobile crankcase drippings (Baker and Huber, 1984), and grease deposited by parked vehicles and become the primary land use source of oil and grease in urban runoff. Storms et al. (1984) observed concentrations of oil and grease up to 15 mg/l in parking lot runoff. Automotive sources of metals in urban runoff include zinc from tire wear (Hedley and Lockely, 1975) and motor oil (Davis et al., 2001), platinum from catalytic converter emissions (Rauch and Morrison, 1999), and lead from motor fuel (Davis et al., 2001).

In addition to automotive sources, urban runoff accumulates metals from a variety of other sources. For example, iron originates from the corrosion of steel (Charlock and Wison, 1997), zinc from the corrosion of galvanized metals (Hedley and Lockely, 1975), roofing, and painted wood (Davis et al., 2001). Lead and copper from cord and painted surfaces (Davis et al., 2001). Other metals in urban runoff include chromium and nickel (Klein et al., 1974; Hesel et al., 1979; Bhods and Bahill, 1999). Manganese urban runoff accumulates in stream sediments (Gaines and McIntosh, 1986; Rauch and Morrison, 1999), where concentrations are related to both population and traffic densities (Callender and Rice, 2000).

Urban runoff is high in nutrients such as nitrogen and phosphorus that can result in detrimental algal blooms and increased dissolved oxygen levels. Nutrient levels in streams are typically predictable from land use (e.g., Herlihy et al., 1998). For example, the risk of nutrient pollution increases as nonforest land cover reaches 10% of the watershed (Wickham et al., 2000). Historically, nutrient pollution has been associated with agricultural land use, but urban land often produces greater nutrient loading. For example, concentrations of total phosphorus and total nitrogen in urban streams were 2 to 10 times higher than agricultural and forested streams in Missouri (Smart et al., 1985). Other studies have reported higher concentrations of nitrogen and phosphorus in urban streams than in agricultural and forested streams (Osborne and Wiley, 1988; Wall et al., 1997).

Biological Impacts of Urbanization

Altered and impaired biotic communities are characteristic of urban streams. Urban microinvertebrate communities have reduced tax richness (Gaines and McIntosh, 1986; Jones and Clark, 1987; Kemm and Spottis, 1991), reduced diversity (Gaines and McIntosh, 1986) and lower index of biotic integrity (B) scores (Oston and Wender, 1998; Karr, 1999), lower functional diversity (Pederson and Perkins, 1986), and lower taxonomic diversity (Patt et al., 1981; Stutes, 1984; Pederson and Perkins, 1986). In an extensive survey of New Jersey streams, Karr (1995) found that locations with severe microinvertebrate community impairment were most commonly downstream from urban areas. Urbanization reduced tax diversity and richness by reducing the density of pollution intolerant taxonomic orders (Ephemeroptera, Coleoptera, Megaloptera, and Plecoptera) and increasing the density of pollution tolerant Diptera in Virginia streams (Jones and Clark, 1987). Microinvertebrate diversity may decline progressively as streams flow through urban areas (Patt et al., 1981).

Impacts of Highways and Landscapes on Urbanization

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Macrocenotivertebrate diversity was reduced to taxa-tolerant of physical disturbances in an urban Washington stream (Podemer and Perkins, 1986).

Fish communities are similarly impaired by urbanization. Urban stream fish communities have lower overall abundance (Weaver and Garman, 1994; Altenbach and Matlack, 1998; Wang et al., 2000, 2003), diversity (Tramer and Rogers, 1973; Klein, 1979; Scott et al., 1986; Weaver and Garman, 1994; Orentolo et al., 2000; Wang et al., 2000), IBI scores (Schloegger, 2000; Wang et al., 2003), taxa richness (Weaver and Garman, 1994; Altenbach and Matlack, 1998; Schloegger, 2000), and larger species richness (Wang et al., 2003). Lead content in fish tissue is higher in urban areas (Steinberger and Chen, 1998). Furthermore, the proximity of urban streams to humans increases the risk of nonnative species introduction and establishment.

Although many studies describe the alteration of stream macroinvertebrate and fish communities by urbanization, the mechanisms linking specific urban impacts to specific community responses are largely unknown. Since multiple chemical and physical impacts of urbanization occur simultaneously, it is difficult to determine how specific environmental stressors affect biotic communities. However, changes in physical habitat likely impact biotic communities more than changes in water chemistry. For example, fish and macroinvertebrate communities become impaired at the onset of urbanization (Klein, 1979), whereas physical changes are more prevalent than water chemistry changes. Most water chemistry changes are detectable until urban land cover exceeds 40% of a watershed (May et al., 1997).

Threshold Effect of Urbanization

In the last 100 years, the field of stream ecology has expanded its spatial focus from small habitat patches to entire watersheds (Miranda and Rabon, 2000). Consistent with this paradigm shift and advances in geographic information systems and remote sensing, recent studies have addressed how different spatial configurations of urbanization affect stream communities. For example, investigators have documented differences between percent urban land cover (UCK) (Steedman, 1988), percent impervious area (Klein, 1979; Booth and Jackson, 1997; Wang et al., 2000), percent impervious area with direct connections to streams (Booth and Jackson, 1997; Wang et al., 2001, 2003), and biotic parameters.

These studies overwhelmingly conclude that very low levels (8–10% of ULC) or surrogate measures result in highly altered fish and macroinvertebrate communities. Even after this low level of development, successful restoration of these communities back into preurban conditions may be near impossible, as this small change could result in a shift into a new, less desirable state that is difficult to reverse (Mayer and Rienkink, 2004).

Initial watershed urbanization following the construction of a new highway is more damaging to stream ecosystems than later, more extensive, development. In macroinvertebrate and fish communities, pollution- and stress-tolerant species rapidly replace intolerant species as ULC approaches 10%. After ULC exceeds 18%, further increases result in little or no fish community changes (Schaerer, 1994; Booth and Jackson, 1997; Wang et al., 1997, 2000, 2001). For perspective, 10% ULC is characteristic of areas typically considered "urban" (Wang et al., 2000). Although urban streams can have similar effects, streams may support relatively healthy fish communities until agricultural land cover exceeds 80% of the watershed (Wang et al., 1997). Because fish communities in currently undeveloped or agricultural watersheds are likely to be severely degraded by the onset of urbanization (Wang et al., 2000), protection against urbanization impacts should focus on watersheds where urbanization has not yet begun (May et a., 1997). In the context of highway impacts, this means that the greatest damage to stream health is inflicted by building new highways through undeveloped watersheds, which, ultimately, become subject to urban sprawl.

Conclusions

The short-term environmental consideration of transportation projects in EISs and EAs focuses on the initial construction impacts. However, the most serious threats to stream ecosystems are the long-term secondary effects of a highway’s presence in the watershed and the cumulative effects of urban development. For example, the biotic integrity of streams is jeopardized (primarily forested agricultural watersheds) significantly degraded by the onset of urbanization, thus, streams in undeveloped watersheds are more sensitive to the construction of new highways than streams in urban watersheds. Because many aquatic impacts from the existence of the highway and urban development are long-term considerations, the narrow, short term focus of EISs and EAs provides inadequate protection for stream ecosystems. As new highways continue to diminish the percentage of the landscape that is unaffected by roads, expanding the spectrum of environmental considerations for highway projects is increasingly important.

Highway construction and highway presence impose a variety of impacts on stream habitat and biota. Urban development results from the construction of new highways and is clearly the most pernicious threat, as stream habitat and biota are sensitive to even low levels (<10%) of development in a watershed. watershed urbanization is a predictable indirect or secondary effect of the construction of new highways and NURP, the CSG, and various state environmental laws require consideration of indirect and cumulative effects in EISs and similar documents (CJQ, 1997). Although secondary and cumulative impacts are often important considerations of environmental agencies that comment on such measures (CJQ, 1995), the Converse Natural Resources Conservation Program (NWCR) (2002), landscape urban development resulting from the construction of new highways is generally ignored by the transportation agencies preparing the assessments. The importance of considering the impacts of landscape urban development during initial planning is amplified because this is the final opportunity to consider all effects cumulatively. Landscape urbanization ultimately results from the “enchantment of small decisions” (Glied, 1982) on many individual projects, the cumulative impacts of which are overlooked by the Clean Water Act section 401 permitting process (Stain and Ambrose, 2001), as well as other regulatory mechanisms. Given the severity and extent of impacts on stream biota, we were impressed by the paucity of peer-reviewed literature on many aspects of those impacts. We believe the lack of published studies demonstrates a failure of both management agencies and academic researchers to address a severe and politically thorny environmental issue. The design of future urbanization development should be a focus of more comprehensive knowledge about how highways affect ecosystem function, make that knowledge available to the public (e.g., in EISs and EAs), and apply that knowledge to policy decisions regarding development of sustainable transportation systems.
Although highway construction is ongoing, pervasive, and has severe biological consequences, we found few published investigations of its impacts on streams. We encourage environmental and fisheries scientists to pay closer attention to the effects of new highway construction or highway improvements on streams. Carefully designed, comparative investigations could contribute substantially to our understanding of the differential impacts of various construction techniques, as well as the efficacy and risk of failure of various mitigation practices.

There are many unexplored opportunities to investigate the impacts of highway proximity on stream health. Researchers know little about the occurrence, loading rates, and biofouling responses to specific contaminations in highway runoff. Understanding the dynamics and rates of specific pollutants could facilitate more effective mitigations. Future investigations should address the relative importance of chronic pollution, such as metals accumulated in stream sediments, versus acute impacts such as pulses of petroleum and diesel oil. Additional research is also needed to understand how highway crossings, especially culverts, affect fish populations via constraints on movement and how highway networks alter flow regimes of watersheds.

Impairment of stream biotic communities due to urbanization is severe and widely studied. However, opportunities still exist for relatively simple descriptive investigations. For example, we are impressed but the paucity of studies addressing stream thermal pollution from urban runoff and reduced riparian areas. In addition, techniques for minimizing impact or restoring biofouling integrity are poorly developed. Research topics that may yield especially useful results include a) the relative importance and biological effects of specific components of urban development; e.g., highways, commercial, or residential, b) the scenarios under which impacts are reversible, and c) the efficacy of mitigation measures; e.g., stormwater treatment or riparian buffers.

Science, comprehensive risk analyses, that incorporate both social and ecological factors and are badly needed to estimate potential for catastrophic events during all phases of new highway impacts. Risks include mitigation failures and catastrophic spills during the highway construction, occupation, and urbanization phases. Depending on the nature of the biotic community (e.g., is it isolated), the stream small, does it contain sensitive species), it may be more or less vulnerable to these kinds of events. Without a spatially explicit, rigorous risk analysis framework, managers cannot properly weigh the risks and benefits of road projects proposed in their areas and have no scientific basis for proposing alternatives that may be less damaging to stream ecosystems.

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