Evaluating the potential for sediment delivery at forest road-stream crossings in New Zealand

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Abstract

Forest road-stream crossings can represent a significant pathway for sediment delivery to streams. Careful planning of road location, stream-crossing design and implementation of best management practices (BMPs) for water quality protection are necessary to provide access for the expansion in forest harvest volumes in New Zealand while meeting the goals of the Resource Management Act 1991. However few studies in this country have examined the relationship between current BMPs and sediment delivery potential at forest road-stream crossings. A field survey of 39 corporate haul road-stream crossings covering six regions in New Zealand was conducted to characterise the potential for sediment delivery to the stream.

Mean length, slope and road camber of the crossing approaches was 40 m, 7.2% and 4.4%, respectively. Median cover on the running surface component of the approaches was 75% and estimates of potential erosion using the Universal Soil Loss Equation modified for forest land (USLE-forest) were relatively low (range = 0.01 to 8.73 tonnes/ha/yr; median = 0.7 tonnes/ha/yr) in comparison to previous forest road erosion studies in New Zealand (range = trace amounts to 150 tonnes/ha/yr). Bare soil area within 15 m of the crossing ranged from 2.3 to 421 m^2, with a median value of 82 m^2. Soil erodibility decreases with time through the processes of surface armouring and vegetation re-establishment on cut slopes, fill slopes and water table drains. Collectively, these findings show that aggregate surfacing and an avoidance of long, steep road gradients can reduce sediment delivery potential at road-stream crossings in the long term and minimise soil disturbance during construction in the short term.

Introduction

The New Zealand forest industry is currently in an expansion phase. Timber harvest volume increased from 19 Mm^3 in 2004 to 30 Mm^3 in 2014, and is expected to increase by an additional 40% by 2025 (NZFOA, 2014). Many of the forests to be harvested over the next decade are characterised as having steep slopes, erodible soils and little existing infrastructure to provide access for harvesting and log transport. As such, approximately 1,400 to 2,000 km of new forest roads will need to be constructed annually for the next five to 10 years (Fairbrother, 2012; Neilson, 2012). Careful planning of road location and implementation of BMPs related to earthworks, slope stability, water control and surface cover will be critical to protect water quality during the expansion phase (Payn et al., 2015; Baillie & Rolando, 2015).

The major concerns about steepland forestry operations, erosion and sediment delivery relate to the effects of infrastructure (i.e. roads and landings) and timber harvesting on slope stability, together with the timing and magnitude of low-frequency, high-intensity rainfall events (Bloomberg et al., 2011; Marden & Rowan, 2015). Infrequent storm-induced landslides can dominate catchment sediment yields over the course of a forest management rotation (Grant & Wolff, 1991), and these events are likely to have the greatest impacts on water quality and aquatic habitat (Fransen et al., 2001). Phillips et al. (2012) suggested that in New Zealand shallow landslide risk is greatest one to six years after harvesting due to reduced mechanical (root) stabilisation and increased soil moisture. Alternatively, forest roads can increase landslide erosion rates by two orders of magnitude over areas with mature forest cover (Phillips et al., 2012). Fransen et al. (2001) reported that the magnitude of mass erosion at the road-network scale ranges from 40 to 8,000 tonnes/km of road length.

In contrast to mass erosion rates, surface erosion from roads ranges from trace amounts to 150 tonnes/ha/yr, or one to three orders of magnitude less than road-related landslides (Fransen et al., 2001). Nonetheless, road surface erosion represents a water quality concern due to the permanency of forest roads on the landscape, the often high degree of road-to-stream connectivity at stream crossings, and the chronic nature of sediment inputs (i.e. surface run-off generation for low-intensity rainfall events) (Croke & Hairsine, 2006). Additional pathways for sediment delivery include valley bottom road segments and gullies that form below cross-drain culvert outlets (Croke & Mockler, 2001; Takken et al., 2008). These sediment sources can degrade stream water quality (e.g. decreased water clarity, increased nutrients and stream temperature) and aquatic habitat (e.g. sedimentation of stream beds).

Concurrent with the harvest expansion, there has been an increase in environmental regulatory initiatives to improve water quality conditions throughout New Zealand. These include the 2014 National Policy Statement on Freshwater Management (MFE, 2014) and the 2015 Proposed National Environmental Standard for Plantation Forestry (MPI, 2015). Forestry BMPs are the primary mechanism for the management of water quality associated with plantation forestry. Therefore, field studies are needed to document the effectiveness of current BMPs to reduce erosion and sediment delivery to streams.

BMP guidelines for harvest planning managers and logging contractors are provided in documents such as the *NZFOA Forest Road Engineering Manual* (NZFOA, 2011) and the Environmental Code of Practice for Plantation Forestry (NZFOA, 2007). However few studies in New Zealand have examined the relationship between current BMPs and sediment delivery potential at forest road-stream crossings. Field measurements to characterise stream-crossing approach length, slope and road camber, and the geometric design and surface cover associated with cut slopes, fill batters and table drains, can be used to evaluate the potential for sediment delivery to streams.

In this paper we focus on assessing haul road-stream crossings as one source of sediment. This was done by: 1) documenting the degree of water control at road-stream crossings through measurements of road approach length, slope and road camber; 2) estimating potential erosion on the running surface and total bare soil area (m^2) near the stream; and 3) evaluating the degree to which the crossing structure protects water quality and aquatic habitat.

Methods

From April to August 2015, site visits were made to 39 corporate haul road-stream crossings covering six regions in New Zealand. A haul road-stream crossing was classified as any crossing on an arterial, secondary or spur road. Most of the sites (24) were located in the South Island: Southland (3), Otago (3), Canterbury (13) and Nelson–Marlborough (5). Site visits in the North Island (15) included Gisborne (10) and Waikato (5). Crossing types included single culverts (25), open fords (9), drift decks (3) and battery culverts (2) (Figure 1). Drift decks and battery culverts were grouped into the category 'vented fords' in accordance with Keller and Clarkin (2007). Using this classification, 64.1% of the crossings surveyed were single culverts, 23.1% were open fords and 12.8% were vented fords.

Soil erosion estimates on the running surface

The Universal Soil Loss Equation as modified for forest land (USLE-forest) (Dissmeyer & Foster, 1984) can be an effective tool for estimating potential erosion rates from disturbance areas associated with timber harvesting (Christopher & Visser, 2007), as well as evaluating different BMP implementations and their influence on potential erosion for forest roads (Brown et al., 2013) and skid trails (Sawyers et al., 2012; Wade et al., 2012). We used USLE-forest because the input parameter values can be easily obtained through office planning and rapid field surveys. Also, model performance in ranking different road BMP implementations with regard to measured erosion rates is similar to more parameter-intensive, physically-based models such as the Water Erosion Prediction Project (Brown et al., 2013). USLE-forest was used to estimate annual surface erosion rates associated with the running surface component of the crossing approaches and to characterise water control and surface cover BMPs near the crossing.

Figure 1: Stream-crossing types included in the field survey of road design, water control and surface cover BMPs: a) single culvert; b) open ford; c) drift deck; d) battery culvert

USLE-forest uses the following site-specific data to predict long-term average soil erosion resulting from sheet and rill erosion: long-term rainfall averages; soil erodibility values determined by the USDA Natural Resources Conservation Service for a given soil series; and factors for slope length and steepness, soil cover and conservation management practices. The USLE equation is described below:

$$A = RKLSCP,$$

where A is soil erosion per unit area, R is the rainfall and run-off factor, K is the soil erodibility factor, LS is the length and slope factor, C is the cover and management factor (including bare soil, residual binding, soil reconsolidation, mean canopy height and cover, stepped topography, on-site storage and vegetation) and P is the support practice factor (e.g. contour tillage).

R-values for each site were selected from a map of rainfall erosivity index values for New Zealand (Haas, 2014). An intermediate K-value of 0.033 (t ha hr/ha MJ mm) was chosen for all sites because soils associated with the running surface are highly modified. For example, many forest road pavements in New Zealand are comprised of a compacted subgrade soil layer underlying an aggregate surface layer (Fairbrother, 2011).

LS factors were determined by using the slope effect chart in the USLE-forest manual (Dissmeyer & Foster, 1984) and the lengths and slopes of the stream-crossing approaches that were measured during site evaluations. Stream-crossing approach length was defined as the distance from the stream to the nearest water control structure (i.e. cross-drain culvert or cut-out). If no water control structures were present, approach length was estimated as the length of road that contributes run-off directly to the stream channel. Approach width was representative of the running surface plus road shoulders (i.e. the road formation width). Approach lengths were measured with either a cloth tape or laser rangefinder and approach slopes were measured with a clinometer.

The *C* values were determined using sub-factors for disturbed soils. Surface cover was estimated by walking in a zig-zag pattern on the running surface for the entire length of the stream-crossing approaches and counting the number of footsteps where the toe of the boot fell upon covered soil (i.e. ('covered' steps/total steps)*100 = percent surface cover). Erosion estimates (tonnes/ha/yr) were divided by the running surface area on each approach to calculate the mass of potential erosion per unit time (tonnes/yr).

Stepwise regression analysis was used to evaluate the relationships between potential soil erosion and the following explanatory variables: bare soil percentage, *LS* factor, *R* factor and time since disturbance (months). Time since disturbance was representative of the time since road construction, the most recent harvest or road maintenance activity (e.g. grading).

Road camber and total bare soil area (m^2) near the stream

On each stream-crossing approach, transects were established perpendicular to the direction of road travel at distances of 5 m, 10 m and 15 m from the stream. Transect length was representative of the road right-of-way or the disturbed area associated with road construction. At each transect, road camber (cross-slope) was measured to characterise the degree to which the road profile (crown, inslope or outslope) shed water from the road surface (see photo). Road camber was measured by laying a metal rod on the road surface and using a laser rangefinder to measure the slope of the road running away from the road centre. A crowned road, for example, might have slopes of –4% on either side of the road centre line. For each transect, mean cross-slope was quantified from the absolute value of road camber measurements.

If water table drains were present in a given transect, drain depth was measured relative to the elevation of the road centre line. Additional measurements associated with the water table drain included bare

Road camber measurements

soil percentage (visual estimate), width and shape (flat bottom, V-shaped, or U-shaped). For cut batters and fill slopes, measurements included slope, slope length and bare soil percentage. Bare soil percentages associated with each road component (road formation, water table drain, cut batter and fill slope) were multiplied by their respective surface areas to calculate total bare soil area (m^2) within 15 m of the crossing. Bare soil area and soil erosion estimates from the running surface were used to assess sediment delivery potential near the stream.

Evaluation of the stream-crossing structure

A series of questions related to the level of water quality, aquatic habitat and channel protection afforded by the crossing structures was adapted from the Virginia Department of Forestry's BMP audit program (VDOF, 2011). Relevant questions for single culverts, fords, drift decks and battery culverts were answered 'yes' or 'no' in the field and the results were summarised as the percentage of positive responses by crossing type and crossing evaluation question. All components of the approaches and the crossing structure were photographed to allow further post hoc examinations, if needed. The stream-crossing evaluation questions are shown below:

1. Are stream crossings installed at or near to right angles, where possible?
2. Are culverts of adequate length?
3. Are culverts covered with gravel to reduce erosion near the stream?
4. Are culvert pipes installed properly in the channel to avoid undercutting and channel erosion?
5. Could fish easily pass through the crossing structure?*
6. Are headwalls or fill slopes stabilised with vegetation, rock or fabric to minimise cutting?
7. Is the culvert open and not plugged with slash, debris and/or sediment?
8. Are fords used only where a natural rock base (or geoweb) and gentle approaches allow?
9. Do all ford crossings avoid restricting the natural flow of water?

* Note that no in-stream evaluation was carried out to determine if fish were present.

Results and discussion

Water control

Mean length and slope of the stream-crossing approaches was 40 m and 7.2%, respectively (Table 1). Approximately three-quarters of the approaches were shorter than 50 m with less than a 10% gradient (Figure 2). However approach lengths could be shortened further by adding another water control structure. Sessions (2007) states that surface run-off from the road and table drains should be redirected from the road at least 20 m before the stream crossing. In this way, direct hydrologic connectivity could be limited to a 20 m road segment immediately upslope of the crossing, while road run-off originating upslope from the water control structure could be redirected and dispersed over the forest floor before reaching the stream.

Table 1: Length, slope and road camber for the stream-crossing approaches

Water control attribute	n	Mean	5th Percentile	95th Percentile
Approach length (m)	68	40.0	8.7	93.8
Approach slope (%)	68	7.2	1.0	12.6
Camber (%)	198	4.4	1.3	8.5

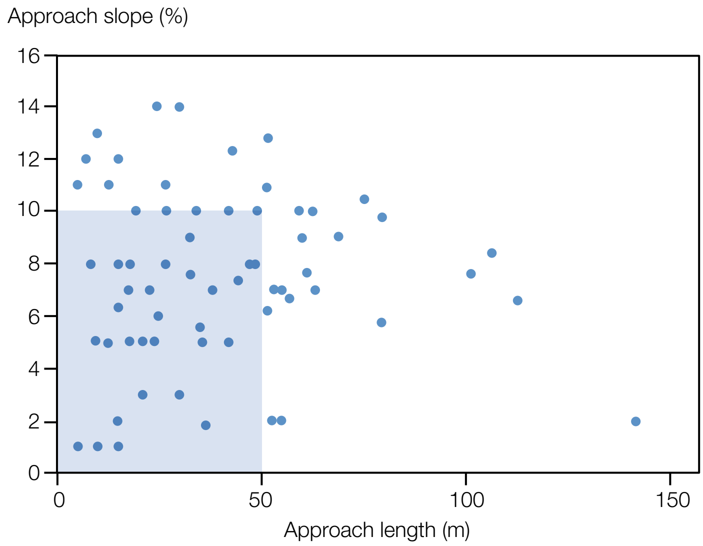

Figure 2: Scatter plot of stream-crossing approach length (m) and slope (%). The grey screen indicates approaches that were ≤50 m long with slopes ≤10%

In 4% of the road camber transects, the road profile was sloped toward the road centre line. This means that water would travel down the road, as opposed to draining toward the drain or toward the fill slope. In 10% of the road camber transects, ruts compromised the function of the road profile. Overall, rutting and/or road drainage toward the centre line occurred in 13% of the road camber transects. Such road surface defects occurred most frequently (19 of 25 occurrences) for newly-constructed roads with poor surface cover.

The New Zealand Forest Road Engineering Manual (NZFOA, 2011) suggests a road camber between 3%–6% for effective road surface drainage. Road camber was less than 3% in 51 of 198 transects, or 26% of the time (Figure 3). Road camber was greater than 6% in 40 of 198 transects, or 20% of the time.

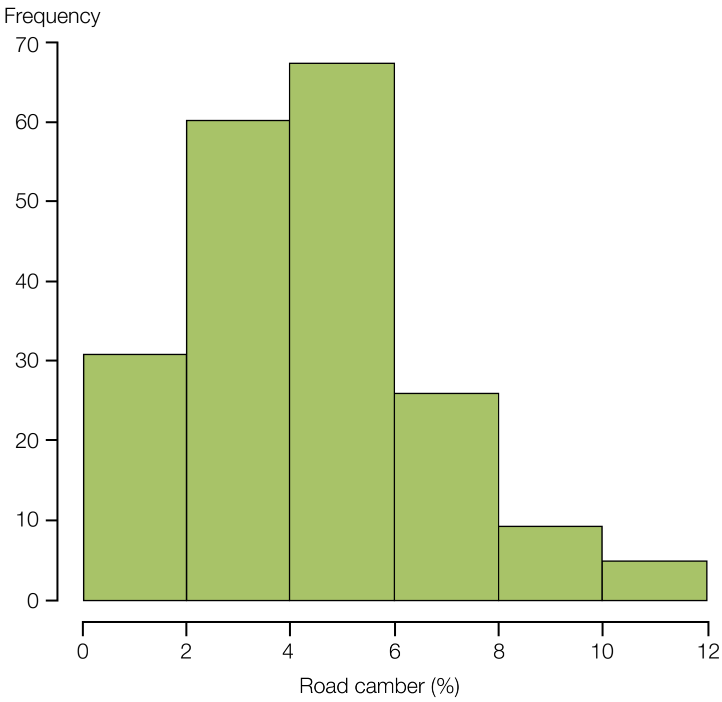

Figure 3: Distribution of road camber measurements (%) on the stream-crossing approaches within 15 m of the stream

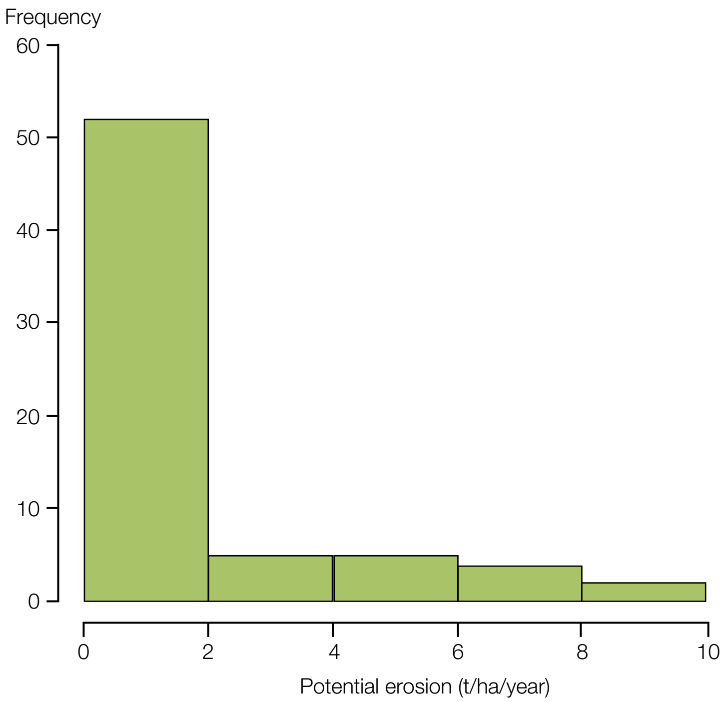

Figure 4: Distribution of potential erosion rates (tonnes/ha/yr) on the running surface component of the stream-crossing approaches

Potential soil erosion

USLE-forest estimates of potential erosion on the stream-crossing approaches ranged from 0.01 to 8.73 tonnes/ha/yr, with a median value of 0.7 tonnes/ha/yr. Potential erosion was less than 1 tonne/ha/yr in 62% of the approaches surveyed (Figure 4). Adequate cover (i.e. aggregate surfacing) on the running surface reduced potential erosion rates. For example, percent bare soil ranged from 5%–90%, with a median value of 25%. Conversely, potential erosion was greater than 2 tonnes/ha/yr in 24% of the stream-crossing approaches. The majority of these sites (12 of 16 cases) were recently constructed roads with poor running surface cover.

Findings from Fransen et al. (2001) highlight the need for field studies to further document the effectiveness of current BMPs to reduce surface erosion and sediment delivery from New Zealand forest roads. Our field estimates of potential erosion from the running surface indicate that aggregate surfacing and road location planning to avoid excessive approach lengths and slopes are working to reduce sediment delivery potential at stream crossings.

Bare soil area within 15 m of the stream crossing

Total bare soil area ranged from 2.3 to 421 m^2, with a median value of 82 m^2. Bare soil area decreased with time since disturbance (Figure 5), indicating that the potential for erosion and sediment delivery is highest during and shortly after a disturbance event, such as road construction and harvesting (Fahey & Marden, 2006). During this time, exposed soil is most susceptible to rainfall and run-off erosion. Soil erodibility decreases with time through the processes of surface armouring and vegetation re-establishment on cut slopes, fill slopes and water table drains.

Total bare soil area within 15 m of the crossing was dominated by contributions from the road formation (mean relative contribution = 53%). Mean contributions from the cut slope, fill slope and water table drain, were 26%, 16% and 10%, respectively

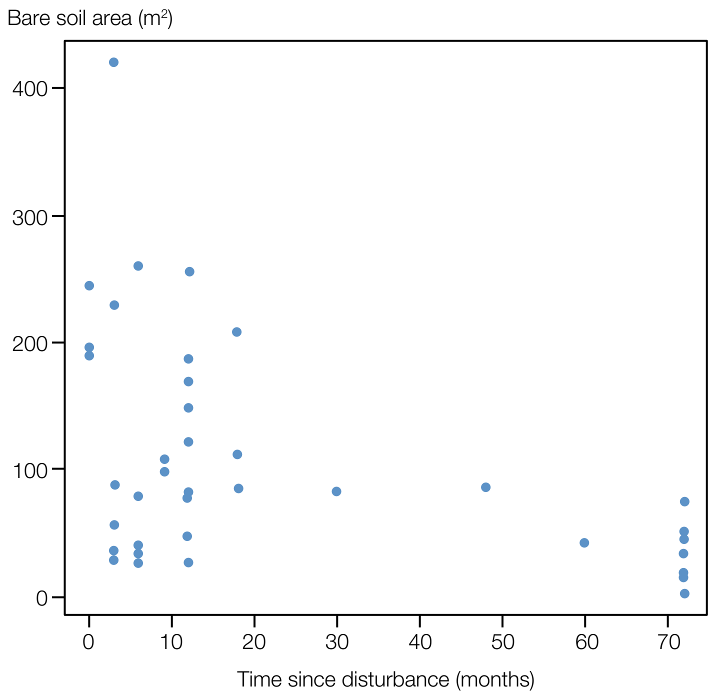

Figure 5: Total bare soil area within 15 m of the crossing as a function of time since road construction or the most recent harvest or major road maintenance activity

(Table 2). Estimates of bare soil area by road component largely reflect differences in the surface area associated with each road component, rather than differences in bare soil percentage. For example, despite generally adequate surface cover, the road formation often contributed more to the total crossing bare soil area because of its larger surface area.

Table 2: Descriptive statistics of the relative contribution (in %) of different road components to the total bare soil area (m^2) within 15 m of each crossing. The 'Other' category refers to areas of bare soil on the side of the road that could not be readily characterised as cut slope, fill slope or table drain

Road component	n	Mean	5th Percentile	95th Percentile
Running surface	39	53	13	100
Cut slope	31	26	2	59
Fill slope	30	16	0	43
Table drain	31	10	1	23
Other	8	28	4	55

Stepwise regression analysis of factors governing potential soil loss

Stepwise regression analysis was used to evaluate the relationships between potential soil erosion on the approaches and the following explanatory variables: bare soil percentage, LS factor, R factor, and time since disturbance (months). The resulting model was:

$y = -8.43 + 0.04X_1 + 1.74X_2 + 0.02X_3 - 0.02X_4$ where y is natural-log-transformed soil erosion (tonnes/yr), X_1 is percent bare soil, X_2 is the LS factor, X_3 is the R factor, and X_4 is time since disturbance (months).

The model explained 74% of the variability in potential soil erosion from the stream-crossing approaches ($p < 0.001$). Higher potential soil erosion rates were associated with poor surface cover and steep and/or lengthy approaches. To a lesser extent, potential soil erosion rates increased with higher rainfall erosivity (i.e. Waikato, Nelson–Marlborough and Gisborne). Potential soil erosion decreased with time, likely due to surface armouring and vegetation encroachment on the road formation for older roads (72 months or more).

Approach length, slope and bare soil percentage were the most important factors governing potential erosion in this study. Fortunately, these factors can be readily managed by forest managers. Road location planning can be used at select stream-crossing locations with gentle approach gradients. Water control structures (e.g. cross-drain culverts, turnouts and broad-based dips) and gravel application near the stream can be used to control approach length and surface cover.

Evaluation of the stream-crossing structure

Most single culvert crossings were installed perpendicular to the stream, had gravel cover over the culvert, were installed properly in the channel to avoid undercutting and channel erosion, and had stable headwalls and fill slopes (Table 3). Study findings indicate that problem areas associated with culverts included culverts blocked with slash, debris and/or sediment, and inadequate culvert length (i.e. culverts that did not project beyond the toe of the fill slope). Blocked culverts can result in damage to roading infrastructure or fill slope failure during flood events (Phillips, 1988). While the streams were not evaluated for the presence of fish or fish passage requirements, only a few culvert installations had substrate in the culvert, low velocity of water flow in the pipe, or no entry or exit steps to ensure ease of fish passage.

Findings for open fords indicate that all crossings avoided restricting stream flow and that most had gentle approaches and a stable rock base. Open fords that did not cross perpendicular to the stream were observed in three of eight cases. Also, perceived fish passage impediments occurred in four of eight cases, such as a smooth concrete base with high flow velocity, a vertical flow drop over the downstream edge, or a waterfall downstream of the crossing.

Table 3: Percentage of responses to the stream-crossing evaluation questions answered 'yes' for single culverts, open fords, and vented fords. Open fords included unimproved fords and fords with a concrete base. Vented fords included battery culverts and drift decks

Crossing evaluation question	Single culverts (n=25)	Open fords (n=8)	Vented fords (n=5)
1. Stream crossings installed at right angles?	88	63	100
2. Are culverts of adequate length?	76	—	—
3. Culverts covered with gravel?	80	—	—
4. Culvert pipes installed properly in the channel?	83	—	100
5. Easy fish passage?	20	50	80
6. Stable headwalls or fill slopes?	92	—	100
7. Culvert free of blockages?	72	—	100
8. Stable base and gentle approaches for fords?	—	88	80
9. Do fords avoid flow restriction?	—	100	60

Note: One ford crossing was not evaluated because construction was in progress.

Findings for vented fords indicate that all crossings were installed at right angles to the stream, all pipes were installed properly in the channel to avoid undercutting and channel erosion, all headwalls and fill slopes were stable, and all culverts were free of blockages such as slash, debris and/or sediment. Most vented fords would allow for easy fish passage and most had gentle approaches. Battery culverts restricted stream flow, whereas drift decks did not.

Conclusions

This paper focused on haul road-stream crossings as one source of sediment associated with corporate forestry operations. A field survey of 39 road-stream crossings covering six regions in New Zealand was conducted to characterise the potential for sediment delivery to the stream. Mean length, slope and camber (cross-fall) of the stream-crossing approaches was 40 m, 7.2% and 4.4%, respectively, indicating that excessive road drainage lengths and slopes are being avoided near the stream. Water control could be enhanced by adding a cross-drain culvert, cut-out or broad-based dip to limit the approach length to 20 m.

Estimates of potential erosion on the approach running surface ranged from 0.01 to 8.73 tonnes/ha/yr. Recently constructed road-stream crossings were characterised as having higher sediment delivery potential due to greater soil disturbance. This study demonstrates that the risk of surface erosion and sediment delivery at road-stream crossings can be greatly reduced with BMPs such as aggregate surfacing and avoiding long, steep approaches. Future research should evaluate BMP effectiveness in reducing storm-induced mass movements and channelised flows, which are likely to have the greatest impacts to water quality. These sediment sources include gully formation below cross-drain culvert outlets, scarification of hillslopes from cable logging extraction, or road-related landslides resulting from blocked culverts or poor water control during low-frequency, high-intensity rainfall events.

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