THE MAGNITUDE AND TIMING OF RUNOFF FROM FOREST ROADS RELATIVE TO STREAM FLOW AT LIVE STREAM-CROSSING CULVERTS IN WESTERN OREGON

By
Elizabeth M. Toman and Arne E. Skaugset

Department of Forest Engineering, Oregon State University

ABSTRACT. Forest roads alter the pathways of water through a watershed by intercepting and redirecting subsurface flow, along with road surface runoff, down the roadside ditch. At live-stream-crossing culverts, water from the ditches flows directly into the stream. This research investigated the effect of road runoff on the magnitude and timing of peak flows at stream-crossing culverts, by monitoring discharge at the culvert and in the corresponding roadside ditches in the headwaters of Oak Creek, Corvallis, Oregon. The effect of runoff from the road on peak flows in the stream depended on the interaction of the road with the hillslope. Where the road intercepted subsurface flow from the hillslope, the peak flows and flow volumes were affected more greatly than for those road segments where the ditch flow was primarily road surface runoff. These effects were highly variable and could not be predicted using traditional topographic indicators. For live stream-crossing culverts high in the watershed that had small contributing areas, the effect of road runoff on peak flow and volume was more pronounced than for those lower in the watershed where the contributing area was larger.

Introduction

Forest roads have come under increased scrutiny in recent years because they have been linked to deleterious impacts on water quality and aquatic habitat. Forest roads have slower infiltration rates and hydraulic conductivities than the surrounding soil and thus can be source areas for overland flow (Ziegler and Giambelluca 1997). Bilby et al. (1989) describe forest roads as potential chronic sources of fine sediment and other researchers define methods to predict sediment production from roads (Luce and Black 1999; Elliot et al. 1999; Ketcheson et al. 1999). The greatest opportunity for water quality impacts is at stream-crossing culverts where the road runoff drains directly into the stream. Wemple et al. (1996) suggests that road segments connected directly to streams are the road segments that are most likely to cause changes in watershed hydrology and water quality.

Roads not only direct surface runoff to the streams but may redirect subsurface flow as it is intercepted by the road cut-bank (Wemple 1994). In this way, forest roads have the ability to act as extensions of the natural stream network. At live stream-crossing culverts this may produce increases in volume and instantaneous maximum discharge. Also, as road related response involves a different mechanism for delivery of water to the stream, peak flows at the culvert due to the road might not be synchronized with peak flows in the stream at the culvert.

1 Correspondence to: Elizabeth M. Toman, Oregon State University, Department of Forest Engineering, 215 Peavy Hall, Corvallis, OR 97331-5706, U.S.A. Email: Elizabeth.Toman@orst.edu
The objective of this study is to observe and quantify how the timing and magnitude of peak flows at live stream-crossing culverts are altered by runoff from forest roads.

**Study Area**

We conducted this research in an 824 ha watershed in the headwaters of Oak Creek, Corvallis, Oregon on the McDonald-Dunn Research Forest, the school forest for the College of Forestry at Oregon State University (Figure 1). Elevations in Oak Creek range from 150 m to 650 m. The average annual precipitation is 140 cm that occurs primarily between November and April as rain. Hillslope gradients within the forest range from 20 to over 60 percent. The soils are predominantly silty clay loams with an average soil depth of 125 cm.

There are 4,877 meters of stream within the basin resulting in a stream density of 5.92 m/ha. Oak Creek is a fish-bearing stream with measured flow rates as high as 2.0 L/s/ha (18.9 csm). The 4,572 meters of road (5.55 m/ha) were constructed primarily during the 1950’s and 1960’s, however significant upgrading of the drainage on the road system has occurred in recent years. The road system has 99 drainage structures installed and 24 of them are live stream-crossing culverts.

Sixteen stream-crossing culverts were chosen for this study. They varied in elevation from 150 m to 500 m and were located along actively traveled road segments with contributing ditches averaging 90 m. Data from two of the sites was not complete and was not used in all of the analysis.

**Instrumentation and Monitoring**

We instrumented the sixteen stream-crossing culverts with water height recorders at the culvert inlet and trapezoidal flumes in the contributing ditches. The trapezoidal flumes were each equipped with a stilling well and water height recorder. Between September 2002 and May 2003, the recorders in the flumes and at the culverts logged stage height at 10-minute intervals and were downloaded monthly. Four tipping bucket rain gauges recorded precipitation. We calculated stream discharge from water height at the culvert entrance using:

\[
Q = 0.432 \sqrt{g (h - z)^{1.9} d^{0.6}}
\]

where \(Q\) is discharge (m³/s), \(g\) is the acceleration of gravity (m/s²), \(h\) is the water surface elevation above a datum (m), \(z\) is the culvert entrance elevation minus the datum elevation (m), and \(d\) is the culvert diameter (m) (Henderson 1966). We computed discharge in the ditch using an equation for large 60° V trapezoidal flumes:

\[
Q = 1.55 h^{2.58}
\]

where \(Q\) is discharge (ft³/s) and \(h\) is the water surface elevation within the stilling well (ft) (Robinson and Chamberlain 1960).
We analyzed data from an eight-day March 2003 storm. Total precipitation for the storm was 9.5 cm with a maximum intensity of 5.4 mm/hour. Discharge measurements from the stream at the stream-crossing culverts were matched in time to the road runoff discharges from the corresponding roadside ditches. We subtracted ditch discharge estimates from discharge at the stream-crossing culvert to give an estimate of what discharge in the stream would have been without the influence of the road. We compared instantaneous maximum discharge in the streams to the corresponding values in the ditches. For example, stream flow at site four was increased over 15% by the influence of the road when the ditch flow peaked (Figure 2).

Results

Surface road runoff was observed in the ditches of all the study road segments in response to the March 2003 storm. However, the runoff response was highly variable. At four road segments (27%) the instantaneous maximum discharge was less than 0.25 L/s and at eight road segments (53%) it was less than 1.0 L/s. The instantaneous maximum discharge ranged from 0.09 to 9.6 L/s for the ditches and 1.5 to 231 L/s for the streams at the stream-crossing culverts.

Lag to peak, as described by Montgomery and Dietrich (2002), is characterized by the time elapsed from when half the storm rainfall has fallen to the peak discharge. For streams at the stream-crossing culverts, lag to peak estimates ranged from 5.0 to 51.9 hrs with a mean value of 10.2 hours. The lag to peak for the ditch response ranged from 3.3 to 13.0 hrs with a mean value of 5.9 hours. On average, the peak discharge from the ditches occurred 4.6 hours before the peak discharge at the corresponding streams.

At one particular site, the road caused almost a 640% increase in stream discharge. The stream had a baseflow of 0.3 L/s and an instantaneous maximum discharge of 1.5 L/s. The flow in the adjoining ditch peaked at 9.6 L/s. If this site is excluded, the peak flows of the streams were increased on average by 11.5%.

The interaction of the roads with the hillslope is highly variable and not all road segments appeared to intercept subsurface flow during this storm. At over half of the sites the roadside ditch flowed only in direct response to intense precipitation, and for the remaining road segments ditch flow responded throughout the storm and continued after rainfall had stopped. At eight road segments we classified the ditch flow as ephemeral, which means that ditch flow is assumed to come primarily from road surface runoff. At the remaining seven road segments the ditch flow was classified as intermittent, which means that the ditch flow is assumed to come primarily from intercepted subsurface flow (see Gilbert 2002) (Figure 3). The hydrographs of the road ditches with ephemeral flow had quick responses to rainfall. The road segments that had intermittent flow had greater maximum instantaneous discharges, greater storm flow volumes,
and hydrographs with attenuated falling limbs. At road segments with intermittent ditch flow, intercepted subsurface flow dominated the hydrograph. The maximum instantaneous discharge for road segments with ephemeral ditch flow averaged 0.49 L/s and 5.3 L/s for road segments with intermittent ditch flow.

The interception of subsurface flow was highly variable throughout the watershed. For example, sites 31 and 35 are on the same road at similar elevations but had different responses to precipitation. The intercepted subsurface flow and surface runoff at site 35 increased the maximum peak discharge at the stream by 42%. At site 31, ditch flow was primarily road surface runoff and increased the maximum peak discharge only 4%.

**Discussion and Conclusions**

The influence of forest roads on the magnitude and timing of peak flows at the streams they intersect was dependent on the interaction of the road with the hillslope. At all road segments flow at the stream-crossing culvert was increased by ditch flow. When the road segment intercepted subsurface flow this increase in peak flow was on average 10 times greater than when the road segments captured only surface runoff. At half of our study sites the roads intercepted subsurface flow. These sites were located throughout the watershed and were not predicted by elevation, cutbank height, or contributing area.

Peak flows in the ditches occurred, on average, 4.6 hours before their corresponding streams. At some sites this could contribute to reduced lag times and/or more volume of water on the rising limb of the storm hydrograph.

Small streams are much more likely to be affected by road crossings. These occur at higher elevations where streams have smaller contributing areas. Site 35 is an example of a small stream high in the watershed where the road influence substantially increased stream flow at the stream-crossing culvert. The ditch flow at this site, which appeared to consist of intercepted subsurface flow and surface runoff, peaked 30 minutes before the stream and at the peak of ditch flow, increased stream flow by 54%.
Along with increased sediment entering the streams, increased peak flows from ditch flow at the stream-crossing culvert are a forest management concern for sizing culverts. Increases in flow from subsurface interception and surface runoff could increase the return interval of flow at the culvert outlet.

This research suggests that it is not possible to predict the increase of stream flow from topographic indicators. Further research in this area is required to help us better understand how roads influence stream flow.

References


