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REVIEW ARTICLE

Ecohydrological disturbances associated with roads: Current knowledge, research needs, and management concerns with reference to the tropics

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Abstract
Roads are a pervasive form of disturbance with potential to negatively affect ecohydrological processes. Some of the most rapid growth in road networks is occurring in developing countries, particularly in the tropics, where political agendas are often focused on strengthening the economy, improving infrastructure, bolstering national security, achieving self-sufficiency, and increasing citizen well-being, often at the expense of the environment. We review what is known about road impacts on ecohydrological processes, focusing on aquatic systems, both temperate and tropical. We present seven cases that represent the broader trends of road development and impacts in tropical settings. Many of these process dynamics and impacts are not different from those experienced in temperate settings, although the magnitude of impacts in the tropics may be amplified with intense rainfall and lack of best management practices applied to road construction/maintenance. Impacts of roads in tropical settings may also be unique because of particular organisms or ecosystems affected. We outline a set of best practices to improve road network management and provide recommendations for adopting an agenda of research and road management in tropical settings. Importantly, we call for incorporation of transdisciplinary approaches to further study the effects of roads on ecohydrological processes in the tropics. Specific emphasis should also be placed on collaboration with governments and developers that are championing road development to help identify the drivers of road expansion and thresholds of negative impact, as well as methods of sustainable road construction and maintenance.

KEYWORDS
aquatic ecology, erosion and sedimentation, road impacts, tropical ecohydrology

1 | INTRODUCTION

Roads provide important functions such as facilitating travel, trade, tourism and national defense, supporting resource access and management, and enabling the transport of commodities (Laurance, Sayer, & Cassman, 2014a; Lugo & Guczinski, 2000; Sidle & Ziegler, 2012). Despite these societal benefits, the presence of transportation corridors of all types, ranging from interstate highways to unpaved forest roads and footpaths, has been associated with adverse hydrological and ecological impacts (Andrews, Gibbons, Jochimsen, & Mitchell, 2008; Seiler, 2001; Takken, Croke, & Lane, 2008; Thomaz & Peretto, 2016; Trombulak & Frissell, 2000; Wemple & Jones, 2003). Commonly cited road-related terrestrial ecological disturbances include the interference of species mobility or dispersal, habitat fragmentation, mortality by roadkill, noise effects on wildlife populations, and microclimate changes affecting vegetation composition or animal habitat viability (e.g., Andrews, 1990; Coffin, 2007; Forman & Alexander, 1998; Spellerberg, 1998; Young, 1994). Worldwide, the development of road networks has also been associated with permanent land-cover conversion, including loss of primary forest (Chomitz & Gray, 1996; Cropper & Griffiths, 2001).

The negative effects of roads on aquatic and coastal ecosystems, the focus of this review, are diverse. Direct ecohydrological impacts include the obstruction of the movement of fish or other aquatic organisms at road crossings or the increased mortality resulting from discharge of harmful contaminants into streams and the coastal zone from roads (Trombulak & Frissell, 2000). Indirect impacts include stream habitat destruction or disruption of food webs through changes of natural stream run-off response, increased sediment loads related to accelerated erosion, and/or mass wasting on and adjunct to the road prism (Coffin, 2007; Forman & Alexander, 1998; Forman et al., 2003; Gucinski, Furniss, Ziemer, & Brookes, 2001; Larsen & Parks, 1997). From an ecological perspective, road-induced changes in sedimentation and run-off patterns may induce taxon-specific responses in macroinvertebrates (Doeg & Milledge, 1991; Imbert & Perry, 2000; Molinos & Donohue, 2008; Richardson, 1985; Rosenberg & Wiens, 1978; Shaw & Richardson, 2001), further amplifying change in benthic community structure (Larsen & Ormerod, 2010). Some roads have been shown to influence the timing and magnitude of stream flows, as well as water quality through the delivery of sediment and road-related contaminants (e.g., Forman & Alexander, 1998; Ramos Scharrón & LaFevor, 2016; Wemple, Jones, & Grant, 1996). Although many studies set in tropical locales in the last few decades have verified a commonality in hydrological and geomorphological impacts of roads between temperate and tropical areas (see below), most of what is known about road-related impacts on aquatic ecosystems systems comes from research in developed countries in temperate areas. Currently, many of the negative consequences on aquatic organisms listed above do not have documented tropical analogies, although they may exist in many cases.

The tropics lie within the latitudes of the Tropic of Cancer and the Tropic of Capricorn (±23°). Tropical regions are typically warm, experience little seasonal change in daily temperatures, experience prevalent rainfall in the moist inner regions near the equator, and increasing seasonality of rainfall with distance from the equator (State of the Tropics, 2014). Nevertheless, topography and local geography contribute to great local climatic variation, making it difficult to identify variables that create drastic road impact differences between the tropical and temperate areas in general. In this paper, we focus on the tropics where periodic or seasonal rainfall often generates high run-off and erosion rates on roads. We also pay close attention to developing areas of the tropics where fast economic growth has resulted in the aggressive "deforesting" of rural lands for agricultural export and mining and subsequent migration of rural peoples to urban areas resulting in urban expansion (DeFries, Rudel, Uriarte, & Hansen, 2010; Ewers, 2006; Rudel, 2007; State of the Tropics, 2014). These practices force the opening of new roads, which further drives land-use change, and in many cases, degrades the environment (Geist & Lambin, 2002; Goosem, 2007; Laurance, Goosem, & Laurance, 2009; Freitas, Hawbaker, & Metzger, 2010; DeFries et al., 2010; Barber, Cochrane, Souza, & Laurance, 2014; Laurance et al., 2014a, Laurance, Clements, Sloan, et al., 2014b; Fearnside, 2015).

Agribusiness fuels road building in many developing regions of the tropics, including in the Amazon, where plans for roads continue "as fast as money allows" (Fearnside, 2015). Extractive industries (e.g., timber extraction, oil production, and mining) and remotely situated infrastructure development, particularly the construction of hydroelectric facilities, are some of the key drivers of extensive road system building in the developing world, as demonstrated in the lower Paute Basin of Ecuador (Figure 1). Other drivers include infrastructure expansion due to growth in tourism and recreation demand in erosion-vulnerable and previously unroaded areas, such as coastal zones (e.g., in Florianópolis, Brazil; Figure 2) and mountain slopes (e.g. Brooks, Larson, Devine, & Schwing, 2015; Browning et al., 2016; Ito, 2011; Macdonald, Anderson, & Dietrich, 1997). The opening of international borders (Fox & Vogler, 2005) and the expansion of agricultural frontiers (Fearnside, 2001, 2008), common in tropical regions worldwide, further drives road development. The development of new roads has also led to transboundary disputes, as seen in a recent International Court of Justice case along the boundary of Costa Rica and Nicaragua (ICJ, 2015).

In the face of rapid population growth and intense development pressure in tropical regions, we argue that more attention be given to understanding and managing the ecohydrological disturbances caused by roads. In Part 1 of this paper, we summarize important negative hydrological and geomorphological impacts of roads, which have been documented in work done in both tropical and temperate areas. In Part 2, we discuss the implications of road phenomena on aquatic ecology and other ecological systems. Where work on roads is limited, we draw from studies that address the ecological consequences of landscape degradation in general, as the processes are often similar. In both Parts 1 and 2, we focus primarily on unpaved roads constructed to access natural resources in remote settings, although we also reference studies documenting impacts of logging skid trails, footpaths, and improvised paths. We also highlight cases of urban road development in the tropics, underscoring this important dimension of growth driving road development. Where appropriate, we showcase findings from a set of seven case studies that summarize our experiences in tropical locales in South America, SE Asia, the Caribbean, and the Pacific (presented in Figures 1–7). Finally, in Part 3, we update past calls (e.g., Elliot & Foltz, 1997; Luce, 2002) for research on road impacts, with a focus on tropical settings, and provide recommendations for new research and management improvements to address road-related ecohydrological impacts, some of which may be applicable to roads worldwide.

2 | PART 1: HYDROLOGICAL AND GEOMORPHOLOGICAL IMPACTS OF ROADS

2.1 | Stream flow alteration

Urban centers generate large volumes of surface run-off during storm events because of the high density of impermeable surfaces including roads (Walsh, Fletcher, & Burns, 2012). In rural and forested settings, where infiltration rates are otherwise high, unpaved road surfaces also have the propensity to generate erosion-producing overland flow during most rain events (Luce & Cundy, 1994; Ramos Scharrón & MacDonald, 2005, 2007a; Ziegler & Giambelluca, 1997; Ziegler et al., 2001a; Ziegler et al., 2007). In mountainous terrain, road cuts

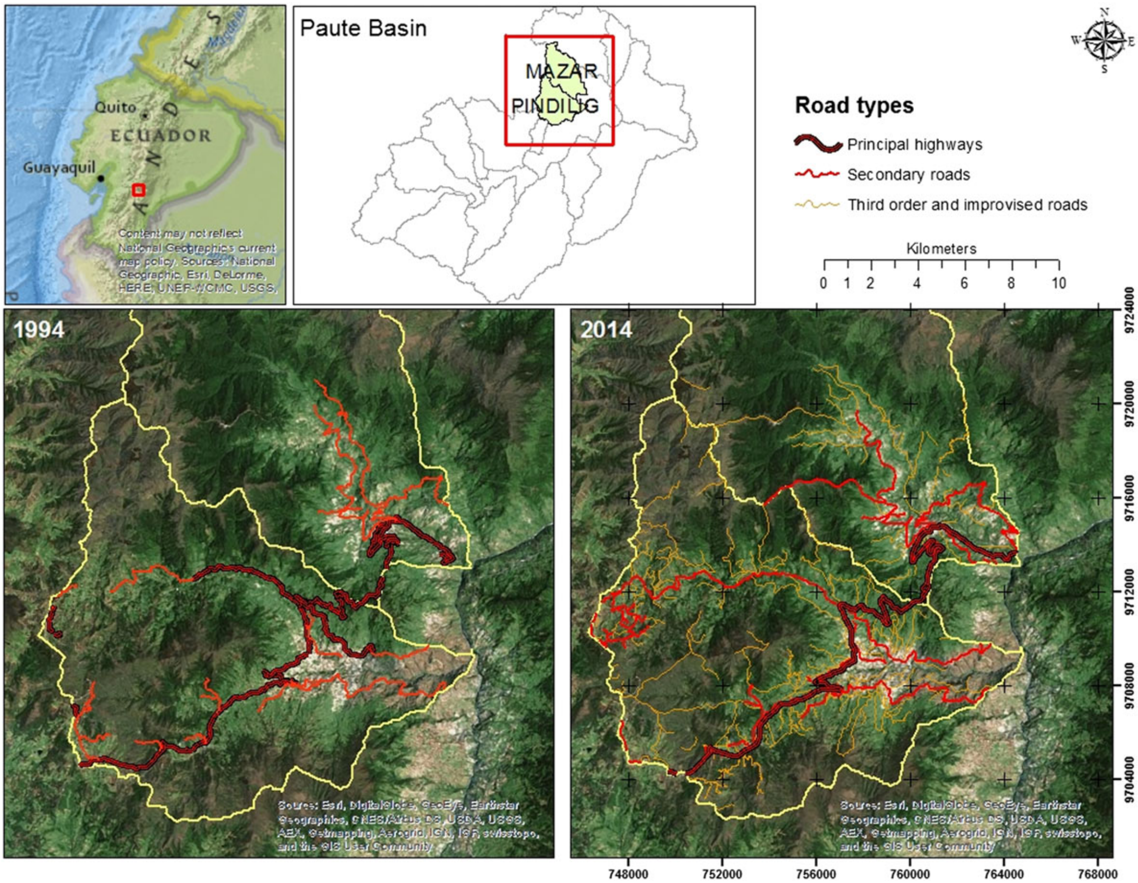

FIGURE 1 Rural road expansion for infrastructure development, lower Paute Basin, Ecuador. Recent road expansion in Ecuador suggests some important and unintended consequences of planned development strategies in rapidly developing tropical regions. The government of Ecuador has recently promoted the generation of hydroelectric power to meet national electrification needs, promote development, and produce renewable and more efficient energy (Peláez-Samaniego, Garcia-Perez, Cortez, Oscullo, & Olmedo, 2007). Specifically, they have backed the development of rural hydropower projects, most without extensive river impoundments and reservoirs in regions where sedimentation behind dams has been a historical challenge. Hydropower projects are developed in high elevation watersheds to harness the potential energy of mountainous terrain. This development scheme and the spatially dispersed nature of these hydro facilities along river networks necessitate an extensive road system. Empirical observations indicate that road networks in this terrain require numerous slope excavations and are associated with widespread consequences related to erosion and sedimentation of receiving waters, including landslides and debris flows (Sarmiento, 2010). One such project is the Mazar–Dudas project, in Cañar province, initiated in 2005 within the lower Paute River basin. The Paute Basin, located in the southern Ecuadorian Andes, forms part of the Amazon River basin, with altitudes ranging from 1,991 to 4,680 msl in the upstream areas (Vanacker, Molina, Govers, & Deckers, 2007). The Mazar–Dudas project provides around 125 GWh/year to the National Interconnected System (CELEC EP, HIDROAZOGUEZ, 2016). Analysis of historical imagery for the Mazar and Pindilig (containing the Dudas catchment) watersheds in the lower Paute basin illustrates the rapid rate of road development common across the tropics. We obtained historical imagery for 1994 and 2014 and digitized principal highways that connect the region to larger cities to the southwest and northeast, secondary roads that provide access to small settlements and project sites, and tertiary roads often constructed for temporary access and excavation for transport of material or by rural settlers living in or expanding into the region. Over the period bracketed by this analysis, road development has expanded considerably. Most notable is the extensive network of tertiary roads evident on recent imagery. Total road length in these two catchments has increased from 128.6 km in 1994 to 457.3 km in 2014, a more than doubling of the road network. Road density increased from 0.38 km/km^2 in 1994 to 1.37 km/km^2 in 2014 (Image sources: Universidad del Azuay, Instituto de Estudios de Régimen Seccional del Ecuador, 1994; Ministerio de Agricultura, Ganadería, Acuacultura y Pesca, 2014)

may intercept subsurface flow, diverting it quickly to the stream (Megahan & Clayton, 1983; Negishi, Sidle, Ziegler, Noguchi, & Nik, 2008; Wemple & Jones, 2003). Through this propensity to intercept subsurface water and generate overland flow, road networks alter the way water and sediment move through the landscape to the stream network and ultimately the coastal zone (Coffin, 2007; Gucinski et al., 2001). Consequently, changes in run-off routing effectively enhance hillslope-to-channel connectivity (Bracken & Croke, 2007), in turn increasing storm peak flow generation in some catchments (Harr, Harper, Krygier, & Hsieh, 1975; Jones & Grant, 1996; King & Tennyson, 1984; Sauer, Thomas, Stricker, & Wilson, 1982; Thomas & Megahan, 1998).

Work in the past decade in tropical settings has confirmed these impacts of roads on run-off production and routing. At one tropical location, Ramos Scharrón and MacDonald (2007a) showed that a monitored road section on the island of St John in the eastern Caribbean could generate run-off during storms as small as 3–5 mm. Subsequent work verified the sensitivity of catchment response to disturbances occupying as little as 1% of the land surface (Ramos Scharrón & LaFevor, 2016). Work at the Bukit Tarek Experiment Catchments in

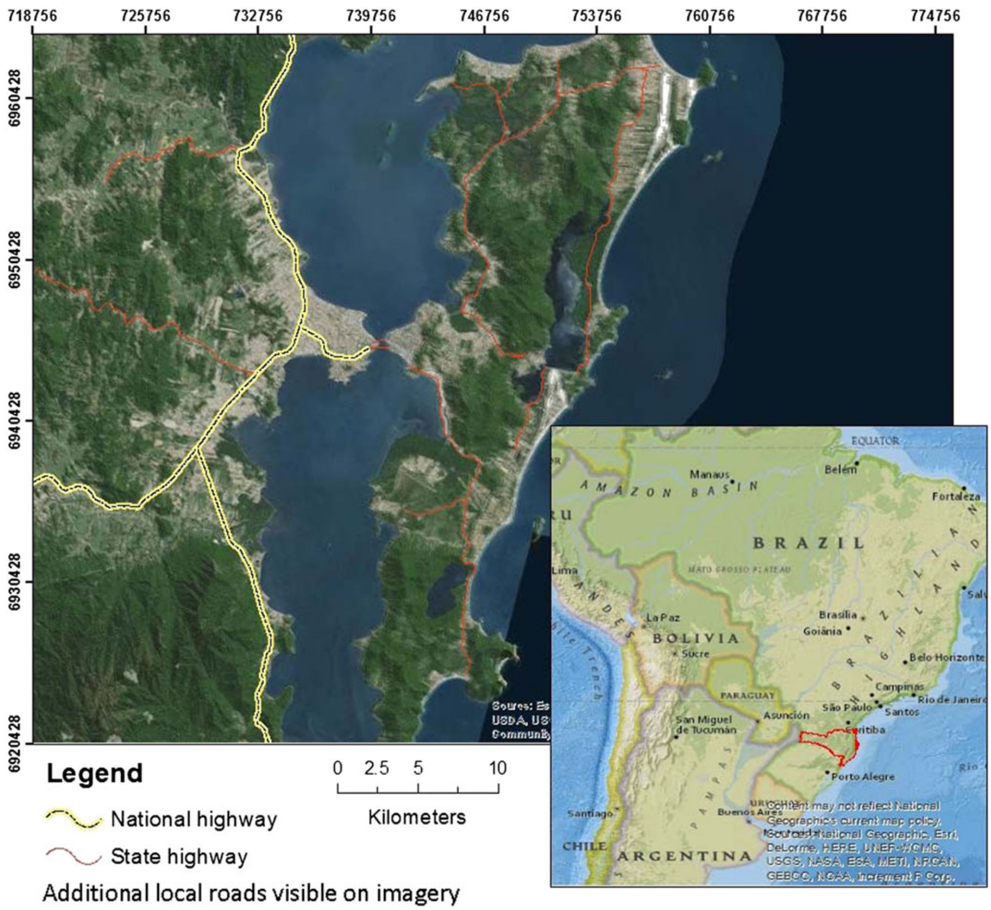

FIGURE 2 Tourism and rapid urbanization in the tropics, Florianópolis, Brazil. Florianópolis, capital of Santa Catarina state (outlined in red on inset), is located in the southern region of Brazil and includes a coastal island (655 km^2) and mainland region (20 km^2), which has been linked since 1926 by the Hercilio Luz Bridge (Ferreira, Silva, & Polette, 2009; Oliveira, 2003). The coastal area's 98 km of beaches have been a major draw for tourism, driving the development of new roads and resulting in subsequent urbanization (da Silva, Lamotte, Donard, Soriano-Sierra, & Robert, 1996) and a 23% population increase in the last decade (Guerra et al., 2016). These changes have had critical impacts on both the landscape and organisms, including altered plant species distribution (Gandolfo & Hanazaki, 2014), increased metal contamination in coastal mangroves and lagoons (da Silva et al., 1996), and brackish water quality degradation (Fontes et al., 2006). Additionally, the zooplankton community has been negatively affected due to an increase in salinity instigated by changes to the terrestrial and marine morphology in the South Bay of Santa Catarina Island (Veado & Resgalla, 2005). Throughout this period of intensive growth, Florianópolis has faced serious urban mobility problems, related to constraints on road building (hilly terrain and coastal wetlands), large numbers of vehicles, and inefficient public transportation. Despite these challenges, new sustainable city initiatives have aimed at addressing transportation challenges and implementing car-free neighbourhoods to limit additional road development and associated impacts (Borges & Goldner, 2015; Guerra et al., 2016)

Malaysia demonstrated the importance of intercepted subsurface flow in augmenting road-generated overland flow (Negishi et al., 2008). Further, roads at Bukit Tarek continued to contribute to surface flow generation long after they were abandoned, if they were cut deeply into the hillslope where they intercepted natural subsurface flow pathways (Ziegler et al., 2007). In our case study set in tropical northern Thailand (Figure 3) roads with low permeability in heterogeneous agricultural/forest landscapes were important in converting substantial amounts of overland flow into elevated stream peak flows in the 97-ha Pang Khum Catchment. Computer hydrological simulations showed that compared with an all-forested scenario, roads within a fragmented landscape converted greater amounts of overland flow into higher peak flows (Cuo, Giambelluca, Ziegler, & Nullet, 2008). Without roads, the patchy land-cover pattern buffered the impacts of the scattered overland flow source areas and limited increases in peak flows (Cuo et al., 2008).

2.2 | Sediment production and delivery to water bodies

In any setting, tropical or temperate, the volume of sediment produced by a native road depends on the erodibility of the road surface, sediment supply, traffic levels, the drainage system in place, maintenance, road geometry, surfacing, soil properties, nearby vegetation cover, and the magnitude and frequency of precipitation events (Horner & Mar, 1983; Anderson & Simons, 1983, Grayson, Haydon, Jayasuriya, & Enlayson, 1993; Ramos Scharrón, 2010). Road-induced sediment production can occur by several processes: (a) removing vegetation along the road prism during road construction, maintenance, and grading (Castillo, Martinez-Mena, & Albaladejo, 1997; Ramos Scharrón & MacDonald, 2005); (b) mobilizing fine-grained sediments from the compacted roadbed and roadside margin (Anderson & Potts, 1987; Araujo et al., 2014; Ramos Scharrón, 2012; Ramos Scharrón &

FIGURE 3 Impacts of mountain roads on run-off and erosion in Pang Khum, Thailand (left: Villagers repairing road ruts to allow passage during the rainy season. Right: A new bridge is being constructed to replace the old log bridge after funds became available). Northern Thailand, like many mountainous regions of the tropics, contains remote mountain roads, most constructed by hand following historical foot/animal tracks. Regionally, the shift towards the cultivation of marketable crops followed the evolution of road and irrigation infrastructures, the development of urban market demands for agriculture products, and the initiation of crop substitution programs (Ziegler et al., 2009). The road network has subsequently expanded in the mountains to support national security, law enforcement (narcotics and anti-logging), population growth, and agriculture intensification (Ziegler & Giambelluca, 1997; Ziegler et al., 2004). As with many other roads built on steep terrain in the region, sound design and maintenance guidelines were often not implemented to limit potential environmental impacts (Ziegler et al., 2000). Instead, roads are largely left unpaved, designed without effective water drainage systems, and terminated at streams or temporary log bridges. Increased sediment loads in northern Thailand are a concern, but most research and outreach programs addressed accelerated hillslope erosion associated with hilltribe agriculture (Sidle, Ziegler, Negishi, Nik, & Siew, 2006), which was beginning to intensify following the ban on the production of opium, a cash crop that caused exceptionally high erosion on steep hillslopes (Ziegler et al., 2009). Research in the 94-ha Pang Khum Experimental Watershed, established in 1997, has led to a number of discoveries illustrating how roads in this landscape were impacting hydro-ecological processes: (a) roads often produced sediment loads that were disproportional to the area they occupied in the catchment (Ziegler et al., 2004); (b) the erodibility of the native road surface was dynamic, effected by the generation and removal of easily entrained surface material by road surface maintenance activities, vehicular detachment, and overland flow (Ziegler, Giambelluca, & Sutherland, 2002; Ziegler, Giambelluca, Sutherland, Vana, & Nullet, 2001a; Ziegler et al., 2001b); (c) road maintenance was intermittent, performed at the end of the wet monsoon period as needed, during the wettest part of the rainy season when storms could mobilize large volumes of fresh sediment made available by the maintenance (Ziegler et al. 2001b); (d) roads within heterogeneous landscapes were important in converting substantial amounts of overland flow into elevated stream peak flows (Cuo, Giambelluca, Ziegler, & Nullet, 2006; Cuo et al., 2008); (e) naturally occurring buffers were potentially an economical means of mitigating road-related impacts in upland basins when combined with measures limiting sediment and run-off production on contributing road sections (Ziegler et al., 2006); and (f) even the sparse road network in Pang Khum contributed to shallow mass failures where road run-off water was concentrated on the hillslope (MacNamara et al., 2006). Collectively, the findings from northern Thailand highlight the role of roads in accelerating erosion, destabilizing hillslopes, and increasing stream sediment loads (Sidle & Ziegler, 2012). Although the long-term consequences of alteration in stream functioning on downstream aquatic environments may have been severe, they were largely unrecognized by officials charged with catchment planning and transportation management. Importantly, the current building/maintenance practices were simply deemed acceptable and in line with the need to improve transportation infrastructure to meet development goals (Sidle & Ziegler, 2012; Ziegler et al., 2009)

MacDonald, 2005; Ziegler, Sutherland, & Giambelluca, 2000); (c) initiating gullying at culvert outlets (Croke & Mockler, 2001; Takken et al., 2008; Wemple et al., 1996); (d) triggering of shallow landsliding events both above and below roads (Beschta, 1978; MacNamara, Ziegler, Wood, & Vogler, 2006; Montgomery, 1994; Sidle, Ghestem, & Stokes, 2014; Sidle & Ziegler, 2012; Swanson & Dyrness, 1975; Ziegler, Sidle, Song, Ang, & Duangnamon, 2012); and (e) failing of culverts (and associated sediment mobilization) during extreme rainfall events (Wemple, Swanson, & Jones, 2001). Although some eroded material accumulates on lower slopes and is subject to subsequent erosion, the remainder is often transported to the stream system during run-off events. High-density logging and unpaved roads in particular produce high sediment yields, especially if gullying and mass wasting occur on adjacent hillslopes (Anderson & MacDonald, 1998; Forman & Mellinger, 1998; Fu, Lachlan, Newham, & Ramos, 2010a; Grayson et al., 1993; Rice & Lewis, 1991; Swanson & Dyrness, 1975).

Important advances have been made in understanding the role of roads on sediment production in the tropics. Dunne (1979) highlighted the important role of roads in sediment budgets developed for small catchments in Kenya. Harden (1992) recognized the importance of rural roads and footpaths on accelerated erosion rates in the Ecuadorian Andes and included this dynamic in models she developed to assess watershed-scale sediment budgets. Anderson and MacDonald (1998) and Ramos Scharrón and MacDonald (2007c) estimated via modelling that unpaved roads on St. John Island increased sediment delivery rates by threefold–ninefold over natural rates. Earlier studies on St. John had concluded that sediment production rates from unpaved roads were several orders of magnitude higher than surface erosion rates from undisturbed hillslopes and that unpaved roads were the principle source of the fine sediment delivered to the coastal zone (MacDonald, Sampson, & Anderson, 2001; Macdonald et al., 1997). In a rural agricultural area of Thailand, Ziegler et al. (2004) found that the sediment delivery rate on native roads was more than an order of magnitude higher than that on adjacent fields. Sediment production estimates on coffee farms in Puerto Rico (11 $Mg \cdot ha^{-1} \cdot year^{-1}$) were about two-orders of magnitude higher for forests. At the farm-scale, only 2–8% of the total

FIGURE 4 Stream sedimentation from logging roads in Bukit Tarek, Malaysia (left: High density of logging roads cover the opposite hillslope; right: Hortonian overland flow exits a steep skid trail on to the main logging trail through a deep gully that has formed since logging operations ceased). Beginning in the 1990s, several research experiments were carried out in the subcatchments within the Bukit Tarek Experimental Watershed, in Peninsular Malaysia, which at the time was covered with secondary forest that had regenerated following logging in the 1960s (Noguchi et al., 1997). The site was under the auspices of the Forest Research Institute of Malaysia and provided an opportunity for detailed catchment- and hillslope-scale investigations of the hydrology of a recovering catchment. Following new logging operations conducted in the early 2000s, additional experiments were undertaken to investigate the hydrologic and geomorphologic impacts of logging road construction and timber extraction activities. Like most intensive logging operations in the region, roads were not designed to mitigate potential run-off or erosion impacts. For example, inboard ditches were not used to prevent surface run-off from flowing onto unprotected hillslopes, and road/trail surfaces were not treated with rock/gravel surfaces to reduce erosion. The logging road and skid trail length of 3,990 m in the catchment (13 ha) equated to a density of about 30 km/km^2 and was approximately seven times longer than the stream network in one basin. Sidle et al. (2004) estimated surface erosion from logging roads and skid trails to be 272 ± 20 and 275 ± 20 Mg·ha^{-1}·year^{-1}, respectively. Nearly 80% of the soil loss from the road system (including log landings) was delivered to the stream in the first 16 months after logging commenced (Sidle et al., 2004). Further, much of the surface run-off generated during storms exited the road onto the unprotected hillslope, initiating gullies (Negishi, Noguchi, Sidle, Ziegler, & Nik, 2007; Negishi et al., 2008). Sediment loading to the stream is high owing to the direct connectivity of the two systems (cf. Sidle, 2010). These impacts can be long-lasting given the persistence of roads cut deep into hillslopes to generate overland flow even after abandonment (Ziegler et al., 2007). Sidle and Ziegler (2012) portray the roads in Bukit Tarek as representative of highly intensive logging operations that have erosion rates that exceed the highest rates reported from any agricultural practices in the region. Further, they argued that such erosion and sedimentation problems related to roads are proliferating in Southeast Asia, where the impacts on the environment are under studied

sediment was attributable to cultivated hillslopes, whereas unpaved roads accounted for over 90% of the sediment budget, even though they comprise only 15% of the farm surface area (Ramos Scharrón & Thomaz, 2016). The studies at all of these tropical sites indicate that unpaved roads contribute sediment to the stream network at a rate disproportionate to the areas they occupied in their catchments.

A more extreme case of road erosion was found in our featured case study conducted in the Bukit Tarek Experimental Catchment in Peninsular Malaysia, which is a high-density logging site (Figure 4). Nearly 80% of the very high soil loss rate (on the order of 275 Mg·ha^{-1}·year^{-1}) associated with the road system, which included skid trails, was delivered to the stream in the first 16 months after logging commenced (Sidle, Sasaki, Otsuki, Noguchi, & Nik, 2004). About 60% of the soil loss was generated from erosion of the running surface; disturbed cut and fill material along the road were the sources of the other 40%. As roads and skid trails had no designed drainage systems, run-off discharged directly onto the hillslope where gullies established persistent connections between roads and the stream network. Elsewhere in the tropics, Rijsdijk, Bruijnzeel, and Sututo (2007) found that landslides occurring at the end of the rainy season in the upper Konto Basin in Indonesia boosted the already elevated erosion rates on unpaved roads. In the 44-ha Baru Catchment on Borneo, Chappell, Douglas, Hanapi, and Tych (2004) reported how a 10-year, 167-mm storm event generated 40% of the yearly total sediment yield in 1 day by triggering a debris flow and the collapse of fill material. Investigating more than 1,600 landslides in Puerto Rico, Larsen and Parks (1997) found fivefold–eightfold increases in mass wasting disturbance inside 170-m swaths along road corridors.

As shown by studies cited above, perhaps some of the most widely learned lessons regarding road impacts have been gleaned by studies conducted in both temperate and tropical regions documenting how roads alter the production and routing of water and sediment. These dynamics have important ecological implications, as demonstrated by the studies described below. Understanding the linkages between hydrology and ecology (i.e., ecohydrology) requires integrated, transdisciplinary studies among physical and ecological scientists. We highlight some of these linkages in Part 2 and call upon the ecohydrology community in Part 3 to advance our understanding of these dynamics in tropical settings, where intense development pressures, sensitive and understudied ecological systems, and unexplored ecological and social dynamics warrant more attention.

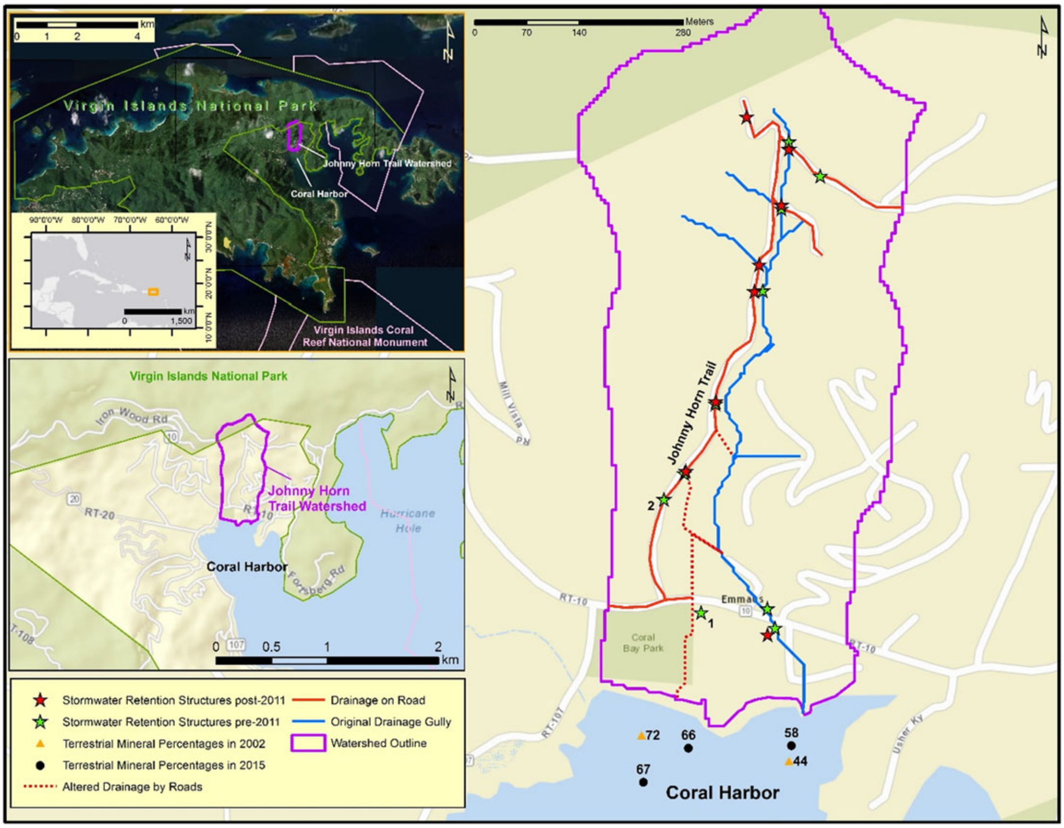

FIGURE 5 Enhanced sedimentation by roads in sensitive coastal areas, U.S. Virgin Islands Coral Harbor, St. John, U.S. Virgin Islands, has experienced a ~10-fold increase in coastal sedimentation rates since 1900 (Brooks et al., 2015). Numerous studies link enhanced terrestrial sediment input with road construction and use in St. John and the Caribbean (Bégin et al., 2014; Brooks et al., 2015; Ramos Scharrón, 2012; Ramos Scharrón & MacDonald, 2007b). Rapid new home construction in Coral Harbor, a 4-fold increase in the last 30 years (US Census, 2014), has resulted in increased usage of existing dirt roads (Reed, 2012). Dirt roads on St. John deliver greater amounts of terrigenous sediment to the coastal zone than paved roads (Ramos Scharrón & MacDonald, 2007b). The visible results of this impact, including turbid sediment plumes in the bay, have increased local concern for their vulnerable coastal ecosystems. These ecosystems (e.g., coral reefs) are critical to the fishing and tourism industries in the tropics and are pressured by increasing turbidity and sediment deposition (Brown & Tompkins, 2012; Edmunds & Gray, 2014; Edmunds et al., 2014). The Johnny Horn Trail (JHT) in St. John illustrates how rapid development within a watershed leads to increased deposition in coastal systems. JHT is a dirt road (red line above) in a small watershed along the north coast of Coral Harbor that was built during original colonization in early 1700s. In the late 1990s, JHT was still a vegetated, infrequently used path (Reed, 2012). It is closely paralleled by a natural gully (blue line) that drains the watershed (Browning et al., 2016). In the early 2000s, maintenance (grading) began on JHT, transforming it from a permeable vegetated path to semi-impermeable dirt road (Reed, 2012). This action increased overland storm water flow and triggered preferential flow down the road (red line) and onto a new path (dashed red line). This flow was delivered directly into Coral Harbor, bypassing existing water retention structures (green stars 1 and 2). A corresponding increase in regional turbidity was documented directly downslope of the new path, where before it only existed downslope of the natural gully (Reed, 2012). Surficial marine samples in 2002 (orange triangles) showed higher percentages of terrestrial minerals downslope of JHT (dashed red line) compared with samples downslope of the gully (blue line). In 2011, measures were taken to direct flows off JHT and retain storm water (using swales, rain gardens, and culverts; shown as red stars (Reed, 2012). The mineralogy was updated in 2015 and new samples (black circles) were taken from the same general areas. It was found that terrestrial mineral percentages had decreased by ~8% downslope of the road and increased by ~25% near the natural gully since 2002. This finding suggests that the swales and rain garden were successful. This example demonstrates why road placement is crucial in steep tropical watersheds that drain to sensitive ecosystems. (Unpublished data from the Browning et al., 2016 study)

3 | PART 2: ECOHYDROLOGICAL IMPACTS OF ROADS ON ECOLOGICAL SYSTEMS

3.1 | Effects of sediment loading on aquatic systems

Work conducted in tropical regions on various land disturbances, including road construction, agriculture, shoreline development, and forest loss/degradation, has shown that the downstream delivery of sediment from affected areas alters water chemistry, degrades the quality of benthic habitats, and disrupts structural functions of freshwater and marine ecosystems (Forsyth, Bubb, & Cox, 2006; Golbuu et al., 2011; Jaramillo, Baccard, Narinesingh, Gaskin, & Cooper, 2016; Latrubesse, Amsler, de Morais, & Aquino, 2009; Rogers, 1990; Wolanski, Martinez, & Richmond, 2009). The occurrence and types of benthic invertebrates specific to a river are in part controlled by the grain size of a riverbed, with cobble or pebble substrates supporting both greater diversity and abundance than sand or silt-dominated substrates (Angradi, 1999; Hynes, 1970; Minshall, 1984; Vouri & Joensuu, 1996). Fine sediment entering streams increases turbidity and/or suspended solid concentrations (Grayson et al., 1993),

FIGURE 6 Metal loading from urban roads (pictured: Manoa Stream, located in an urban neighbourhood in Honolulu, Hawaii). The finding by the National Contaminant Biomonitoring Program that fish from Manoa Stream in Honolulu, Hawaii (United States) had some of the highest concentrations of selected heavy metals in the United States prompted research to explore the linkages between stream pollution and heavy metal contamination on urban roads (Sutherland & Tolosa, 2000). An initial investigation examined a variety of trace metals in the bed sediments of a 6-km section of Manoa Stream. Sutherland (2000a, 2000b) reported high concentrations of Cu, Pb, and Zn indicating anthropogenic enhancement, with Pb the most drastically impacted. A detailed follow-on examination of background (uncontaminated) soil, roadside soils, and roads sediments indicated that Pb, and to a lesser extent Zn and Cu, were anthropogenically enriched in the Manoa Catchment (Sutherland, Tolosa, Tack, & Verloo, 2000). Given the proximity of most sample locations to roadways, the researchers concluded that automotive emissions plus vehicle wear were likely the primary contributors of metals to the roadside system draining to the stream. The Manoa study presented strong circumstantial evidence supporting a link between terrestrial Pb contamination and the highest whole-body fish concentrations surveyed by the National Contaminant Biomonitoring Program (Sutherland et al., 2000). The work demonstrated the importance of roads in generating and conveying pollutants to stream channels—even in settings that are not intuitively associated with substantial pollution. Subsequent work in Honolulu found very high concentrations of lead in the Nu'uanu Watershed (Andrews, 2002). Another study assessing the potentially bioavailable Pb in upper stream bed sediment layers of the Palolo, Pukele, and Waiomao streams in Honolulu found that contamination of bed sediments was associated with the direct transport of legacy Pb from the leaded gasoline era to stream channels via a dense network of storm drains linked to road surfaces, presenting a significant potential risk of bed sediments to bottom-dwelling organisms (Hotton & Sutherland, 2016). To add context, a recent study conducted in Singapore showed that road sediments on residential roads can have heavy metal concentrations that are comparable to industrial roads because of transport of road dust from one location to another by moving vehicles; inefficient removal of sediments and sorbed elements during sweeping; and metals also being derived from the materials to build road surfaces and traffic safety measures such as guard rails (Yuen et al., 2012). Collectively, these urban investigations revealed the importance of roads as potentially major stressors to urban aquatic environments

disrupting stream ecosystems by inhibiting photosynthesis and changing channel morphology and stability (Beschta, 1978; Brown, 1994; Eaglin & Hubert, 1993; Reid & Dunne, 1984).

Increases in sediment transport rates and turbidity in streams have been shown to decrease feeding efficiency, decouple food web dynamics, and cause physiological stress for fish in studies conducted in temperate zone systems (Schofield, Pringle, & Meyer, 2004; Shaw & Richardson, 2001; Walde, 1986). Increased sedimentation may also mediate food resource quality and quantity for algivorous consumers. Food resource quality of periphyton for macroinvertebrates that feed on them may be reduced by an increasing inorganic content (Graham, 1990; Molinos & Donohue, 2008; Suren, 2005; Yamada & Nakamura, 2002), especially when flow is moderate enough to allow particles to settle, or when abrasion of periphyton by coarse sediment occurs (Biggs, Smith, & Duncan, 1999). Such changes in food quality may affect life history traits of organisms such as ingestion rates (Kent & Stelzer, 2008). Altered texture of substratum surfaces may result in changes in retention functioning for organic matter and thus availability of types of food resources for macroinvertebrates (Parker, 1989). Changes in sedimentation and run-off patterns may promote drifting behaviour in macroinvertebrate populations (Doeg & Milledge, 1991; Imbert & Perry, 2000; Molinos & Donohue, 2008; Richardson, 1985; Rosenberg & Wiens, 1978; Shaw & Richardson, 2001). Such taxon-specific behavioural responses amplify change in the benthic community structure (Larsen & Ormerod, 2010). Excessive deposition of fine sediment from roads can change the physical nature of the substratum, resulting in ecosystem-wide responses, as found for both freshwater and marine systems in response to a variety of land-use impacts (e.g., Mattahei, Weller, Kelly, & Townsend, 2006; Rogers, 1990). For example, burial can reduce the availability of permanent and spawning habitats for fish species seeking cover above or in the benthic interstices within the substratum (Trombulak & Frissell, 2000).

Sedimentation of finegrained material originating from roads can also affect the dynamics of the hyporheos, a critical zone for various transformations of water chemistry and stream metabolism (Krause et al., 2011; Strommer & Smock, 1989; Valett, Fisher, & Stanley, 1990; Williams & Hynes, 1974). Transformations of water chemistry are dependent on physicochemical environments and depths and

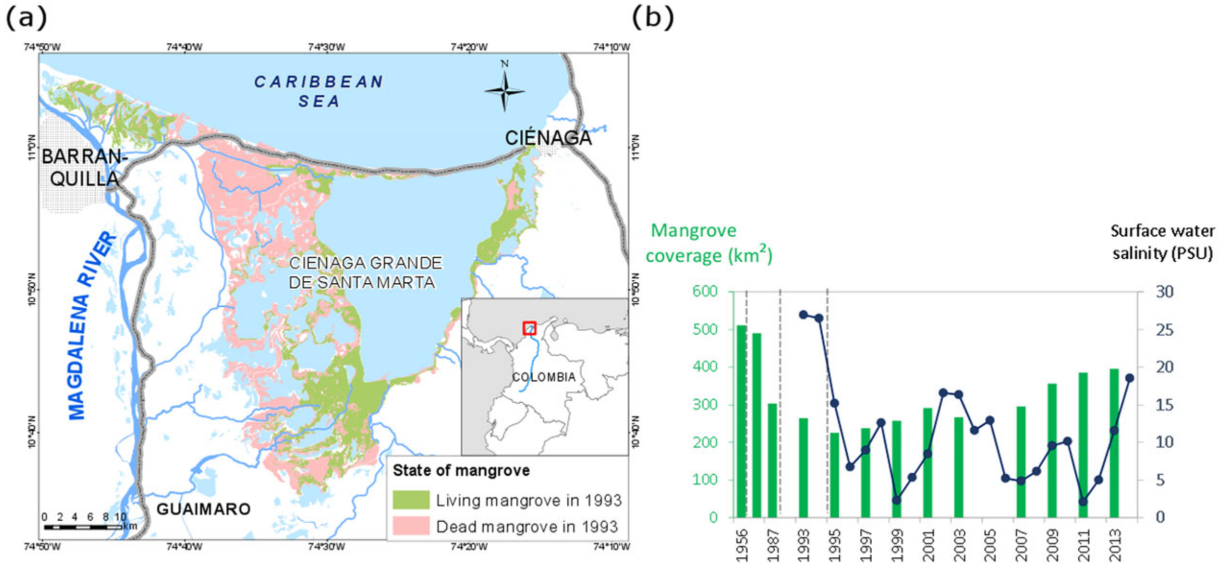

FIGURE 7 Impact of a major transportation corridor on the estuarine ecosystem of the coastal estuary complex Ciénaga Grande de Santa Marta (CGSM), Colombia. (a) The CGSM has a current mangrove population of 278 km^2 and became a United Nations Educational, Scientific and Cultural Organization biosphere reserve in the late 1990s. It is delimited on its western boundary by the Magdalena River and on the east by a coastal mountain range. The wetland also receives fresh water and sediments from the east through three main rivers that descend from the Sierra Nevada de Santa Marta. Between 1950 and 1960, a main road connecting the cities of Barranquilla and Ciénaga was constructed along the wetland's northern perimeter, blocking the flow of sea water and hindering the natural functioning of the wetland ecosystem. Additional modification and blockage of freshwater inflows from the Magdalena River, due to the construction of a road on the western side of the CGSM in 1975–1980 from Barranquilla to the settlement of Guaimaro also contributed to degradation of this aquatic ecosystem by blocking freshwater input from the Magdalena River. (b) Due to restoration efforts by environmental authorities, mangrove coverage and basal area has recovered since but will not reach original extent due to the hydrological transformations of the wetland complex after the construction of the roads and consequent hydrologic isolation. With the loss of hydrological connectivity, the wetland has lost resilience to withstand drought episodes of the El Niño/Southern Oscillation; during these periods (e.g., 2002–2004 and 2012–2015), interstitial and superficial salinity increased substantially beyond the tolerance levels of mangrove species in many areas of the wetland (geographical data and surface water salinity data supplied by INVEMAR, 2015)

residence time of hyporheic-zone exchange (Boulton, Findlay, Marmonier, Stanley, & Valett, 1998; Findlay, 1995; Jones & Holmes, 1996). Deposition of sediment substantially reduces the surface and subsurface exchange of water and shortens residence time of water, thus leading to lower dissolved oxygen levels, changes in nutrient retention, and alterations of water chemistry (Strommer & Smock, 1989; Whitman & Clark, 1982). Along with surface–subsurface exchange of water, particle size composition determines community composition of hyporheic invertebrates (Olsen & Townsend, 2003; Packman & Mackay, 2003; Richards & Bacon, 1994). Reduced interstitial flow and dissolved oxygen concentration resulting from the filling of hyporheos has been link to reduction in spawning bed quality, in particular those of salmonids (Ringler & Hall, 1975; Waters, 1995).

In some tropical environments, the far-reaching effects of sedimentation include impacts on sensitive coastal ecosystems (e.g., Richardson, 1985; Rogers, 1990; White, 1987). For example, Short et al. (2011) recently found that low-level declines in seagrass meadows at Babelthraup, Palau, were related to increased sediment loading from road construction. Sediment entering the coastal zone has the duality of bolstering the food supply within the coastal zone, while also burying, and thus suffocating, sessile organisms attached to the substrate (Bégin et al., 2014). It may also threaten other organisms by reductions in shortwave radiation needed for synthesis. Burial of coral reefs can exacerbate coral reef degradation and reduce species abundance and diversity in this fragile ecosystem (Friedlander & Parish, 1998). In one of our case studies, the Johnny Horn Trail road on St. John Island (Virgin Islands, United States) was implicated as the likely source for the enhanced sedimentation that negatively affected sensitive coral and seagrass ecosystems in Coral Harbor (Figure 5).

3.2 | Degradation of stream water quality

In addition to fine sediment, various other pollutants from road run-off can affect stream ecosystems negatively (Brown, 1994; Gilson, Malivia, & Chareneau, 1994; Lamont & Blyth, 1995; Yousef, Wanielista, Harper, & Skene, 1983; Yousef, Wanielista, & Harper, 1985). Depending on the location, rural versus urban, as well as the land use (e.g., agriculture and mining), road run-off may include a range of pollutants such as fertilizers, pesticides, herbicides, solutes, heavy metals, plastics, polycyclic aromatic hydrocarbons, mineral oil hydrocarbons, pharmaceutical contaminants, and soluble salts (Froehner et al., 2012; Göbel, Dierkes, & Coldewey, 2007; Hussain, Rahman, Prakash, & Hoque, 2015; Wang, Zhang, Wu, & Wang, 2017). Roads may even contribute to thermal pollution if run-off from hot concrete or asphalt surfaces elevates temperatures in small streams to the point of affecting dissolved oxygen concentrations or harming aquatic organisms directly (Herb, Janke, Mohseni, & Stefan, 2008).

Many studies investigating road run-off in temperate areas have focused on de-icing salts and heavy metals. The primary de-icing agent, sodium chloride (NaCl), is toxic to many species of plants, fish, and other aquatic organisms (Amrhein, Strong, & Mosher, 1992; Brown, 1994). Calcium chloride (CaCl), commonly used to decrease road dust in the tropics, may also inhibit amphibian movement (DeMaynadier & Hunter, 1995). Heavy metals or other toxic substances, which are more frequently associated with run-off on urban roads than rural/forest roads, may contaminate sediment, thereby reducing substratum suitable for macroinvertebrate colonization (Forrow & Maltby, 2000; Perdikaki & Mason, 1999). Heavy metals are relatively immobile and heterogeneously distributed along roadside areas, including drainage ditches and curb-side soils (Black, Braddock, Bradow, & Ingalls, 1985; Hewitt & Rashed, 1991; Wust, Kern, & Hermann, 1994). Road run-off during storms is the primary mechanism moving potentially harmful heavy metals into stream systems, especially lead, zinc, copper, chromium, and cadmium (Brown, 1994; Gilson et al., 1994; Kerri, Racin, & Howell, 1985; Yousef et al., 1985). Fish mortality in streams has been related to high concentrations of various metals, with negative effects on populations recorded several kilometres downstream (e.g., Morgan, Porak, & Arway, 1983). Furthermore, both high traffic volume and high metal concentrations in run-off are correlated with mortality of fish and other aquatic organisms (Horner & Mar, 1983).

The linkage between negative ecosystem effects and heavy metal pollutants entering streams from roads in the tropics is demonstrated in two of our case studies: the coastal lagoons of Florianópolis, Brazil (Figure 2) and the urban Manoa Stream in Honolulu, Hawaii (Figure 6). In another tropical study conducted in Singapore, concentrations of Cu, Pb, and Zn in road dust exceeded aquatic sediment probable-effect concentration levels, suggesting they could generate a toxic response in bottom-dwelling aquatic organisms (Yuen et al., 2012). Street sweeping was effective in removal of large organic debris and inorganic road deposited sediments, but it was ineffective in removing the geochemically important fractions <125 μm. Further, metal pollutants entering urban streams from high-density road networks are nearly unpreventable during intense and frequent tropical storms during the rainy season (see Hawaii case study, Figure 6). Difficulties in sweeping efficiency in congested urban environments exacerbate this problem (cf. Yuen et al., 2012). Less frequently studied is heavy metal loading in streams in rural areas. In one tropical study, Ling, Kho, and Nyanti (2012) attributed lead increases in the Serin River in Malaysia to contributions from vehicular sources associated with agriculture.

The chemical effects of road run-off on surface water ecosystems may be confined primarily to small streams owing predominantly to dilution in large rivers (Fennessey, 1989). Furthermore, transformations of water chemistry are dependent on the physicochemical environment and the residence time in the hyporheic zone (Boulton et al., 1998; Findlay, 1995; Jones & Holmes, 1996). Thus, there are inherent spatio-temporal scale issues at play when considering the impacts of road run-off pollution entering streams. There are also indirect ecohydrological impacts associated with road pollution. For example, the various agents applied on roads may also increase the mobility of chemical elements in soil, including some heavy metals (Amrhein et al., 1992), potentially allowing them to move offsite via subsurface flow pathways.

3.3 | Stream obstruction and landscape connectivity

The site and stream-reach scale impacts of roads highlighted above have cumulative and broad-scale ecological implications. The lens of connectivity (Bracken et al., 2013) and its application to road networks (Wemple et al., 1996; Croke & Mockler, 2001) provide useful context for these broader impacts. Roads alter connectivity through changes in hillslope-to-channel delivery mechanisms as described above and through creation of altered aquatic habitats and migration pathways. The construction of raised road surfaces and adjacent drainage ditches can create new and connected habitats for aquatic species in areas where they formerly did not exist. For example, the construction of a road through pristine tropical lowland rain forest in the Ulu Temburong National Park (Brunei Darussalam) facilitated the in-migration of eight new frog species (Konopik, Linsenmair, & Grafe, 2013). O'Neill, Rogers, and Thorp (2016) found that communities of crustaceans in artificial waterbodies, including roadside ditches, were indistinguishable from those in naturally formed wetlands. The authors attributed this finding to the increase in road density, which facilitated population increases within species that thrive in environments associated with roads. Thus, roads potentially create habitats and migration corridors for undesirable species. In contrast, Cairo and Zalba (2007) found that roads had a significant impact on redbellied toads (*Melanophryniscus* sp.) by augmenting mortality, hindering the mobility of the species, and increasing habitat isolation.

Roads can also impact aquatic connectivity by blocking pathways between water bodies, reducing the mobility of many types of aquatic species, including fish and macroinvertebrates (Gibson, Haedrich, & Wernerheim, 2005; Maitland, Poesch, Anderson, & Pandit, 2016; Ward, Anderson, & Petty, 2008). Maitland et al. (2016) recently showed that stream crossings influence abiotic habitat characteristics, restrict biotic connectivity, and impact fish community structure at whole-stream and within-stream scales (see also Perkin & Gido, 2012). Road crossings with culverts may also block the upstream passage of adult aquatic insects, thereby reducing larval density upstream of roads (Blakely, Harding, Mcintosh, & Winterbourn, 2006). Temperate diadromous species, such as salmonid fish and atyid shrimps, which migrate between upland river systems and the sea, are vulnerable to obstructions (Brown & Hartman, 1988; Resh, 2005). In tropical settings, Cooney and Kwak (2013) found that crossings on small roads occasionally hindered tropical, freshwater fish migration for sites studied in Puerto Rico. However, Hein et al. (2011), also working in Puerto Rico, did not find road crossing and culverts to be dispersal barriers for fish or shrimp species they studied. Together, these studies in tropical settings raise unanswered questions about how and where roads impact aquatic connectivity.

Recent work has also highlighted the role of roads in altering river-floodplain connectivity. The continental-scale assessment for the United States performed by Blanton and Marcus (2009) showed that roads and railroads are ubiquitous features along the floodplains of large river systems, where they limit lateral migration of alluvial rivers, thereby altering flood-pulse processes that create and maintain ecosystem function in river landscapes. In work conducted in the Pacific Northwest United States, these authors found that large river reaches adjacent to transportation infrastructure had degraded riparian forest cover, lower channel complexity in the form of channel bars and islands, and less in-stream and riparian habitat refugia for aquatic species (Blanton & Marcus, 2013).

The construction of road embankments may also alter connectivity of coastal ecosystems, including mangrove forests (Jimenez, Lugo, & Cintron, 1985), by permanently altering the flow of water and sediment (Röderstein, Perdomo, Villamil, Hauffe, & Schnetter, 2014). Modifications of hydrological regimes due to human actions appear to be the main reason for mangrove mortality in the tropics (Barreto, 2008; Sakho et al., 2011). Blockage and reductions of tidal flushing and freshwater input from by road embankments have been shown to change the structure, vigour, and mortality patterns of mangrove stands by altering salinity, nutrients, redox potentials, pH, sediment, and organic matter content (Cardona & Botero, 1998; Rivera-Monroy et al., 2011). Events of massive mangrove mortality caused by road construction, have been documented for various countries such as Colombia (Botero & Salzwedel, 1999; Restrepo et al., 2007), the Federated States of Micronesia (Allen, Ewel, & Jack, 2001), Saudi Arabia (Mandura & Khafaji, 1993), Venezuela (Barreto, 2008), and Mexico (Batllori-Sampedro, Febles-Patrón, & Diaz-Sosa, 1999). In the Colombian example where hypersalinity has been the cause of mangrove mortality, road construction contributed to more than 50% loss in mangrove area from over 50,000 ha in 1956 to 22,000 ha in 1993 in the Ciénaga Grande de Santa Marta coastal estuarine system in northern Colombia, making it possibly the largest mangrove mortality on record (Figure 7).

3.4 | Other ecological impacts

The spread of exotic vegetation is a commonly cited road impact in a diverse range of tropical locations such as in the cloud forests of Puerto Rico, the rainforests of North Queensland Australia, the dry forests of southern India, and the volcanic landscapes of Hawaii (Goosem, 2012; Jakobs, Kueffer, & Daehler, 2010; Olander, Scatena, & Silver, 1998; Prasad, 2009). Another potential indirect effect of roads and trafficking is the spread of forest diseases. For example, the transportation of fungal spores in mud carried by vehicles has been implicated in the spread of *Phytopthora lateralis* (Port Orford root disease) and *Phytophthora cinnamomi* (a mould that causes root rot or dieback) in forests in the Western United States and southern Australia (Jules, Steenbock, & Carroll, 2015; Marks, Fagg, & Kassaby, 1975; Pickering & Hill, 2007); however, see Peterson, Hansen, & Kanaskie, 2014 regarding *Phytopthora ramorum*. Indirect consequences of these types of diseases are changes in hydrological response or stream channel morphology, depending on the extent of the disease within affected forests (Weste, 1974).

A handful of studies conducted in recent years have demonstrated the capacity by which roads indirectly affect the ecology of human diseases in tropical areas (e.g., Norris, 2004; Patz, Graczyk, Geller, & Vittor, 2000). The construction of roads in previously inaccessible forested areas can lead to erosion, deposition, and the ultimate formation of stagnant ponds by blocking the flow of streams during the rainy season (Patz et al., 2000). One study showed that puddles forming on the road surface were abundant with *Lefionella pheumophila*, the bacteria that is the major cause of community-acquired pneumonia. Further, larvae of *Anopheles gambiae* (the savanna form), an important vector for malaria transmission in Burkina Faso, were found to be prevalent in small, rain-dependent, ephemeral habitats, such as puddles and road ruts (Pombi, 2004).

In Ecuador, Eisenberg et al. (2006) found that the construction of roads affected the epidemiology of diarrheal illnesses. In particular, villages closer to a newly constructed road had higher rates of infection. Although the exact mechanisms causing the increased rates were not articulated, they could be related to the role of roads channelling contaminated surface water into drinking water resources (Eisenberg et al., 2006). Elsewhere, the construction of roads in the Brazilian Amazon was shown to allow Anopheline mosquitoes to invade and colonize previously unroaded and inaccessible areas (Hassan, Scholes, & Ash, 2005). Forest-dwelling *Anopheles* species either adapted to newly changed environmental conditions or disappeared from the area, offering other Anopheline mosquitoes a new ecological niche (Hassan et al., 2005; Povoa, Wirtz, Lacerda, Miles, & Warhurst, 2001).

In Asia, the construction of roads, dams, and irrigation systems to support agriculture intensification is believed to increase the connectivity of habitats that support the complex ecological cycle of *Opisthorchis viverrini* (Sithithaworn, Ziegler, Grundy-Warr, Andrews, & Petney, 2012; Ziegler et al., 2013; Ziegler et al., 2016). This waterborne trematode parasite is believed to be a cause of cholangiocarcinoma in the Lower Mekong River Region of Southeast Asia (Sithithaworn et al., 2012). Fish ponds, created from soil excavation pits made during road construction, were stocked with fish infected with the *O. viverrini* parasite. Owing to poor sanitation conditions that promoted the return of human faeces contaminated with *O. viverrini* eggs to the ponds, these man-made water features associated with road building became new aquatic wetlands where the entire life cycle of the parasite could be completed (Sithithaworn et al., 2012).

3.5 | Synthesis of impacts

Although several authors have highlighted tropical-versus-temperate differences in stream ecology, climate and development trajectories (Boulton, Boyero, Covich, & Pearson, 2008; Easterly & Levine, 2003; Gallup, Sachs, & Mellinger, 1999; Sachs, 2001; Wohl et al., 2012), the results presented in the prior sections of this paper suggest that many of the negative influences of roads on hydrology, geomorphology, and ecology are largely driven by similar processes or phenomena: the propensity of roads to generate run-off; high sediment production rates associated with roads; high degree of connectivity of roads to stream systems; concentration of pollutants on road surfaces; physical blocking of streams and their floodplains by roads; and sensitivity of aquatic organisms to road-generated sediments and pollutants. Major differences among geographic settings tend to be related largely to the sensitivities of specific ecosystems or organisms (e.g., coral in the tropics or salmonoid fish in temperate zones), types of disease present in an area, nature of the precipitation regime (snow melt vs. intense tropical storms), and the management attitudes in different locales. This review also demonstrates that much of our current understanding of the impacts of roads on aquatic ecology has been drawn from discipline-specific research (e.g., hydrology, geomorphology, and ecology), rather than transdisciplinary approaches that render holistic assessments. In the next section, we build on the insights of the review to identify means of improving road network construction and management and to identify research needs for the tropics. We argue that future pressures, including human population growth, land-use intensification, and climate change, will require continued attention to and new research on road impacts in tropical settings. In particular, we encourage new transdisciplinary approaches, in the spirit of ecohydrology, that link methods and insights from the fields of hydrology, geomorphology, and ecology and engage with the social dynamics driving and responding to road development pressures.

4 | PART 3: RECOMMENDATIONS AND RESEARCH NEEDS

4.1 | Adopting a tropical agenda

The realm of known road-related ecohydrological impacts, reviewed in Parts 1 and 2, has motivated new calls to improve road building and management globally (Laurance et al., 2014b; Lugo & Guczinski, 2000). However, implementing sustainable or eco-friendly strategies in specific settings requires understanding the context and pressures driving road management and expansion, as well as the potential ecohydrological impacts, in particular areas. The case studies we present in Figures 1–7 illustrate a wide range of road impacts on tropical ecosystems, which can be summarized as the following: (a) construction of road networks in steep terrain to support infrastructure development (Lower Paute Basin, Ecuador; Figure 1) and resource extraction (Bukit Tarek, Malaysia; Figure 4) promotes landsliding and very high rates of surface erosion, resulting in high rates of sediment transport to streams; (b) failure to perform proper road building and maintenance leads to enhanced overland flow production and peak flows, as well as substantial road surface erosion (Pang Khum, Thailand; Figure 3); (c) roads built near the coastal zone often contribute to sediment loading to coastal estuaries containing coral and seagrass ecosystems that are sensitive to high levels of turbidity and burial by sediment (St. John, U.S. Virgin Islands; Figure 5); (d) high-density road networks in urban systems are source areas of potentially toxic metals and other pollutants entering the stream system (Florianópolis, Brazil and Honolulu, Hawaii, United States; Figures 2 and 6); and (e) the disruption of hydrologic connectivity can disrupt ecosystem function through alteration of salinity, nutrient, and sediment inputs (Ciénaga Grande de Santa Marta, Colombia; Figure 7). These impacts, although often associated with roads in temperate areas of the world, may at times differ in the tropics because of other factors, such as political and economic setting (e.g., in Ecuador, Brazil, and Thailand), infrastructure and hydroclimate (e.g., Colombia and St. John), degree of disturbance (e.g., high-density logging roads Malaysia), specific types of habitats affected (e.g., coastal systems in St. John and Colombia vs. mountain settings in Ecuador, Malaysia, and Thailand), and type of road surface, traffic, and maintenance level (e.g., rural roads vs. urban roads), as pointed out by Robinson and Thagesen (2004). This understudied situation calls for the development of a “tropical agenda” that recognizes these differences as a fundamental starting point for the implementation of sound management strategies, as well as new research if needed to guide policy.

As the human population grows, additional infrastructure will be needed to support basic needs such as water, power, food, and healthcare. Meeting these needs generally requires the expansion of transportation networks. Of particular importance is the construction of roads to support/access remote locations of mining, logging, or hydroelectric operations, as demonstrated in our case study in Ecuador (Figure 1). During road expansion, dirt roads are often the first built and are therefore prevalent in the typical emerging economies found in the tropics, especially in rural and mountainous areas (Sidle & Ziegler, 2012), as outlined by the research conducted in the northern Thailand case study (Figure 3). Dirt roads in regions of steep terrain degrade rapidly, are rarely repaired properly, and often go without maintenance or the application of known best practices to mitigate erosion (Sidle & Ziegler, 2012). In addition, many are built in environments where their physical presence degrades the environment producing deleterious effects on downstream aquatic systems, such as coral reefs and seagrass beds at the St John study site (Figure 5) and mangroves at the Colombian case study location (Figure 7). In Ecuador, uncontrolled river rock and sand mining for house and road construction is now deeply modifying river habitats, water quality, and linked ecological and hydrological processes (Celi, unpublished data). Laurance et al. (2014b) claim that globally, road proliferation has been chaotic or poorly planned and the rate of expansion has often overwhelmed the capacity of environmental planners and managers.

Compounding these issues is that some of the fastest and most rapid development is occurring in developing countries where political agendas are often focused on strengthening the economy, improving infrastructure, bolstering national security, achieving self-sufficiency, and increasing citizen well-being, often at the expense of the environment, particularly with respect to road building (Figures 1–3 and 5). Rigg (2016) argues that in time, development typically becomes increasingly environmentally friendly for a range of reasons, but this transition may not occur in all cases. For example, the importance of developing roads to support economic growth in Singapore, one of the most developed countries in the tropics, often supersedes environmental conservation (e.g., the redevelopment of Bukit Brown; Han, 2013). Activism and research on human mobility, road and associated development impacts on ecosystems, and designing sustainable cities have gained some traction in urban locales of the tropics, as illustrated in our case in Florianópolis, Brazil (Figure 2) though economic resources and political constraints limit progress. We believe that these social dynamics associated with road development warrant much more attention in tropical settings than previously given, because these social dynamics will ultimately impact ecohydrological processes.

In most cities, the need to channelize streams to reduce flood risks, which arise from aggressive urbanization, outweighs preserving stream ecology, as is the case in Hong Kong and Bangkok (D. Dudgeon, personal communication, August 2016). This issue is amplified in cities that are naturally low-lying or have experienced subsidence from groundwater pumping, such as the case in several Southeast Asian cities (Feng et al., 2008; Phien-wej, Giao, & Nutalaya, 2006). In many developing countries, insufficient attention has been given to mitigating ecohydrological impacts of roads, both rural and urban (cf. van der Ree, Smith, & Grilo, 2015). With all these issues in mind, we argue that reducing the ecohydrological impacts of roads in these areas requires new research that will lead to sound planning, design, and management strategies, as well as a better understanding of the processes and phenomena that are driving substantive road impacts in developing areas of the tropics and other areas where limited work has been done to date.

4.2 | Improving road network management

Due to the conditions prevalent in tropical areas and the heightened sensitivity of some tropical ecosystems, including coral reefs, seagrass, mangroves, and primary forest, avoiding fragile and undisturbed areas is the best strategy for preventing road impacts (van der Ree et al., 2015). However, given the current trends in road network expansion in the tropics and projected increases in human population, road building and expansion will almost certainly continue to occur, even in sensitive areas (Laurance et al., 2014b; State of the Tropics, 2014). Several authors give sound advice with respect to planning, design, construction, and maintenance of roads (e.g., Goosem, 2007; Gunderson et al., 2005; Robinson & Thagesen, 2004; Sessions, 2007; Wong, Breen, & Lloyd, 2000). Common themes from the literature for both road construction and remediation of eroding road segments include

a. Minimize building roads on steep slopes and in hillslope hollows; attempt, where possible to place roads onto ridgetop positions in the steepest terrain where impacts to hillslope processes can be minimized, as demonstrated in the Pacific Northwest of the United States (Swanston & Swanson, 1976);
b. Design roads using accepted standards to employ outsloped roads where possible, minimize water accumulation on the road surface and channelization in in-board ditches, and reduce erosion both on the road surface and adjacent road prism (Sessions, 2007);
c. Employ flow dissipation and erosion control devices on steep roads to prevent severe erosion of road surfaces and gully formation below culvert outlets and other hillslope drainage locations (Wong et al., 2000);
d. Pay particular attention to the design and placement of bridges and other types of stream crossings to minimize disturbance during construction, limit the discharge of sediment and other pollutants during run-off events, and avoid the obstruction of the movement of aquatic species (Robinson & Thagesen, 2004; Sessions, 2007;
e. Minimize riparian vegetation fragmentation and consider natural channel migration processes along higher order alluvial rivers, taking care to maintain intact riparian zones, and keep road infrastructure outside the flood zone, where costly damages can occur and where flood-pulse events maintain important riverine processes (Blanton & Marcus, 2009; Goosem, 2007).

Additional insight can be gleaned from the reviewed case studies conducted within tropical settings (Figures 1–7). For example, the design and planning of roads should be done with consideration for the natural geographical setting, rainfall intensities, and ecology of the area to minimize impacts during and after construction. Management strategies in urban versus rural settings might differ in focus because of unique stressors and different histories of disturbance. Roads that access coastal zones are especially problematic owing to effects of the harsh environment on the road (e.g., storm surges and high-salinity water), the sensitivity of coastal ecosystems to inputs of materials that run-off from roads (e.g., Florianópolis, Brazil and St. John Island, United States; Figures 2 and 5) and the potential for road embankments to block natural flows (e.g., mangrove ecosystem in Colombia; Figure 7). Countries that do not regulate road building and maintenance may consider implementing programmes to prevent *ad hoc* road construction that will impede larger environmental protection objectives (e.g., Thailand and Colombia; Figures 3 and 7). Further, construction and maintenance should be conducted in dry seasons, rather than the wet seasons in monsoon climates when storms are frequent and occasionally large (Figure 3).

Special care should be taken in remote areas and mountain environments where erosion and mass wasting processes can be severe (e.g., in remote areas of Ecuador, Thailand, and Malaysia profiled in our case studies). Attempts should be made to reduce the hydrological connectivity between the road and stream networks, particularly in areas with high-density road systems, for example, in plantations and logging areas (e.g., Bukit Tarek, Malaysia; Figure 4). Finally, new evidence is pointing for the need to limit the formation of zones of stagnant pools of water (roadside ditches and fill-dirt excavation ponds) that may create unnatural habitats for unwanted species, including disease pathogens. Again, the building of roads and other infrastructure features (dams and irrigation canals) has little-known effects on the dispersal and ecology of many waterborne parasites. These common themes and insights are recommendations, based largely on current research, as to how the negative effects of roads on ecohydrological processes can be reduced. As we have mentioned throughout, the full impacts of roads are not completely understood, and more research is necessary to adequately manage road-related construction and maintenance activities.

4.3 | Research needs and opportunities

Wheeler, Angermeier, and Rosenberger (2005) noted that although highway construction was pervasive and had severe biological consequences, there were few investigations regarding the impacts of such construction on streams. Subsequently, little was known about the occurrence, loading rates, and biotic responses to specific contaminants in road run-off. They called for an increased understanding of how highway crossings, especially culverts, affect fish populations via constraints on movement and how highway networks alter natural regimes including streamflow and temperature. A decade later, this dearth of knowledge is still arguably the case for most types of road networks, particularly those in the tropics. Notable work conducted in the tropics to date includes studies examining the impacts of roads on coastal ecosystems (e.g., Bégin et al., 2014; Ramos Scharrón & MacDonald, 2007a, 2007b; Ramos Scharrón, Torres-Pulliza, & Hernández-Delgado, 2015) and the general impacts of roads used in timber extraction operations (cf. Bonell & Bruijnzeel, 2005; Bruijnzeel, 1990; Douglas, 1999). In one example, Dias, Magnusson, and Zuanon (2010) demonstrated the potential of reduced impact logging (including the minimizing of logging roads) as an alternative to clear-cutting in the Amazon.

Although this growing body of work has provided insights for managing roads, additional research on the impacts of roads on specific ecosystems in the tropics is still needed. There is still a need to identify and prioritize the variables for quantifying road effects on aquatic ecosystems in diverse settings. For example, much work addresses chemical loading from roads in urban streams (Drapper, Tomlinson, & Williams, 2000), but fewer studies attempt to quantify the negative effects of chemical pollutant inputs from roads in agricultural areas (e.g., Donald, Hjelmfelt, & Alberts, 1998; Ling et al., 2012; Withers et al., 2009). In many areas in the tropics, agricultural intensification is being achieved through increased applications of fertilizers and pesticides (Keys & McConnell, 2005; Laurance et al., 2014a; Sangchan et al., 2012; Smithson et al., 2004; Ziegler et al., 2009). Additional monitoring studies are needed to identify threshold concentrations of harmful materials that trigger negative ecosystem-wide responses on habitat viability, ecological interaction, mortality, and productivity (e.g., Kaller & Hartman, 2004). These responses may be species- or family-specific; and some organisms may emerge as important indicator species for identifying road-related impacts on aquatic environments (e.g., as salmon and trout are in some temperate areas). Alternatively, mesocosm experiments could identify thresholds of toxicity, for example, those associated with heavy metals or other potentially harmful materials that are sorbed to road dust (cf. Clements, 1991).

In the spirit of truly transdisciplinary work promoted in ecohydrology, we also see a need to link sediment loading research with work addressing metal sorbing to investigate its role as a factor in ecosystem degradation (Solomon et al., 2009). Research should also examine the effects of nutrient cycling on solute retention and processing rates (Grimm et al., 2003; Kadlec & Reddy, 2001). Given the sensitivity of coastal ecosystems, one or all of these impacts may degrade a particular community. Overall, more work is needed to link road-induced run-off changes with negative responses in sensitive coastal communities, such as coral reefs, mangrove forests, and seagrass beds (Bégin et al., 2014; MacDonald et al., 1997; Short et al., 2011). Study is also needed on the effectiveness and feasibility of alternative management or remediation strategies—for example, natural riparian buffers, artificial wetlands, storm water retention structures, road drainage improvements, and alternative surfacing to reduce sediment detachment (Ramos Scharrón, 2012; Ziegler & Sutherland, 2006). Road reclamation or decommissioning (e.g., Luce, 1997; Tarvainen & Tolvanen, 2016) has rarely been investigated as a means of reducing long-lasting road impacts in the tropics. In one study conducted at the Bukit Tarek research site in Malaysia, abandoned roads continued to generate road run-off because of interception of subsurface flow, as infiltrability of the road had not been restored (Ziegler et al., 2007).

Apart from ecohydrological perspectives, trade-offs between livelihoods and environmental concerns related to rural development and road construction should be considered further (Bonell & Bruijnzeel, 2005). More evidence is needed to convince advocates of new roads to implement design standards and policies that serve both local interests and international environmental expectations (cf. Fairhead & Leach, 1995). Compromise solutions may be needed to reconcile development with conservation needs (Caro, Dobson, Marshall, & Peres, 2014). Road impacts are also typically affected by social settings, demographics, and levels of development at different scales ranging from countries (e.g., a national road network) to communities (e.g., urban road network), to singular tracks of land (e.g., temporary access road). Transdisciplinary approaches, involving ecologists, engineers, physical scientists, social scientists, economists, and government officials, may be best suited for investigating these issues, which have great complexity (e.g., Bring, Asokan, Jaramill, et al., 2015; Stærdahl, Schroll, Zakaria, & Abdullah, 2004; Ziegler et al., 2016).

Databases for road impact investigations can be developed by linking multiple disciplinary datasets. Although remote sensing products can provide spatial land change information, continuous monitoring stations can provide high-resolution ecohydrological data that show temporal changes across important time scales: diurnal, synoptic (in response to a storm event), seasonal, or multi-year. Although advances have been made in modelling road run-off and erosion (see review by Fu, Lachlan, Newham, & Ramos, 2010b), many of the popular models used to assess catchment impacts of development are unable to include roads explicitly. New work should also target the space and time scales at which various stressors are important. For example, road erosion and sediment/pollutant loading in many areas of the tropics have distinct seasonality (Ziegler et al., 2001b). In addition, sediment transport to streams is often high immediately following construction but diminishes over time (Megahan, 1974). However, degradation of ecological systems and species loss may be lagged (Findlay & Bourdages, 2000). Thus, there is a need to better understand how various ecohydrological impacts may operate on different time and space scales.

With respect to governance, Gunderson et al. (2005) stress that at national and regional scales, environmental issues associated with road impacts are often treated as permitting issues to protect particular types of lands (e.g., wetland) or threatened species, rather than dimensions of an overall project design to address myriad negative consequences. They argue that governments should (a) provide policy, guidance, and funding for transportation design and decision-making that take ecological processes into account; (b) expand the knowledge base for assessing potential effects of transportation activities through nationally funded research projects; and (c) encourage cross-disciplinary dialogue between engineers, ecologists, and other environmental professionals to raise mutual awareness of each other's expertise, needs, and challenges (Gunderson et al., 2005).

As road network expansion is inevitable, at least for the time being, we as scientists have a responsibility to study systems that we may not have had access to before and to look for compromise solutions to limit the ecohydrological impacts (Caro et al., 2014). We see the construction of roads—and other major infrastructure projects—as opportunities for builders to work with scientists to gain knowledge about particular ecosystems. For example, if trees are to be removed permanently, the carbon biomass can be measured by scientists before construction begins to augment databases needed for climate change investigations (Yuen, Ziegler, Webb, & Ryan, 2013). Pre-construction biodiversity surveys should also be encouraged to facilitate long-term impact monitoring, which will ultimately lead to better road building/managing strategies both *in situ* and elsewhere. This "type" of research differs from environmental impact assessments, as it would be implemented after the road project is approved, thereby reducing the conflict between conservation advocates and those championing the road.

Finally, we need to consider how climate change will impact temperature and precipitation regimes in many tropical areas, with potentially important implications for aquatic ecosystems that are already impacted by roads (IPCC, 2013; Trenberth, 2011). Many climate change projections have demonstrated that tropical temperatures are increasing, precipitation patterns are changing, "norms" are strengthening with dry areas getting drier and wet areas getting wetter (Greve et al., 2014), and storms are intensifying (Boulanger, Martinez, & Segura, 2007; Coelho & Goddard, 2009; Hulme & Viner, 1998; Johns et al., 2003). Despite considerable uncertainties in climate change projections, it is likely that a warmer planet will intensify the hydrological cycle (*sensu* Huntington, 2006), potentially increasing the magnitude of extreme events, such as large storms, floods, and cyclones in some locations (IPCC, 2013; Trenberth, 2011; Ziegler et al., 2003). In areas where tropical rainfall events become more intense, accelerated erosion rates could result in stream ecosystem degradation from increased sediment and nutrient loading (Casimiro, Labat, Guyot, & Ardoin-Bardin, 2011; Costa, Coe, & Guyot, 2009; Dore, 2005; Guimberteau et al., 2013; Jaramillo et al., 2016; O'Gorman, 2015). Increased rainfall may also affect flow regimes, with changes likely amplified in catchments with dense road systems. These changes are expected to alter stream hydro-geomorphological processes that affect aquatic systems, leading to potential ecological disturbances, including freshwater fish extinction in the biodiversity-rich tropics (Eliot, Finlayson, & Waterman, 1999; Food and Agriculture Organization of the United Nations, 2006; Xenopoulos et al., 2005). Moreover, there are exacerbated secondary effects associated with changes in drainage network structure and connectivity (De Wit & Stankiewicz, 2006).

Biodiversity datasets that are suitable for assessing how climate and road changes contribute to species extinctions still need to be developed. Additionally, the potential temperature and precipitation changes may increase the vulnerability of plants to diseases (Chakraborty, Tiedemann, & Teng, 2000) or lead to unprecedented biome shifts (Hilbert, Ostendorf, & Hopkins, 2001; Loarie et al., 2009; Pounds, Fogden, & Campbell, 1999), potentially altering the way roads interact with the landscape where they have been built. Integrated climate change impacts related to peak discharges, erosive flows, and hydrological extreme events are very likely to add pressure on the stream ecosystem functioning and biodiversity, which are often already adversely affected by roads and urbanization (e.g., Meyer, Sale, Mulholland, & Poff, 1999; Nelson et al., 2009 and Palmer et al., 2008). Therefore, new monitoring data and studies, drawing in an integrated fashion on the fields of hydrology, geomorphology, and ecology, are worthwhile for understanding the mechanisms of how changing climate patterns, land-use conversion, and road building will collectively affect tropical ecosystems.

5 | CONCLUSION

Despite decades of realization that roads often have negative impacts on aquatic environments, scientists, managers, and planners all too often fail to adequately address them within the high pressure developing areas of the tropics. The challenge remains to properly identify the primary drivers and mechanisms influencing road-related environmental disturbances and to uncover important process interactions that span the realm of hydrological, geomorphological, ecological, and social (including governance) dynamics. The seven case studies we summarize from Ecuador, Brazil, Thailand, Malaysia, the United States, and Columbia demonstrate some of the diversity and complexity of the impacts associated with road building and maintenance throughout the tropics, as well as other locations worldwide. Those studies, and others mentioned in the review, demonstrate that although good work has been done on understanding road-related hydrological and geomorphological (sediment loading) impacts in the tropics, less work has been directed at understanding the direct and indirect impacts of roads on aquatic organisms. Researchers in future endeavours should impress upon their colleagues to hone their research and attempt to reveal the drivers underlying road impacts on ecohydrological systems to facilitate sustainable development and management in ecologically sensitive areas. Meanwhile, society should prepare for the likelihood that a changing climate may create additional stressors on aquatic systems in general, in particular, those negatively affected by road run-off during storms. We believe that not only are new research projects and experiments needed but new frameworks should be employed, including transdisciplinary approaches, that will facilitate the study of complex natural and anthropogenically affected systems over a wide range of temporal and spatial scales.

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