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Review

A review of surface erosion and sediment delivery models for unsealed roads

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ABSTRACT

This paper reviews available models for estimating surface erosion and sediment delivery to streams from unsealed roads. It summarises current progress and identifies directions for ongoing research and model development. The paper provides a framework for assessing road erosion and sediment delivery models and it includes an overview of road erosion and sediment delivery processes and how they are commonly represented in models. Seven road models are reviewed in terms of their representations of erosion and sediment delivery processes, assumptions, application and limitations. While simple models are thought to be more useful and easily applied for land management purposes, more complex models provide a basis for building and consolidating scientific knowledge. This article reveals some of the limitations and needs of existing road erosion models. These include limitations of their ancestor hillslope erosion models, the imbalance between representation of erosion processes versus sediment delivery, a lack of representation of subsurface flow interception and the lack of model testing and uncertainty analysis. One of the most fundamental limitations to developing improved models of road erosion and delivery is access to data of an appropriate standard.

1. Introduction

The significance of unsealed roads to off-site water quality decline is widely acknowledged, especially in forested catchments (Anderson and MacDonald, 1998; Croke et al., 1999b; Forsyth et al., 2006; Grayson et al., 1993; Motha et al., 2004; Ramos-Scharrón and MacDonald, 2007c). Erosion rates from unsealed roads have been shown to be much greater than in adjacent undisturbed hillslope areas. For example, Ramos-Scharrón and MacDonald (2007b) and Croke et al. (1999b) observed erosion rates of four and six orders of magnitude higher than from undisturbed hillslope areas in the U.S. Virgin Islands, and coastal southeast Australia, respectively. The development of cost-effective land management decisions requires an adequate understanding of road erosion and sediment delivery processes for effective planning and execution of mitigation activities. Road erosion and sediment delivery models provide a quantitative tool to assess and guide those activities.

The general approaches used to quantify erosion from roads include field-based roadside or stream monitoring, sediment tracing experiments and the use of road erosion models. Roadside sediment traps provide useful information on coarse sediment yields (i.e. sand and gravel) but they are prone to losses of the finer sediment fractions (i.e. clay and silt) (Robichaud and Brown, 2002; Ramos-Scharrón and MacDonald, 2007b). Highly variable bedload inputs and the unpredictable efficiency of sediment traps results in high uncertainty in measured sediment yields when sediment trap data is used to estimate total sediment yields (Sheridan and Noske, 2007). Other more reliable but field-intensive and expensive monitoring methods are available. For example, Sheridan et al. (2006) use a design consisting of a bedload trap, a tipping bucket for measuring discharge, and a split sampler for measuring suspended load. Stream monitoring techniques can provide information on the integrated effect of variable sources of erosion but the contribution from roads at the catchment scale is often difficult to specify due to the mixing of sediment from multiple sources and the complexity of processes controlling sediment routing and deposition.

Environmental tracers such as fallout radionuclides have been used successfully in forest road erosion studies to isolate the sediment contribution of roads at catchment scales (Wallbrink et al., 2002). However, many sediment tracing results are affected by factors such as stream water geochemistry, organic matter and particle-size sorting (Foster and Lees, 2000). The influence of these factors can make interpretation of sediment tracing results difficult (Fu et al., 2006).

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Models have the advantages of allowing catchment-scale assessment which is an important consideration for prioritising catchment management effort. Model results can be used to reconstruct the effects of past disturbances, assess current conditions or estimate future management scenarios. Models used to assess other aspects of water quality have been extensively developed and applied in the last half century, and are therefore more highly developed and have been more thoroughly tested than road erosion models.

The purpose of this review is to take stock of recent progress in road erosion modelling and to provide guidance for future research and model development. The review is constrained to focus on techniques for estimating surface erosion and delivery of road-derived sediment to streams. No consideration is given to in-stream processes.

2. Overview of road erosion and sediment delivery processes

The integrated effect of erosion and sediment delivery dictates the amount of sediment reaching a stream or any other waterbody. For the purpose of this paper, road erosion is defined as sediment detachment and deposition processes occurring on the surface of road features, including cutslopes, ditches and fillslopes; sediment delivery specifically refers to the delivery of eroded sediment from road features to stream networks. Mass wasting processes are not considered here.

2.1. Definition of road features

Unsealed roads lack surface protection afforded by tar- or cement-based materials. A typical unsealed road cross section contains all or a subset of the features shown in Fig. 1. A consistent nomenclature is used throughout this paper but terms may vary locally.

The road surface is the compacted area used to support traffic. A ditch is the drainage structure along one or both sides of a road that acts as a conduit for runoff and associated sediment. Road surfaces can be insloped, outsloped or crowned. Insloped roads deliver runoff to the ditch while outsloped roads deliver runoff to the fillslope, usually via a diffuse pathway. Ditches are usually absent on low traffic, outsloped roads. Crowned roads deliver part of their runoff to a ditch and part to a fillslope. Cutslopes are the slope of a cutting, while a fillslope is the slope of a fill. The hillslope connecting the fillslope to a stream is referred to as the lower hillslope area, while the hillslope above cutslopes is referred to as an upper hillslope area.

The two most common drainage structures used for unsealed roads are: (i) mitres/push-outs and (ii) culverts. A mitre/push-out is an excavated drain constructed at an angle to the road, allowing runoff to drain away from the road surface and onto a fillslope or a lower hillslope area. A culvert is a conduit constructed under the road surface that delivers runoff from a ditch on the upper hillslope side of a road. A road segment is that length of road draining to a drainage structure or stream-crossing. The width of the road surface is the distance between the break from the cutslope or the ditch to the road surface, to the break of slope from road surface to the ditch or the fillslope. The contributing road surface area is the upslope area of road that connected to a drainage point. It is usually determined by the combination of the effective road width and the road segment length.

2.2. Factors affecting erosion from unsealed roads

Sediment can be eroded from all road features. On unsealed roads, road surface erosion is generally the dominant source of sediment (e.g. Ramos-Scharrón and MacDonald, 2007b), and much more common than mass wasting (Ketcheson et al., 1999). The factors affecting surface erosion from roads include rainfall intensity and duration, snowfall, the characteristics of surface materials, the hydraulic characteristics of the road surface, road slope, traffic, construction and maintenance, and the contributing road area (MacDonald and Coe, 2008). Rainsplash and flow energy are the primary energy sources that cause surface erosion of road features in most areas.

Snowfall can also influence erosion processes. Snow cover, especially when prolonged, reduces erosion by shielding the road surface from raindrop energy and by slowing overland flow at the snow–soil interface. The result is that surface erosion rates on roads during snowmelt are considerably less than during rainfall events. This is illustrated by Vincent (1985) who showed that the road surface sediment yields caused by snowmelt in the mountains of Idaho, U.S. were less than 10% of the total annual sediment production, while the remaining 90% was caused by rainfall.

Snow also affects the road surface hydrology. Although snowmelt rates are usually relatively lower than rainfall rates, the additional runoff generated during rain-on-snow events and the increased duration of saturated conditions can be a trigger of increased erosion, mass wasting and suspended sediment yields in

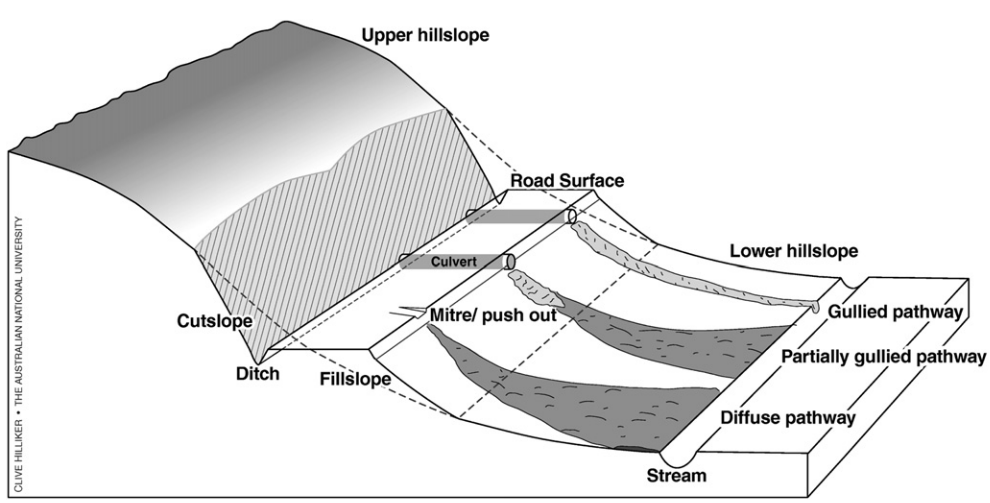

Fig. 1. A typical cut-and-fill road cross section and features. The dashed lines indicate the hillslope profile prior to the construction of the road.

streams (Bulygin et al., 2006; Harr, 1981; Pentz and Kostaschuk, 1999; Rekolainen, 1989; Weigert et al., 2003).

The surface materials of unsealed roads are often locally sourced and may contain a high proportion of fine particles that are easily eroded. The erodibility of road surface materials is determined by many attributes including cohesiveness, particle-size distribution, organic matter content, and permeability (Geeves et al., 2000). Road surfaces that have low cohesiveness, high silt or fine sand content, low rock or gravel content, and low organic content tend to be most erodible (Geeves et al., 2000). Unsealed road surfaces have typically low infiltration rates due to compaction, which lead to higher level of infiltration excess overland flow than on undisturbed hillslope areas (Croke et al., 1999a; Ramos-Scharrón and MacDonald, 2007c). With little vegetation cover, unsealed road surfaces typically have much greater erosion rates than adjacent hillslope areas. Concentrated flows in ruts have been observed to be a dominant sediment source from unsealed roads (Elliot et al., 1999a) but exceptions have been noted (e.g. Sheridan and Noske, 2007).

Slope steepness has long been recognised as an important factor in soil erosion by water (Wischmeier and Smith, 1965) with steeper roads tending to have greater erosion rates. Ramos-Scharrón and MacDonald (2005) demonstrated that sediment yield increases exponentially with increasing road slope for roads that are regularly graded (at least once every two years). Luce and Black (1999) found that sediment yield normalised by slope length is linearly related to the square of the road slope.

Traffic volume has been observed to be one of the major factors affecting surface erosion from unsealed roads (Grayson et al., 1993; Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005; Reid and Dunne, 1984; Sheridan and Noske, 2007; Ziegler et al., 2001b). This is because the coarse particles on the road surface can be broken down by vehicles through crushing and abrasion. Fine particles below the surface layer may also be pumped to the surface by compaction caused by traffic (Reid, 1981; Dubé et al., 2004). More frequent traffic (Croke et al., 2006; MacDonald et al., 2001), heavier vehicles (Sheridan and Noske, 2007), and traffic during wet weather (Coker et al., 1993; Ziegler et al., 2001b) all result in higher sediment yields. As an illustration, Croke et al. (2006) found that sediment yields (normalised by road length and slope) are up to 30 times greater on high traffic roads than low traffic roads in coastal southeast Australia.

Newly constructed roads often have higher surface erosion rates than older roads. This is likely due to the protection afforded by vegetation and/or rock armouring of the road surface, cutslopes, ditches and fillslopes on older surfaces (Megahan, 1974). Some maintenance activities such as grading may also increase road runoff and surface erosion in the first few years due to disturbance of the road surface (Forsyth et al., 2006; Luce and Black, 1999). Sugden and Woods (2007) reported 63% and 86% declines of sediment yields in the second and third year, respectively, after grading in western Montana, U.S. A similar trend is also reported for forest roads in the U.S. Virgin Islands (Ramos-Scharrón and MacDonald, 2005). However, it is important to note that not all road maintenance activities increase sediment yields. Well maintained roads may also be better drained, resulting in lesser sediment delivery to streams in the long term.

The role of cutslopes on road erosion, including generating additional runoff and sediment, has been investigated in several studies (Croke et al., 2006; La Marche and Lettenmaier, 2001; MacDonald et al., 2001; Megahan et al., 2001; Riley, 1988). MacDonald et al. (2001) reported that subsurface flow interception from cutslopes increases road runoff, and hence road surface erosion, and is mainly controlled by the area of the upper hillslope. Cutslope erosion caused by rainsplash, surface flow and mass failure can also be significant in some areas. For example, sediment yields of up to about 250 t ha^{-1} yr^{-1} were reported from granitic cutslopes on forest roads in Idaho, U.S. (Megahan et al., 2001). These yields are roughly equivalent to the road surface erosion rates of 200–250 t ha^{-1} yr^{-1} reported for the same area (Ketcheson et al., 1999). Several characteristics of the cutslope, including slope, height, vegetation cover, geology and soils were identified as affecting erosion rates from the cutslope (Collison and Anderson, 1996; Megahan et al., 2001). Collison and Anderson (1996) found that vegetation cover played a significant role in controlling cutslope stability together with the permeability of the soil, soil strength and the cutslope height. However, Megahan et al. (2001) reported that the slope of the cutslope may be a more significant factor than its height in affecting sediment yields. No studies were found that investigated the delivery potential of sediment generated from cutslopes independent of the road surface, but delivery ratios of up to 75% have been assumed by Ramos-Scharrón and MacDonald (2007b). This is likely due to the difficulty in distinguishing sediment from cutslopes and road surfaces once mixed. An analysis of particle-size fractions may suggest the delivery potential of cutslope sediment. Sediment tracing techniques may also be useful to discriminate sediment from cutslope and road surface sources.

Studies of erosion from ditches and fillslopes are less detailed than studies of road surfaces and cutslopes. This is likely due to a perceived small long-term contribution to road erosion and the difficulty in distinguishing sediment from ditches and road surfaces once mixed. Nevertheless, ditches and fillslopes are potentially important sediment sources particularly when erosion is caused by scour from road runoff. Ditches may deepen or widen, or be filled with deposited sediment during rainfall events (Croke et al., 2006; Lane and Sheridan, 2002). Sediment eroded from the road surface and deposited in ditches or on fillslopes can be remobilised in subsequent rainfall events. Croke et al. (2006) reported that while coarse sediment is usually trapped in ditches during most low to moderate rainfall, it is washed off in large events (rainfall intensity greater than 110 mm h^{-1}). Uncompacted fillslopes are prone to sheet and rill erosion and scour, especially from concentrated flow from drainage outlets. Lane and Sheridan (2002) suggested that fillslope erosion was primarily responsible for bedload sediment downstream of a road-stream crossing in the Central Highlands of Victoria, Australia, during a five-month period of monitoring.

Mass wasting processes may be significant sediment sources from cutslopes and fillslopes, especially in steep and wet forested regions (Sidle et al., 2006). Such processes include instantaneous and progressive mass failures (Megahan et al., 1978, 1983; Swanson and Dyrness, 1975; Wemple et al., 2001) and dry creep (Megahan, 1978). Mass wasting processes are most often observed on cut-and-fill roads but may also be triggered by high drainage concentrations from ridge-top roads (Montgomery, 1994). Mass wasting occurs as a result of processes that differ from those responsible for surface erosion and hence models of mass wasting warrant separate evaluation to those of road surface erosion. This paper focuses on models of surface erosion only.

2.3. Road surface erosion rates

Road surface erosion rates have been previously reviewed (Dubé et al., 2004; Ramos-Scharrón and MacDonald, 2005, 2007c). These reviews considered a range of roads with different locations, lithologies, climate zones, road conditions and traffic levels. Dubé et al. (2004) reviewed 17 road erosion studies, most conducted in mountainous regions of the western U.S.. The annual sediment yields ranged from 0.4 g m^{-2} mm^{-1} yr^{-1} (mm refers to rainfall) for non-traffic roads to 860 g m^{-2} mm^{-1} yr^{-1} for fine gravel surface roads under moderate to heavy use (Dubé et al., 2004). Ramos-Scharrón and MacDonald (2007c) reviewed studies of small scale erosion from unsealed roads. The sediment concentrations they reported ranged from less than 100 mg L^{-1} to up to 227,000 mg L^{-1}. These reviews suggest a very large range of road erosion rates across different areas. Table 1 provides a summary of estimated road erosion rates from studies published since 2000.

2.4. Road sediment delivery to stream networks

Almost all unsealed road surfaces are erodible, but not all eroded materials reach streams. This is due to deposition between the original location of the sediment, drains and streams. Factors affecting the efficiency of sediment delivery from roads include the placement and type of drainage structures, the distance from drainage outlets to streams, contributing area, hillslope slope and degree of concavity and the trapping efficiency of obstructions (Megahan and Ketcheson, 1996).

As shown in Fig. 1, surface flow is usually drained to ditches, after which it is redirected by mitres/push-outs or culverts. Road-derived sediment can reach the stream directly at road-stream crossings, and indirectly via diffuse, partial or fully gullied pathways. Diffuse and partly gullied flow pathways are less effective than fully gullied pathways in delivering sediment to streams (Croke and Mockler, 2001; La Marche and Lettenmaier, 2001).

The most efficient form of sediment delivery occurs at road-stream crossings where virtually all generated sediment is delivered to a stream (Croke et al., 2005; Lane and Sheridan, 2002). Lane and Sheridan (2002) investigated the impacts of road-stream crossings on downstream water quality in the Central Highlands of Victoria, Australia, and showed that a coarse-fragment metalled road increased suspended sediment loads by 250% downstream from a road-stream crossing. Most of the sediment was observed to be sourced from the fillslope and the unsealed road side.

Partial or fully gullied pathways occur when fillslopes and/or lower hillslopes are eroded by road runoff. Croke and Mockler (2001) used contributing road length and the slope of the lower hillslope at the drain outlet to derive a gully initiation threshold for cut-and-fill roads. Fillslope curvature was also reported by La Marche and Lettenmaier (2001) to be an important contributing factor to gully formation below culverts.

The least efficient road-stream connection is via diffuse pathways. Major factors affecting the delivery of sediment via diffuse pathways include rainfall intensity and duration, volume of erosion, contributing road area, lower hillslope properties such as slope and vegetation cover, and road to stream distance (Croke et al., 1999a; Hairsine et al., 2002; Megahan and Ketcheson, 1996).

3. Modelling road erosion

3.1. Types of road models

The representation of physical processes and complexity vary greatly in road models, so multiple categorisations are required to separate and describe road models. Road models may be categorised into two families depending on the modelling approach: empirical and physics-based models. Empirical models are based on statistical relationships between responses and independent variables, and they are derived from empirical observations (Merritt et al., 2003). Physics-based models are based on a hydrological response model that simulates infiltration and runoff routing, and mass or energy conservation equations that describe erosion and sediment delivery processes often in a high level of detail (Merritt et al., 2003).

Table 1
A summary of reported sediment yields from studies published post-2000. Note that traffic estimates are reported directly from the original publication and direct comparison between studies is difficult.

Sources	Location	Spatial scale	Method	Road surface	Average rainfall (mm yr^{-1})	Traffic (Annual return passes)	Contributing area (m^2)	Slope (%)	Sediment load (t yr^{-1})	Annual sediment erosion rate (g m^{-2} mm^{-1} yr^{-1})
Annual-averaged data										
Sheridan and Noske, 2007	Victoria, Australia	Segment (surface + ditch)	Drain outlet monitoring – as per Sheridan et al. (2006)	Unsealed	723	1319 (light vehicles)	711	4	1.4	2.7
					892	54 (light vehicles)	558	12	0.7	1.4
					1161	51 (light vehicles)	415	11	1.1	2.3
				Gravel	855	3369 (heavy vehicles)	1000	4	0.5	0.6
MacDonald et al., 2001	U.S. Virgin Islands, St. John	Segment surface + ditch)	Filter fabric dam and culvert socks	Unsealed	1150	Very high (leading to tourist camp)	760	9	4.0	4.6
						Medium	405	4	0.1	0.2
						Low	630	14	1.5	2.1
Sidle et al., 2004	Peninsular Malaysia.	Segment (surface + ditch + cutslope + fillslope)	Volumetric estimation via observation of soil pedestal heights	Unsealed	2654	High	4140	–	113 ± 8	10.3 ± 0.8

Sources	Location	Spatial scale	Method	Road surface	Rainfall intensity (mm hr^{-1})	Duration (min)	Traffic	Contributing area (m^2)	Slope (%)	Sediment load (kg)	Hourly sediment erosion rate (g m^{-2} mm^{-1} hr^{-1})
Event-based data											
Croke et al., 2006	Bermagui, Australia	Segment (surface + ditch)	Rainfall simulator and flume – as per Bos et al. (1991)	Unsealed	75	30	Main access road	200	4	110	3.7
					110 *	30	Main access road	200	4	150	3.4
		Segment (surface + ditch + cutslope)			75	30	Feeder access road	600	5	50	0.6
					110 *	30	Feeder access road	600	5	40	0.3
Ziegler et al., 2001a	Pan Khum village, Thailand	Plot (surface)	Rainfall simulator	Unsealed	107	61.2	–	3	14	6	19.1
					108*	10.6	–	3	14	1	0.5
					115	46.5	–	3	26	16	35.9

*: Successive events.

Depending on the temporal scale of model simulation, a road model can be categorised as event-based or continuous. Event-based models simulate erosion and delivery as a result of single rainfall-runoff events, while continuous models estimate sediment yields resulting from multiple rainfall-runoff events. Outputs from continuous models are sometimes reported as annual average volumes. Empirical models are generally continuous models and physics-based models are usually event-based.

Models may also be categorised on the basis of their spatial scale of application into plot, segment and catchment-scale models. Most road models are developed for their application on segment scales and include descriptive parameters that characterise major road features. Plot-scale road models focus on detailed quantification of infiltration runoff and erosion processes on a particular road feature such as the road surface. Catchment-scale models consider roads as a component of a catchment and often involve all road features, including the upper and lower hillslopes.

Depending on the capability of the model to predict sediment production rates for various size classes, road models are classified into single-size and multiple-size models. Models that do not differentiate between particle sizes are regarded as single-size models. Multiple-size models estimate sediment yields for a range of particle-size distributions. Multiple-size models are potentially advantageous in water quality studies because many sediment-associated pollutants are preferentially attached to fine particles (Aksoy and Kavvas, 2005), and particle size is also an important factor that controls sediment delivery. However, data computations and process representations are greater for multiple-size models.

As described in Section 2.1, a road contains many features. Single-feature models estimate erosion and delivery from a single road feature, most often the road surface. Multi-feature models include two or more road features.

3.2. Typical road model

A road model typically includes an erosion and a delivery module. The simplest road models generally consider inputs from surface erosion only, and model the delivery of sediment by a sediment delivery ratio (SDR)-like approach. Unlike a traditional catchment-scale SDR approach, the ratio of sediment delivery to a stream to the total sediment generated from a road feature is defined here as $SDR_{R\text{-}S}$. Moderately complex road models usually consider cutslopes as sediment sources. They also investigate features of fillslopes or lower hillslopes, such as length and steepness, as components in delivering sediment to a stream. The most complex models include representation of detailed erosion processes on both cutslopes and road surfaces, and a larger number of components in sediment delivery, such as transport and deposition through ditch and fillslope, gully initiation, and sediment particle-size sorting. Fig. 2 shows a 'generalised' road model and indicates the levels of complexity associated with various approaches. Note that complexity is also influenced by the level of spatial detail inherent in the application of a model. A simple model that is applied in a highly spatially disaggregated fashion has resulting relatively high overall complexity.

4. Existing road models

Four empirical models and three physics-based models are reviewed here in terms of their process representation, assumptions, applicability and limitations. These models are selected on the basis of their current use and/or development, and diversity of process representation. All the models were developed in the last half century and have sufficient technical documentation to enable informed comparison.

4.1. Empirical road models

4.1.1. WARSEM

The Washington Road Surface Erosion Model (WARSEM) is an empirical model used to estimate long term average road-derived sediment delivered to the stream network. It was developed by the Washington State Department of Natural Resources (Dubé et al., 2004). WARSEM was developed as an Access database application, but has been integrated into a GIS model (SEDMODL) (Dubé et al., 2004). WARSEM is an iteration of the earlier R1-R4 and BOISED models and shares many common characteristics with those models. R1-R4 and BOISED were developed for application in the northern Rocky Mountains, U.S. (Ketcheson et al., 1999).

WARSEM is spatially distributed by road segment and the sediment outputs have a single size fraction. It considers multiple features including the ditch, cutslope and the road surface. WARSEM can be applied at large catchment scales and the effects of a variety of best management practices enable the model to be used to aid catchment decision making.

The acknowledged assumptions of the model include that: road segments over 200 feet (approximately 60 m) from a stream do not deliver sediment; fillslope erosion is negligible; and the ditch and road surface respond similarly to the input factors (Dubé et al., 2004).

4.1.1.1. Erosion module. A maximum of 15 data inputs are required but these vary according to the intended purpose of the modelling exercise (Dubé et al., 2004). These inputs include annual average rainfall, road surface materials, vegetation cover, slope, traffic and maintenance, and the contributing area for road surface, cutslope and ditch. The majority of data inputs are specified for individual segments of a road network.

A base erosion rate is estimated from average annual rainfall corrected for snowfall and modified by factors values derived from published studies (Dubé et al., 2004). The equations of WARSEM are (Dubé et al., 2004):

$$E = (R_s + C_s) \times A_g \tag{1}$$

where E is total sediment delivered to a stream from each road segment (t yr^{-1}), R_s is road surface and ditch sediment delivered to a stream from each road segment (t yr^{-1}), C_s is cutslope sediment

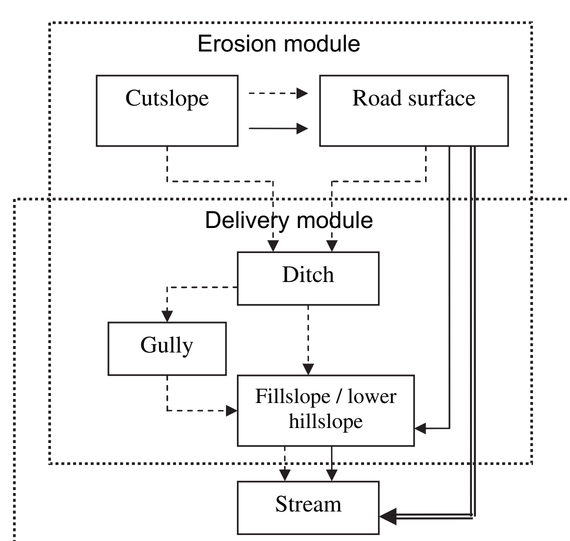

Fig. 2. Conceptual framework of road models indicating low (double solid line), moderate (solid line) and high (dashed line) levels of complexity.

delivered to a stream from each road segment ($t\,yr^{-1}$), and A_g is a road age factor (dimensionless). And,

$$R_s = G \times S_f \times T \times L \times W \times S \times E_r \times SDR_{R-S} \quad (2)$$

$$C_s = G \times C_f \times L \times H \times E_r \times SDR_{R-S} \quad (3)$$

$$E_r = a \times R^b \quad (4)$$

where G is a geologic erosion factor (dimensionless), S_f is a road surfacing factor (dimensionless), T is a traffic factor (dimensionless), L is the segment length (feet), W is the road surface and ditch width (feet), S is a road slope factor (dimensionless), E_r is an erosion rate based on a rainfall factor ($t\,acre^{-1}\,yr^{-1}$), $SDR_{R\text{-}S}$ is an empirical sediment delivery factor (dimensionless) described later, C_f is a cutslope cover factor (dimensionless), H is cutslope height (feet), R is average annual rainfall (inches), and a and b are empirical parameters.

4.1.1.2. Delivery module. The delivery of road-derived sediment to a stream is modelled using a $SDR_{R\text{-}S}$, determined by the downslope distance between the drainage outlets and the stream, based on the study of Megahan and Ketcheson (1996). Values of 100%, 35% and 10% are given when the distances between road drainage and stream are 0, 1–100, and 101–200 feet, respectively (Dubé et al., 2004).

4.1.2. USLE and modifications

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978) is a commonly-used hillslope-erosion model that was developed in the 1950s for application on agricultural land in the eastern U.S.. The outputs of USLE are annually-averaged and single-sized. The USLE has been modified in the last few decades and its modifications include the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991, 1997). The USLE and its modifications are empirical models used to estimate net erosion, hence they do not consider sediment delivery processes.

The greatest limitation of the use of USLE and its modifications for road erosion modelling is that even though it is based on statistical relationships from over 10,000 plot scale observations, none of these originate from road segments. Consequently, using these models to estimate erosion from unsealed road surfaces is questionable, mainly due to the differences in soil properties and usage between agriculture lands and unsealed road surfaces. Road surfaces are typically more compacted than agriculture lands (Ziegler et al., 2000). Traffic levels, which are not currently considered in the USLE, are one of the most important factors contributing to road surface erosion. In contrast, levels of vegetation cover and tillage effects are important factors to be considered for the estimation of erosion from agriculture soils. The RUSLE has been reported to overestimate sediment yields by an order of magnitude for soil erosion from snig tracks in eastern Australia (Croke and Nethery, 2006). Although some studies have applied USLE or its modifications on unsealed roads (e.g. Farabi and James, 2005; Megahan et al., 2001; Sheridan et al., 2006), none are supported by detailed testing of the factor values.

4.1.2.1. Erosion module. The USLE estimates erosion based on five empirical input variables: rainfall erosivity, surface material erodibility, slope, area and cover:

$$A = R \times K \times L \times S \times C \times P \quad (5)$$

where A is the long term average annual soil loss ($t\,ha^{-1}\,yr^{-1}$), R is the rainfall erosivity factor ($MJ\,mm\,ha^{-1}\,hr^{-1}\,yr^{-1}$), K is soil erodibility factor ($t\,hr\,MJ^{-1}\,mm^{-1}$), L is hillslope length factor (dimensionless), S is hillslope slope factor (dimensionless), C is land use factor (dimensionless), and P is the support practices factor (dimensionless) (Foster et al., 1981; Wischmeier and Smith, 1978).

Traffic and maintenance factors may potentially be modelled via the USLE P factor but no published studies were found to support such an approach. Further, Sheridan et al. (2008) argued that the K factor is inappropriate for road applications because it over-represents the significance of rill processes.

It is recommended that the USLE should not be used for estimating road surface erosion until formal tests and modification of the model are conducted. Nevertheless, the USLE provides a simple framework for the estimation of erosion rates. In fact, WARSEM can be seen as a modification of the USLE because WARSEM is framed within a similar model structure as the USLE, but with modified approaches to calculate the factor values and the inclusion of additional factors specially designed for road surface erosion.

4.1.3. ROADMOD

ROADMOD uses a vector-based GIS to predict annual road-derived sediment yield by an empirical relationship between road erosion rates and road surface conditions and a series of network algorithms (Anderson and MacDonald, 1998). The empirical relationships were specifically developed for the U.S. Virgin Islands. ROADMOD is a spatially distributed model (by road segment) whose outputs are annual-averaged and single-sized.

The major limitation of ROADMOD is that the sediment production algorithm was determined by measuring the cross-sectional area of 'missing' road surface material (including rill erosion and compaction) since construction and grading at a single location. Therefore, its applicability to conditions different to those for which it was developed is questionable. The model assumes that sediment deposition on the road surface is negligible, that no significant sediment is contributed from the cutslopes, ditches and fillslopes, and that erosion rates are consistent over space and time (Anderson and MacDonald, 1998).

4.1.3.1. Erosion module. The road surface is the only sediment source considered in ROADMOD. The controlling factors used for model inputs are road slope and contributing road area. An empirical study suggested that sediment yield is linearly related to the road drainage area and road slope (Anderson and MacDonald, 1998):

$$E = a + b \times A \times S \quad (6)$$

Here E is annual average sediment yield from per metre road surface ($m^3\,m^{-1}\,yr^{-1}$), A is the contributing road area (m^2), S is the road slope ($m\,m^{-1}$), and a and b are empirical parameters. Total sediment yield ($m^3\,yr^{-1}$) from a road segment is calculated by multiplying E by the segment length L (m). An assumed bulk density parameter is used to convert the volumetric estimate to a mass.

ROADMOD uses a vector GIS road network with road segments as the basic mapping units. Model parameters are assigned to each digitised road segment. ROADMOD estimates annual sediment yield from each segment using Equation (6). After identifying the network outlet, the sediment delivered to each outlet is estimated by totalling sediment yield from all contributing road segments.

4.1.3.2. Delivery module. Sediment delivery processes in ROADMOD are estimated by using three assumed SDRs, depending on the sediment delivery pathway. A value of 1.0 is assigned when sediment is delivered directly by ditches and culverts into the stream network, 0 when the runoff is directed to vegetated hillslopes, and 0.5 when the runoff discharges to unvegetated hillslopes or mangrove swamps (Anderson and MacDonald, 1998). The SDR concept is slightly different in this case where delivery directly from the road to the marine environment is modelled.

4.1.4. STJ-EROS road submodel

The St John sediment budget model (STJ-EROS) is a GIS-based, catchment-scale model based on empirical data and application of a SDR (Ramos-Scharrón and MacDonald, 2007a). The model predicts sediment yields from coastal watersheds into the marine environment for sediment originating from unsealed roads, stream banks, tree throw, and undisturbed hillslopes. Only the road and the sediment delivery submodels are reviewed in this article. The road submodel of STJ-EROS is spatially distributed by road segment, and the model outputs are annual-averaged and multiple-sized.

The empirical models for estimating road surface erosion developed by Ramos-Scharrón and MacDonald (2005) assumed that rainfall, road length, width and slope, and grading frequency can explain most of the variation of sediment yield from the road surface. Sediment yield from cutslopes are assumed uniform, and a uniform silt-size particle correction is applied.

A comparative study has been conducted between STJ-EROS and ROADMOD (Ramos-Scharrón and MacDonald, 2007a). Both models were applied in catchments in the U.S. Virgin Islands (Ramos-Scharrón and MacDonald, 2007a). It was argued that STJ-EROS provided a more accurate prediction of road sediment because it was based on better field observation data, and the predicted values of STJ-EROS were closer to observed sediment yield values (Ramos-Scharrón and MacDonald, 2007a).

4.1.4.1. Erosion module. Two features are modelled in STJ-EROS: the road surface and the cutslope. Sediment yields from the road surface are estimated based on empirical relationships between sediment yields (estimated from sediment trap data), precipitation and road characteristics (Ramos-Scharrón and MacDonald, 2005). Input variables for erosion from the road surface include rainfall, slope, and contributing road area. Empirical parameters differ for roads with different grading frequencies. Erosion from cutslope areas is assumed to be 9% of the total road segment sediment yield (Ramos-Scharrón and MacDonald, 2007a). The equations used to estimate sediment yields from road surfaces and cutslopes are shown below. Sediment yields from all road segments in a catchment are accumulated to estimate total sediment yields from roads and cutslopes:

$$E = R_s + C_s \tag{7}$$

$$R_s = a + b \times S^m \times R \times L \times W \times S_t \tag{8}$$

$$C_s = (P_c/(1 - P_c)) \times R_s \tag{9}$$

Here E is total sediment yield from the road surface and cutslope (kg), R_s and C_s are sediment yields from the road surface and cutslope, respectively (both in kg), S is road slope (m m^{-1}), R is annual rainfall (cm), L is road length (m), W is road width (m), S_t is a silt content adjustment factor, P_c is the proportion of cutslope sediment to the total sediment yields (0.09), and a, b and m are empirical parameters. The empirical relationship (Equation (8)) is based on data collected from sediment traps, hence a S_t factor is used to adjust for the likely underestimation of fine particles lost when sediment traps are used to estimate yields (Ramos-Scharrón and MacDonald, 2007a). This factor differs for different grading frequency classifications.

4.1.4.2. Sediment delivery. STJ-EROS estimates sediment delivery from roads not to the stream network but to the marine environment, similar to the ROADMOD model. A user-defined SDR is used to account for hillslope, channel and coastal wetland storage between the road and the marine environment (Ramos-Scharrón and MacDonald, 2007a). The SDRs are determined by the potential retention of wetland environments (Ramos-Scharrón and MacDonald, 2007a). In general, SDRs of 0.4–1.0 are assigned to areas that drain directly to the sea. Areas that drain to the sea through coastal wetland or salt pond pathways have SDRs of 0–0.5. A SDR of 0 is given for areas that lack a surface pathway to the marine environment (Ramos-Scharrón and MacDonald, 2007a).

4.2. Physics-based road models

4.2.1. WEPP

The Water Erosion Prediction Project (WEPP) is a physics-based model that estimates soil loss and sediment yields from hillslope erosion at hillslope or small catchment scales (Flanagan and Nearing, 1995). WEPP was originally designed for application in agricultural areas but has also been used for estimating erosion from forest roads. WEPP is a spatially-distributed, daily-continuous model that produces annual-averaged and multiple-sized outputs. For application to roads, WEPP can include multiple features such as road surface, cutslope, ditch, fillslope and lower hillslope. WEPP:Road (Elliot et al., 1999b) is a web-based interface for modelling individual road segments.

4.2.1.1. Erosion and delivery modules. WEPP has a hydrology component which provides inputs (such as rainfall intensity, infiltration and runoff) for the erosion component (Flanagan and Nearing, 1995). The erosion component of WEPP then combines modelling of erosion processes and delivery to the stream network. The estimated sediment yield at the bottom of the hillslope is modelled as being delivered to streams. Sediment loadings are estimated by calculating soil detachment and deposition rates from interrill and rill areas (Foster et al., 1995). Interrill erosion is determined by rainfall intensity, interrill runoff rate, interrill erodibility and an interrill sediment delivery ratio (Foster et al., 1995). Rill erosion is estimated as a function of hydraulic shear stress, soil critical shear stress and sediment transport capacity. Detachment occurs when hydraulic shear stress is greater than soil critical shear stress and sediment load is less than sediment transport capacity (Foster et al., 1995).

In road modelling applications, the road surface, fillslopes and lower hillslope areas are modelled separately by defining them as different Overland Flow Elements (OFE). Each OFE has unique soil and vegetation parameters assigned. These parameters determine different rill and interrill erosion rates.

WEPP, as a physics-based model, requires the estimation of parameters such as rainfall volume and intensity, infiltration, slope, and soil texture and erodibility parameters (Flanagan and Nearing, 1995). WEPP:Road simplifies data input which allows users to specify selected climate, soil texture, gravel addition, road topography, drain spacing, road design and surface condition, and ditch condition (Elliot et al., 1999b). Both rainfall and snowfall are considered for generating daily weather inputs for the WEPP model (Elliot et al., 1999b).

4.2.2. KINEROS2

The Kinematic Runoff and Erosion Model (KINEROS) is a dynamic, event-based runoff and erosion model developed by the Agricultural Research Service, U.S. Department of Agriculture for typically small-scale applications (Woolhiser et al., 1990). KINEROS2 is the second generation of KINEROS, containing modified modules to quantify runoff and erosion processes (Smith et al., 1995). KINEROS2 is a physics-based, spatially-distributed, multiple-size but single-feature model. It is suitable for application for infiltration-excess-dominated sites, and when sediment transport varies during storms (Ziegler et al., 2001a). The outputs of the model include time-varying runoff, sediment yield and sediment concentration for a rainfall-runoff event. KINEROS2 was not developed specifically for road surfaces, but a recent study has proven that it can be applied to estimate runoff and sediment yields from unsealed roads at the sub-segment scale (Ziegler et al., 2001a, 2002). Its application at larger scales is constrained by a lack of understanding of accumulated flow on road segments (Ziegler et al., 2002). The particular road study did not attempt to evaluate its capacity to simulate sediment delivery from road-related features to the stream network.

4.2.2.1. Erosion module. In application of KINEROS2 to road erosion, a road section is assumed either to be a single rectangular surface with fixed length and width, or to be parallel flow planes for rutted roads. The later is a more physically justifiable assumption but the high variability in the morphology of drainage pathways from unsealed roads is not explicitly modelled. Like all process-based models, KINEROS2 begins by calculating excess precipitation as the difference between rainfall rates and infiltration capacity. Infiltration capacity follows Smith and Parlange (1978) and is calculated as a function of the hydraulic properties of the material and the infiltrated depth; downslope runoff routing follows a kinematic wave approach (Chow, 1998). KINEROS2 does not model erosion based on rill and interrill processes but rather uses the concepts of rainsplash and hydraulic shear stress to calculate erosive capacity. When rainfall rate exceeds infiltration rate and ponding occurs, rainsplash erosion is a function of the square of rainfall intensity and soil erodibility, and is inversely related to surface water depth. When no runoff is generated on the surface, rainsplash erosion is assumed to be zero.

Hydraulic erosion represents the sediment exchange between flowing water and the soil surface, and is estimated as the difference between local sediment concentration and transport capacity (Smith et al., 1995). Sediment generated at any point along a road surface flow path is estimated by solving a mass balance equation similar to that used for kinematic runoff routing (Smith et al., 1995).

4.2.3. GA-UH/GA-KW coupled with sediment rating curve

The Green-Ampt – Unit Hydrograph (GA-UH) and the Green-Ampt – Kinematic Wave (GA-KW) models are two event-based hydrological approaches used to simulate surface runoff from an unsealed road surface. These models were used jointly with sediment rating curves to estimate sediment yields from a road segment in the U.S. Virgin Islands (Ramos-Scharrón and MacDonald, 2007c). The Green-Ampt infiltration and kinematic wave equations are physics-based, while the unit hydrograph and sediment rating curves are empirical. The coupled models only estimate erosion from the road surface. The model outputs are single-sized.

4.2.3.1. Erosion module. Both models begin by calculating excess rainfall as the difference between rainfall rates and infiltration capacity estimated by the Green-Ampt equation (Scott, 2000). Excess rainfall is then routed to the road drainage outlet by an empirically-derived unit hydrograph (UH) or a kinematic wave (KW) routing approach (Ramos-Scharrón and MacDonald, 2007c). Sediment yield is simulated by multiplying road discharge by the sediment rating curve. A sediment rating curve is the equation resulting from statistical regression of measured suspended sediment concentration and instantaneous runoff rates.

One disadvantage of the UH approach is that it requires data from the particular road segment to develop the unit hydrograph, while the KW, at least in theory, does not have such previous data requirements. Hydraulic parameters are needed for both of these infiltration-runoff models, and these include hydraulic conductivity, maximum infiltration rate, and surface roughness, among others. Tests showed that both models performed in a similar fashion when compared to measured discharge rates. Much error in model performance was due to inaccuracies in estimating infiltration during the initial stages of rainfall events, and the models performed better for larger storms than for small rainfall events (Ramos-Scharrón and MacDonald, 2007c).

Many assumptions are used in the GA-UH and GA-KW models to simplify the hydrological and sediment transport processes. With regards to the suspended sediment rating curve, the model assumes sediment concentration is exponentially related to discharge rates at the outlet of a road segment. This assumption greatly simplifies the model but may result in poor performance when the correlation between discharge rate and sediment concentration is poor. In a particular application of this approach to a road segment in the U.S. Virgin Islands, poor correlation was found between suspended sediment concentration and discharge when discharge exceeded $5\ \mathrm{mm\,h^{-1}}$ (Ramos-Scharrón and MacDonald, 2007c). As a result, the application of such a model at high discharge rates, when most sediment is expected to be exported from the road, is limited. The use of sediment rating curves may also lead to overestimation of sediment yields when a rating curve is developed under a sediment transport-limited situation, but used in a sediment supply-limited situation. Road sediment supply can be altered by several factors including sediment exhaustion during individual flow events and changes in surface conditions caused by traffic and maintenance activities (Ziegler et al., 2001b).

5. Discussion

5.1. Comparison of reviewed models

The models reviewed in the previous section represent a range of currently available road erosion and delivery models. The models vary in their temporal and spatial scales, the road features considered, the processes they represent and their data requirements see Table 2.

5.1.1. Model families and data requirements

Four of the models reviewed (WARSEM, USLE, ROADMOD, and STJ-EROS) can be categorised as empirical. These models are based on a statistical analysis of the correlation between sediment yields from a road segment and a range of variables describing local climate, road characteristics, and management activities. Among these variables, road slope and surface area (or road length) are used in three of the four models, suggesting the importance of these variables in estimating sediment yields from road surface erosion. Due to the assumptions underlying ROADMOD and STJ-EROS, they apply only to conditions from where they were developed. In contrast, WARSEM and USLE could be more easily adaptable as they were developed based on a more extensive database and therefore incorporate parameters that allow for predicting sediment yields from more variable conditions. Empirical models are usually associated with high levels of spatial and temporal aggregation and have lesser data requirements than physics-based models (Jakeman et al., 1999).

GA-UH and GA-KW coupled with sediment rating curve models can be classified as a combination of physics-based and empirical models. These models contain a physics-based rainfall-runoff

Table 2
A comparison of the models included in this review.

Models	Type	Data requirements[a]	Temporal scale	Spatial scale	Modelled features	Process representation[b]	Sediment size fraction
WARSEM	Empirical	Medium	Annual average	Road network	Surface, drain, cutslope, fillslope	Erosion and delivery	Single
USLE and modifications	Empirical	Small	Annual average	Road network	Surface, cutslope	Erosion only	Single
ROADMOD	Empirical	Medium	Annual average	Road network	Surface	Erosion and delivery	Single
STJ-EROS	Empirical	Medium	Annual average	Road network	Surface, cutslope	Erosion and delivery	Multiple
WEPP	Physics-based	Large	Annual average	Road segment	Surface, drain, cutslope, fillslope	Erosion and delivery	Multiple
KINEROS2	Physics-based	Large	Event based	Plot-small catchment	Surface	Erosion only	Multiple
GA-UH and GA-KW + rating curve	Coupled physics-based and empirical	Medium	Event based	Road segment	Surface	Erosion and delivery	Single

[a] Data requirements are based on the number of model inputs and parameters, as well as the accessibility to these values, including the involvement of filed work.
[b] Process representation includes the consideration of road surface erosion and the delivery of sediment from road to stream.

module and empirically-derived sediment concentration – runoff rating curve. These models generally require more complex data inputs than exclusively-empirical models.

The physics-based road models reviewed include WEPP and KINEROS2. These models solve equations describing runoff and sediment generated from the road surface. Considerable data are required to apply physics-based models, and such data are often not available outside experimental sites. Default parameter values can be assumed in some instances, increasing the potential range of applicability of such models.

5.1.2. Temporal and spatial scales

The temporal scales of road models are largely correlated to their spatial scales. Most temporally lumped models such as those based on annual average simulation have been applied at larger spatial scales. In contrast, event-based models are commonly used to study individual road segments. However, these segment-based models have been (or have the potential to be) expanded to a road network. Although a model such as KINEROS2 provides insight into sediment yield response at a high time resolution and can be expanded to predict responses at a small catchment scale, its parameter calibration requirements are very difficult to achieve. Therefore, this type of event-based, high spatial and temporal resolution model is more apt for research applications than for land management purposes.

5.1.3. Features and process representation

Section 2.1 described a typical cut-and-fill road segment which contains a cutslope, road surface, fillslope and a variety of drainage structures (Fig. 1). The local geometry and material properties of all these features influence the processes controlling road erosion and sediment delivery. However, not all of these features are considered in road models. WARSEM and WEPP contain the most complete modelling of road features and processes; other models consider only a subset, predominantly the road surface. Generally both sediment generation and delivery are simulated, with a few exceptions such as the USLE and KINEROS2, where only sediment generation is considered.

The consideration of erosion from cutslopes in road models is very limited, partly due to the perceived or actual low contribution of cutslopes to total road erosion in many areas (Elliot and Tysdal, 1999; Ramos-Scharrón and MacDonald, 2007a). It is also due to a variety of processes affecting cutslope erosion (surface erosion by rain, freeze-thaw, piping and mass wasting) and also the difficulty of modelling the transport of sediment produced by cutslopes to the drainage outlet.

Fillslope erosion is typically considered in sediment delivery processes, but this feature is modelled least often in the erosion component of the reviewed models. This can be attributed to its generally perceived small sediment contribution and logistical difficulties in implementing field studies. In other soil erosion studies, fillslopes may be modelled in the same way as undisturbed hillslopes, but significant differences are likely in vegetation cover and soil erodibility. Megahan et al. (1991) found, during a plot-scale study in Idaho, U.S., that fillslope surface erosion is dominantly influenced by ground cover density and snowfree period rainfall erosivity. A limitation of current models is the few studies that have investigated the impact of accumulated flow from road drains to fillslope erosion (Croke and Mockler, 2001), an exception being Elliot and Tysdal (1999).

5.1.4. Management applications

Most models are intended as tools to assess current conditions (impact), to evaluate best management practices or to help identify field data collection and resource management priorities. For example, USLE, WEPP and their modifications have been applied in forest road surface erosion assessment in Australia (Ryan et al., 2003) and the U.S. (Heller and Norman, 2005; Riedel and Vose, 2003). WARSEM can be used to investigate best management practices on forest roads by simulating the effects of changes in surfacing, traffic, cutslope vegetation cover, and installation of sediment traps (Dubé et al., 2004).

Models containing stochastic variables can be used to define the probabilities associated with different rates of erosion. However, none of the models reviewed here use a probabilistic approach for prediction. Distributed WEPP, a WEPP Internet interface for forest and rangeland erosion after disturbance, was developed to present the probability of sediment yields (Elliot et al., 2001). The approach may be used in WEPP to provide probabilities for road erosion. Megahan et al. (1991) used Monte Carlo simulation to predict the probability of occurrence of sediment yields from granitic fillslopes in Idaho, U.S., under various levels of ground cover density. Such probabilistic modelling may prove useful for land managers to define the risks from road erosion, as well as to assess management alternatives.

5.2. Limitations and recommendations

5.2.1. Modification of existing erosion models

Most attempts to develop new road erosion studies adapt the theories of existing erosion processes on hillslopes and catchment, and therefore inherit a similar mathematical structure to their ancestor models. The new road erosion models adopt two major approaches: empirical modelling which derives relationships between sediment yields and a range of controlling factors; and physics-based modelling which predicts the hydrologic behaviour of the road surfaces and uses the response to calculate erosion as the difference between erosive potential and surface resistance.

Empirical models are useful for estimating annual loads and for identifying erosion 'hot spots' within a catchment. In contrast, physics-based models simulate single-event or inter-storm sediment loads, which could be used for quantifying the impact of a road segment in the water quality of a particular river. The limitations of the ancestor models also apply to the modified road models, some of which are summarised in Merritt et al. (2003).

A successful application of the empirical modelling approach largely depends on the correct identification of critical factors that influence sediment loads. Factors such as rainfall, effective contributing road area, road slope, traffic, and road maintenance activities are commonly used. Although empirical models require a relatively smaller number of parameters, they have the following limitations:

i) confidence in their application is limited to the environmental circumstances from which the empirical relationships were generated (Merritt et al., 2003);
ii) temporal variation of rainfall, runoff and erosion processes is generally not considered (Merritt et al., 2003); and
iii) the heterogeneity of road/catchment characteristics and non-linearities of the system is largely simplified and hence up- or down-scaling application of the original models is difficult.

Physics-based models have the advantage of being applicable to different environments, potentially producing greater depth of information on hydrology and erosion processes. Theoretically, principles of physics remain unchanged regardless of location; hence if properties of road soils can be adequately determined at a site, they can be applied to another site as long as local climate and road characterization data are available for calibration. This is illustrated by the successful application and testing of the WEPP:Road model to roads in a *Pinus* plantation forest in southeast Queensland, Australia even though the model was developed for the U.S. (Forsyth et al., 2006). Reasonable agreements between WEPP estimates and field observations were also found in a hillslope scale study in southeast New South Wales, Australia (Croke and Nethery, 2006).

Physics-based modelling has several disadvantages. It almost always requires estimation/calibration of more parameters than empirical modelling. The numerous assumptions that describe the hydrology and erosion processes limit the application of such models at large scales (Beven, 1989). This is mainly because the equations of most physics-based models are based on the physics of small scale homogeneous systems, and therefore their applicability to larger scale heterogeneous systems require methodical testing. Other problems that may limit the widespread applicability of physics-based road erosion models include:

i) large computational demands;
ii) the need to develop input databases that describe the spatial variability of model variables appropriately;
iii) the requirement for accurate hydrological prediction; and
iv) the need to implement an adequate monitoring strategy that would allow for variable and parameter calibration, as well as for model testing.

Despite the large number of existing physics-based erosion models for hillslope and catchment applications, the number and diversity of these models for unsealed roads is relatively small. The successful adaptation of selected physics-based models to road erosion and sediment delivery studies indicates the potential of incorporating roads into pre-existing hillslope models without major alterations to their structure. None of the physics-based road models reviewed here can account for the hydrological and erosion processes occurring on surfaces other than the road surface.

5.2.2. Imbalance between modelling erosion and delivery

Most road erosion studies have been undertaken to assess off-site water quality problems. Hence there is a clear need to consider both erosion from roads and the processes that govern sediment delivery from roads to streams. However, in most models, there is a significant bias towards the erosion process, with much less consideration given to delivery processes. This is largely due to the difficulty of obtaining monitoring data to quantify or test road-to-stream connectivity across a range of physical environments. Thorough evaluations of the outputs of road models, particularly in their capacity to estimate the amount of the road-derived sediment reaching a stream, are largely limited. Among the models considered here the delivery component can be considered to be the least reliable.

The most common, and sometimes only, variable to determine sediment delivery from road to stream is the distance between road and stream. However, this ignores other factors, such as the contributing road area and rainfall intensity (Hairsine et al., 2002), gully initiation (Croke and Mockler, 2001), groundcover, slope, and the presence or absence of runoff-detaining features along the flow path. An empirical model of sediment delivery from road to stream has been developed by Megahan and Ketcheson (1996) for forest roads in Idaho in the western U.S.. The travel distance of sediment from unsealed roads are estimated based on the volume of deposited sediment, the capacity of the hillslope to retain sediment, the slope of the lower hillslope, and the upslope contributing area (Megahan and Ketcheson, 1996).

In southeastern Australia, Hairsine et al. (2002) developed an event-based conceptual model called 'Volume to breakthrough' model (Vbt) which predicts the probability of road-derived runoff reaching a stream through diffuse overland flow. Input variables of the Vbt model include the distance from the drain to the stream, contributing road area, rainfall and infiltration rates, and the duration of the rainfall event (Hairsine et al., 2002). The Vbt model was originally developed as a hydrology connectivity model, but with further effort a sediment delivery component could be incorporated. Such work is currently underway in the Lower Cotter Catchment of Australia (Thompson et al., 2008).

A counter argument to the use of both erosion and delivery modelling could be made that modelling the likely locations of highest sediment generation from a road network can be by itself effective in identifying opportunities to control erosion. Field inspection of such sites may quickly reveal whether the generated sediment is being delivered to areas of concern in problematic quantities, and whether the best solution is improved road management or improved off-road practices such as detention ponds. Similarly, modelling the sediment delivery potential of road segment is also useful to identify potential road segments for further investigation or monitoring on sediment generation, and to assess alternative road or drainage locations to control road-derived sediment from entering streams (e.g. Eastaugh et al., 2008).

5.2.3. Buildup-washoff process in erosion

The phenomenon of high sediment concentration at the early stage of a runoff event is usually referred to as the 'first flush' in water quality studies, especially in urban areas. It occurs when loose sediment accumulates between storm events. The amount of readily transportable sediment gradually declines with time during a storm event. A buildup-washoff function is commonly used to represent such processes (Chen and Adams, 2007; Zoppou, 2001). The simulation of buildup-washoff processes is potentially important for temporally distributed models, or when the sediment contribution during buildup-washoff period is significant in long-term sediment generation.

The buildup-washoff process often occurs on the surface of unsealed roads (Ziegler et al., 2001a), or as temporary sediment storage in ditches and other channelized features, but may also arise on steep cutslopes of granitic bedrock and shallow non-cohensive soil, where long-term weathering processes weaken particle bonds allowing for continuing mass wasting for long periods of time (Megahan et al., 1983). Very few event-based road models account for processes affecting road surface conditions between rainfall events. Ziegler et al. (2001a, 2002) noted that road sediment supply is dynamic because inter-storm processes and traffic create loose materials on top of compacted surfaces. During storm events, loose materials, whose supply is determined by inter-storm sediment detachment processes, are eroded first. After removal of loose materials, the road sediments are supplied by the compacted road surface, which is affected by intra-storm events (Ziegler et al., 2001a). Sediment concentration spikes may occur during the first five minutes of storm events (Ziegler et al., 2001a). This implies the significance of inter-storm sediment detachment processes on road modelling, which are generally ignored in many road models.

Three types of buildup functions are identified in water quality modelling: linear, power and exponential (Rossman, 2005). The exponential decay relationship between the available sediment and the duration of time has been widely used (Chen and Adams, 2007), and may be profitably used for road erosion modelling. However, representation of buildup-washoff in most road models is still very limited and is a particular limitation for application of event models in areas of high rainfall variability. Access to data good enough for parameterisation of buildup-washoff processes is essential.

A variation on the buildup-washoff approach has been used by Megahan (1974) to describe the long-term decrease of sediment erosion on unsealed roads following surface disturbance such as road construction. Megahan's model has been supported by several subsequent studies (Ramos-Scharrón and MacDonald, 2005; Sugden and Woods, 2007).

5.2.4. Subsurface flow interception

There are two primary mechanisms by which roads may affect catchment hydrology: generation of infiltration excess runoff from road surfaces and the interception of subsurface flow by the cutslope (Bowling and Lettenmaier, 2001). The focus of this paper is on surface erosion, but the significance of intercepted runoff on road surface erosion and sediment transport, as well as mass wasting, presents significant opportunity for further research.

The effects of forest roads on hydrological processes have been the focus of several studies including Luce (2002), Negishi et al. (2008), Sidle et al. (2006) and Wemple et al. (2001). For example, Negishi et al. (2008) reported that intercepted subsurface flow contributed nearly 30% of the sediment and 80% of runoff on a forest road in Malaysia. In areas where cutslope interception of subsurface flow is substantial, the volume of flow conveyed by road ditches and culverts during and between storm events may add considerably to road surface runoff. For example, a high proportion of road runoff was reported from subsurface runoff intercepted by cutslopes during snowmelt periods in mountainous areas in central Idaho, U.S. (Megahan, 1972).

None of the seven models reviewed accounts for the effects of roads on sub-surface flow interception by cutslopes. The need to incorporate this effect of forest roads has been highlighted by several studies. For example, Busteed et al. (2005) found that the WEPP WATERSHED model underestimated road runoff by nearly fifty percent, and most of this error was due to inaccuracies during large storms. This may partly be explained by the failure to estimate additional runoff intercepted by cutslopes. The latest release of the WEPP model has the capability to quantify subsurface flow rates along forested hillslopes (Covert et al., 2005), but no studies have yet attempted to use this tool to assess the role of road cutslope interception in generating surface runoff. Similarly, the Distributed Hydrology-Soil-Vegetation Model (DHSVM) is a physics-based hydrological model that accounts for both surface and subsurface flow on forest roads (Bowling and Lettenmaier, 2001). Further investigation is required as to the applicability of such models for estimating subsurface flow interception and the ensuing implications on sediment generation and delivery processes.

5.2.5. Model testing and uncertainty analysis

Model testing and uncertainty analysis are critical for developing an understanding of model outputs. However, they are seldom reported for road erosion and delivery models. Most empirical models are validated from datasets collected at the sites used for their development. Very few are applied or tested widely in other places. Even fewer road studies attempt to quantify the uncertainty of road model outputs. Notable exceptions include: (i) the study of Ketcheson et al. (1999) in which an assessment of the accuracy of the R1–R4 and BOISED models is presented; (ii) testing of KINEROS2 by Ziegler et al. (2001a); and (iii) guidance on the reliability of the WEPP:Road model that is provided in the documentation of that model (Elliot et al., 1999b). Other attempts at model testing include the comparison of the ROADMOD model outputs against measured sediment yields as reported in Ramos-Scharrón and MacDonald (2005).

A large and increasingly sophisticated literature describes general model testing and uncertainty analysis and suggests good modelling practices (Jakeman et al., 2006; Saltelli et al., 2000). Much that can be learned from the literature on model testing, uncertainty analysis and modelling practice is directly applicable to road models. For example, the sources of uncertainty of water quality models and accumulation of uncertainty described by Beck (1987) are directly applicable to road models. Limiting factors for model testing and uncertainty analysis include access to data of sufficient quantity, spatial and temporal resolution and reliability for comparison against model outputs, and the large inherent variability in the data.

In addition to traditional monitoring and measurement, sediment tracing techniques may also be useful for model testing, especially at the catchment scale (e.g. Wallbrink et al., 2002; Motha et al., 2003). For example, Motha et al. (2003) successfully used geochemistry and radionuclide tracers to discriminate sediment contributions from undisturbed forest, forest harvest areas, and gravelled and ungravelled road surfaces for a small forest catchment of southeastern Australia. The results of this study can potentially be used to test catchment-scale road models applied for the same area. Sediment tracing can also aid in separating the relative sediment contributions originating on cutslopes and fillslopes from those produced on the road surface if significantly different tracer properties of these sources can be identified.

5.2.6. Guidelines for model selection

The first step in model selection is to determine the kinds of questions the model is intended to address. A model may be needed to aid management of unsealed roads, or for scientific research on the behaviour of unsealed roads. The types of questions that managers ask of road erosion and sediment delivery models include:

- What is the contribution of unsealed roads to catchment-scale, suspended, bedload or total sediment yields?
- Which road segments contribute large amounts of sediment to a stream network?
- How should road drains be constructed or spaced to reduce impacts on stream water quality?

- How should new roads be laid out to reduce impacts on stream water quality?
- How can changes in maintenance, such as grading and resurfacing, affect sediment yields?
- How does traffic affect sediment generation and subsequent delivery to streams?

Simpler models (in terms of process representation, number of features modelled, the level of spatial and temporal aggregation etc.) appear to be preferred for management purposes. More complex models are potentially useful, particularly in building understanding of the physical processes at play, but require a higher level of expertise to be useful for management purposes.

The next step in model selection is to see whether the scope of the model satisfies both the purpose of the study and the characteristics and data availability of the study area. The model selected should have spatial, temporal, and accuracy scales suited to the purpose of the study, while also having the capability to include all sediment sources perceived to be playing a role in sediment production and delivery. These requirements imply *a priori* knowledge of the study area and a clear conceptual understanding of the goals of the modelling effort.

All empirical models, including those with empirically derived $SDR_{R\text{-}S}$, are developed under specific environmental conditions such as climate, topography, and lithology. The conditions of the four empirical models reviewed in this paper are summarised in Table 3. The WARSEM model was developed for areas including snowfall regions, while ROADMOD and STJ-EROS were developed in areas with steep slopes, erodible soils and intense rain events. Even though localised conditions may prevent the widespread use of these particular empirical approaches to areas other than those for which the model was developed, their model structure could prove useful for both researchers and land managers. The conceptual description of processes implied by the model could be used as a framework in the development of new models, in the design of research approaches, and in the development of prevention and mitigation strategies.

Table 3
Summary of the location, climate, topography, lithology, road and land use characteristics of the area where the empirical models were developed.

Characteristics	USLE	WARSEM	ROADMOD and	STJ-EROS
Location	U.S.	Washington State, northwestern U.S.	St John, U.S. Virgin Islands	
Annual rainfall	Diverse	100–3000 mm	900–1400 mm	
Elevation	Diverse	0–4000 m	0–500 m	
Road slope	Diverse	1–13%	0–37% (R)	1–21% (S)
Dominate lithology	Diverse	Sedimentary, volcanic and basalt	Volcanic	
Soil	Diverse	Diverse	Shallow gravelly clay loams	
Dominant road users	–	Truck and light vehicles	Truck and light vehicles (traffic is not modelled)	
Dominant land use	Agriculture	Forest	Forest	

R: ROADMOD and S: STJ-EROS

5.2.7. *The imperative for monitoring*

Access to good data is the greatest limitation to the development of sediment generation and delivery models for unsealed roads. It is important that those responsible for commissioning, developing and applying road models are aware of this limitation and that modelling studies are supported by well targeted monitoring. Monitoring is expensive and therefore must be well prioritised.

Monitoring should be considered on a case-by-case basis. The objectives, the anticipated modelling approach and available resources should be carefully considered in developing a monitoring program. The key guiding principle should be a clear understanding of how monitoring data will contribute to model development and testing.

Monitoring must respond to an a priori understanding of the potential factors controlling road erosion and delivery processes and must be conscientious of the general framework and methodology that will be used to generate, test, or validate a model. For example, application of an empirical model will require information on how its factors respond to specific environmental conditions and road characteristics in its area of application. Monitoring across the intended range of environmental conditions and road characteristics would be required for confident application of an empirical model.

The spatial scale of intended model application is also an important determinant of the monitoring required. Sediment yield data, for example, can be collected in a continuum of increasing spatial scale from rainfall simulator studies ($\sim$1's m^2) to road segment (10^2's m^2) and catchment-scale monitoring (1's–10^3's km^2). In most cases data collection occurs at a finer scale than that intended for model application. For example, modelling catchment-scale impacts will likely require data to support the simulation of sediment generation and delivery from individual road segments, but its validation requires data at the catchment scale.

A particular weakness identified in this review is the monitoring of road-to-stream connectivity. This is evidenced by the lower complexity of delivery modules relative to erosion models in most cases. More complex models may or may not be required, but our poor knowledge of delivery processes inhibits how models are developed and a balance needs to be established between monitoring of erosion and delivery.

The technical aspects of data collection are beyond the scope of this review but Bos et al. (1991), Megahan and Ketcheson (1996), Sheridan et al. (2006), and Ziegler et al. (2001b) provide examples of data collection approaches that may be modified to meet specified objectives.

6. Conclusion

The importance of unsealed roads to off-site water quality is being increasingly recognised. The identification of sediment sources and their delivery potential using mathematical models can assist in recognising critical sediment source areas, evaluating best management practices and/or prioritising data collection and research activities. A range of models have been developed for estimating surface erosion on unsealed roads but they are typically at a lesser level of development than corresponding models for other types of land use activities.

Most models of surface erosion and sediment delivery from unsealed roads can be categorised as empirical and physics-based models. Empirical models generally have lower parameter requirements than physics-based models but are limited in their widespread application as they only represent a rather restricted set of conditions. On the other hand, physics-based models have the potential for more generic applications but the strictness of variable validation requirements make them unlikely choices for other than research purposes.

All of the models reviewed here consider sediment generation from the road surface, but lack consistency in incorporating other road features. The processes of sediment generation and delivery are generally explicitly considered but typically less consideration is given to delivery processes. This is the result of poorer knowledge of delivery processes and the difficulty in obtaining monitoring data to test the extent of road-to-stream connectivity for sediment sources.

A set of guidelines have been provided for model selection. In most instances, the first and most important step in deciding on a modelling approach is to determine the question(s) that a model is intended to address. Model selection should have spatio-temporal scales suited to the purpose of the study and should be expected to have the expected accuracy required for this purpose. Simpler models appear to be preferred for management purposes with more complex models potentially most useful for building understanding of the dominant processes.

Model testing and uncertainty analysis, while critical to developing understanding of model outputs, are seldom reported for road erosion and delivery models. To address this concern there is significant opportunity to take advantage of the literature describing model testing, uncertainty analysis and good modelling practice. However, a fundamental requirement for model testing and ongoing model development is access to data of an appropriate standard to support model development and testing. In collecting data to support model development the key guiding principle is a clear understanding of how monitoring data will contribute to model development and testing.

Significant opportunities exist for future research activities to support modelling of surface erosion and sediment delivery. Building knowledge in the following areas is of high priority: (i) sediment delivery processes from roads to streams; (ii) the importance of buildup-washoff processes in controlling inter- and intra-storm sediment availability; (ii) the effects of roads on hydrologic processes at spatial scales larger than the road segment, especially the effects of subsurface flow interception; and (iv) how to incorporate information from sediment tracer experiments into the model development process.

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