The Hydrologic Impacts of Roads At Varying Spatial and Temporal Scales: A Review of Published Literature as of April 2004

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Roads are a ubiquitous feature across many forested landscapes. Although roads facilitate the use and management of natural resources, roads may also result in adverse changes in watershed processes. In particular, roads can alter hydrologic processes that influence sediment transport, sediment delivery, and mass-wasting.

The Forests & Fish Report (FFR) set a functional objective for managing the hydrologic effects of roads. This was to:

> "Maintain surface and groundwater hydrologic regimes (magnitude, frequency, timing, and routing of stream flows) by disconnecting road drainage from the stream network, preventing increases in peak flows causing scour, and maintaining hydrologic continuity of wetlands."

To guide the field implementation of this objective, a technical group established regional performance targets for cumulative road length draining to streams at a sub-watershed scale. Because scientific understanding was insufficient to ground such targets through physically-based analysis, targets were primarily supported by professional judgment of the technical group.

Examining the state-of-art-knowledge on road hydrology is a fundamental step in addressing the adequacy and feasibility of FFR road connectivity objectives and performance targets. In addition to determining whether targets are supported by existing literature, such a literature review would help determine whether further studies of forest road hydrology should be initiated as part of the FFR adaptive management process.

In particular, some fundamental questions for review are:

1) What are the hydrological processes affected by road systems;
2) At what spatial and temporal scales are these processes affected;
3) What can be done to mitigate the hydrologic effects of roads?

This bibliography focuses on the current knowledge about primary runoff processes altered by the presence of roads in forested ecosystems. This includes the expanded role of Horton Overland Flow (HOF) across relatively impervious road surfaces, the interception of subsurface stormflow (SSSF) by road cutslopes, and the alternate routing of this flow by road drainage structures (i.e., inside ditches, cross-drain relief culverts, waterbars, and rolling dips). A summary of the literature reviewed is provided below and addresses the hydrologic effects of roads at the site-scale (i.e. plot and road segment scale), basin-scale, and various temporal scales.

Site-scale Effects

Horton Overland Flow (HOF) occurs whenever rainfall intensity exceeds the infiltration capacity of the soil. In humid, forested landscapes rainfall intensity rarely exceeds infiltration capacity, and HOF occurs infrequently (except where heavily compacted). In contrast, road surfaces are highly compacted, have high bulk densities, and have little or no pore space (Luce, 1997). As a result, the saturated hydraulic conductivities (K_s) of road surfaces can be one or more orders of magnitude lower than undisturbed forest (Ziegler et al., 1997). K_s values of road surfaces can be highly variable depending upon geology, traffic, or road surfacing (Reid and Dunne, 1984; MacDonald et al., 2001). Despite this variability, lower K_s leads to a preponderance of HOF on road surfaces. Although roads occupy a very small percentage of most watersheds, they can be responsible for the majority of HOF in forested basins. Road surfaces can also produce runoff in the majority of storm events (Ziegler et al., 1997).

Hillslope runoff processes in the Pacific Northwest are dominated by subsurface stormflow (SSSF). SSSF occurs when permeable soil overlies relatively impermeable bedrock. Since roads are typically cut into the soil profile, and sometimes into underlying saprolite and bedrock, roads are capable of intercepting SSSF from upslope contributing areas. Studies have shown that interception of SSSF is responsible for over 90% of the runoff from roads in the Pacific Northwest (LaMarche and Lettenmaier, 2001; Wemple and Jones, 2003). Roads with deep road cuts and roads constructed on shallow soils are especially prone to intercepting SSSF. Road cuts that do not expose the entire soil profile and roads constructed on benches are less likely to intercept SSSF, indicating that the majority of road runoff comes from a small portion of the road network (Wemple and Jones, 2003).

Basin-scale effects

It has been hypothesized that roads increase peak flows by modifying the mechanism and timing of hillslope flow (Jones and Grant 1996, LaMarche and Lettenmaier, 2001). Roads can transform slower subsurface flow to rapid surface flow, and this may alter the synchronization of hillslope runoff to the stream channel. Less drainage area is needed to initiate channels below road drainage than in natural areas (Montgomery, 1994), and roads often facilitate gully development below road drainage structures such as ditch relief culverts, waterbars, or rolling dips (Wemple et al., 1996; Croke and Mockler, 2001). Gully development can lead to channel extension, and this can increase drainage density from 6-39% (Wemple et al., 1996; Croke and Mockler, 2001). Road runoff is directly routed to the stream network at stream crossings or by road-induced gullies (Wemple et al., 1996; Croke and Mockler, 2001). Roads can also divert existing stream channels into road ditches when streamcrossing culverts become blocked by (i.e., stream piracy; Wemple et al., 2001).

Connectivity is the extent to which the drainage features along the road system (mainly ditches) are directly linked to the channel network. Connectivity is generally expressed as the percent of the total road length that is connected to the channel network (Wemple et al., 1996; Croke and Mockler, 2001). Between regions, connectivity is positively correlated with annual precipitation, which is cross-correlated with stream density. The factors that affect connectivity within regions are much more variable. Connectivity is influenced by hillslope position, road design, topography, soil properties, and geology (Wemple et al., 1996; Croke and Mockler, 2001; Veldhuisen and Russell, 1999). Culverts draining long lengths of road and intercepting runoff from steep hillslopes are most likely to be connected to the channel network through gullies (Veldhuisen and Russell, 1999; Croke and Mockler, 2001). As a result, midslope roads are most likely to be connected to stream channels via gully formation (gullying) (Wemple et al., 1996;

Croke and Mockler, 2001). Connected gullies can also occur when roads intercept seeps, or when roads are constructed in areas with shallow bedrock or deep road cuts (Veldhuisen and Russell, 1999; Wemple and Jones, 2003). In drier climates connectivity occurs mostly at stream crossings (Coe and MacDonald, 2001).

Although much of the research done at the plot and segment scale provides compelling evidence of the effects of roads on runoff timing and magnitude, paired watershed studies have not provided strong evidence to back up research done at smaller scales. Fall and winter period peak flows increased significantly when 12% of the watershed was occupied by roads and landings (Harr et al., 1975). Assuming a road prism width of 10 m, this would require a road density of 12 km/km^2, which is higher than in most managed watersheds under current forest practice regulations. A paired watershed study in north central Idaho showed that roads increased peak flows for the 25-year peak by 31%, and this was attributed to the interception of SSSF by roads (King and Tennyson, 1984). However, a treated watershed in the same area showed a 19-29% decrease in the 5-year peak due to roads (King and Tennyson, 1984), and this was attributed to road drainage routing water outside of the watershed (i.e., stream piracy). Studies in the Caspar Creek watershed in northwestern coastal California have shown no increases in peak flows due to roads (Ziemer, 1981; Lewis et al., 2001).

Some researchers believe that there is a synergistic effect between roads, harvest, and peakflows. Using data from the HJ Andrews Experimental Forest in western Oregon, Jones and Grant (1996) speculated that 'roaded' watersheds that had been 25% clearcut had higher peak flows than 'unroaded' watersheds that had been 100% clearcut. The researchers believed that the major mechanism for the higher peak flows was the connectivity of the road system to the channel network. They also asserted that the increases were independent of peakflow size. Thomas and Megahan (1998) disputed these findings, stating that Jones and Grant inappropriately combined various sized peak flow events and used inappropriate statistical methods (i.e., ANOVA rather than ANCOVA). Thomas and Megahan also stated that the pretreatment calibration periods were too short and that watershed treatments were not replicated, resulting in low statistical power. Taking this into account, the authors felt that Jones and Grant's contention of increases in large peakflows could not be substantiated. Beschta et al. (2000) performed a third analysis of this data set and found similar conclusions to Megahan and Thomas.

The ability to detect watershed scale hydrologic change due to roads has been unsuccessful in paired-watershed studies largely due to insufficient calibration periods and little or no replication in watershed treatment (Thomas and Megahan, 1998). In most paired-watershed studies, roads have been coupled with harvesting, making it difficult to separate effects due to roads. Since paired-watershed studies are expensive and time consuming, many researchers have turned to physically based models to explain the flow routing mechanisms that link road segment scale effects to watershed scale response. In particular, the Distributed Hydrologic Vegetation Simulation Model (DHVSM) has proven useful in predicting changes in peak flows due to forest roads. Outputs from the model suggest that:

1. The dominant source of road runoff is from intercepted SSSF (LaMarche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001);
2. Connectivity is best explained by hillslope curvature and distance to channel (LaMarche and Lettenmaier, 2001);
3. Roads could increase the magnitude of the mean annual flood from 2-12% (LaMarche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001);
4. The effect of roads decrease as flow return interval increases but may still be 3-12% for a 10-year peakflow;
5. Roads decreased the lag-to-peak by 2 to 20 hours;
6. Roads coupled with harvest have an additive rather than synergistic effect.

Although the outputs from these models may warrant skepticism, these models may provide the best alternative when evaluating the hydrologic effects of roads in a broader spatial context.

Ongoing Research and Additional Data Sources

Ongoing research on the hydrological effects of roads includes work in the Sierra Nevada of California (Lee MacDonald, Colorado State University), the Cascades of western Oregon (Jeff McDonnell, Arne Skaugset, and Julia Jones, Oregon State University), Idaho (Terry Cundy, Potlatch), and northern Thailand (Alan Ziegler, University of Hawaii). Work in the central Sierra Nevada includes documenting the effect of road connectivity on runoff and sediment yield in the Kings River Experimental Watershed. The paired watersheds are in calibration and results will not be available for some time. McDonnell's Oregon research includes the monitoring of water flux above and below roads, as well as water flux internal to the hillslope. Preliminary results suggest that the mode of interaction between slope water and the road is groundwater recharge (i.e., vertically via preferential flow paths) to groundwater at some meters depth, then a rise in groundwater to intersect the road ditch, and then seepage through the ditch into the drain and under the road prism. Results also suggest that the bedrock topography or topography of the saprolite surface is a better descriptor of lateral flow distribution because saturation occurs directly above the impervious layer. Ziegler is researching the hydrologic effect of roads relative to agricultural practices in northern Thailand. An extensive bibliography on road sedimentation and hydrology was done by the United States Forest Service and can be found at: http://www.stream.fs.fed.us/water-road/.

Summary

A review of the literature suggests that:

1. Roads can dramatically alter runoff processes at the site scale (i.e., both plot and road segment scale) through the production of HOF (Reid and Dunne, 1984; Harden, 1992; Luce and Cundy, 1994; Ziegler and Giambelluca, 1997; Ziegler et al., 2000), the interception of SSSF (Megahan, 1972; Megahan, 1983; Wemple and Jones, 2003), and stream piracy by ditches (Wemple et al., 2001);
2. The interception of SSSF is the dominant mechanism of road runoff modification on steep, humid hillslopes (LaMarche and Lettenmaier, 2001; Bowling and Lettenmaier, 2001; Wemple and Jones, 2003);

3. Road runoff can augment the rising limb of stream runoff hydrographs or coincide with peak runoff (Wemple and Jones, 2003).
4. The majority of road runoff is from a small portion of the road network (Wemple and Jones, 2003);
5. The magnitude of SSSF interception is dependent upon lithology, depth to bedrock, subsurface topography, and the depth of road cut (Wigmosta and Perkins, 2001; Wemple and Jones, 2003);
6. Roads can lead to an extension of the channel network through gullying, or alteration of the channel network through stream piracy (Montgomery, 1994; Wemple et al., 1996; Veldhuisen and Russell, 1999; Croke and Mockler, 2001;);
7. The connectivity of road and channel networks occur at stream crossings and through road-induced extensions of the channel network (i.e. gullies) (Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001; Coe and MacDonald, 2001);
8. Connectivity is related to annual precipitation, soil depth, lithology, road design, hillslope gradient, and topography (Wemple et al., 1996; Croke and Mockler, 2001; Veldhuisen and Russell, 1999; Wemple and Grant, 2003);
9. Existing data suggests that it would be difficult to meet current performance targets set for road-to-stream connectivity;
10. Paired-watershed studies have not shown strong evidence to support road-induced increases in peak flows due to insufficient pre-treatment calibration, lack of treatment replication, and poor experimental control (Thomas and Megahan, 1998);
11. Modeled studies have shown a 2-12% increase in peak flow due to roads, with the effects persisting at higher flow return intervals (LaMarche and Lettenmaier, 2001);
12. Modeled studies suggest that hydrologic effects of roads and harvest are additive, not synergistic (Bowling and Lettenmaier, 2001).

Recognizing the hydrologic effects of roads is vital for understanding hydrologic and geomorphic processes in forested basins. Many consider road sedimentation to be a more important resource effect than road-induced hydrologic changes. However, the two are linked in that the hydrology of road networks has important implications for both road surface sediment production (Luce and Black, 1999) and mass-wasting (Montgomery, 1994; Veldhuisen and Russell, 1999; Wemple et al., 2001). Fine tuning road design and road maintenance BMPs to avoid excessive water concentration is an important step towards avoiding excessive road sedimentation. This may require improved drainage spacing specifications, or avoiding road construction on certain soils or lithologies.

It is clear that roads affect runoff processes such as peak flow magnitude and peak flow timing at the plot and segment scale, and that roads and road-induced gullies are efficient conduits of runoff to low order streams. Future studies should look at the effects of road runoff on the morphology of low order streams. For example, is the increased runoff to low order streams scouring the channel and contributing additional sediment to higher order channels?

There is still much uncertainty regarding the hydrologic effects of roads at the watershed scale. Additional research, such as a meta-analysis of paired watershed studies, could provide insight on the effect of road connectivity, road density, and road hillslope position on peak flows at the watershed scale. The collection of road connectivity data and road runoff data are essential for any future paired watershed studies (i.e. intensive monitoring), and may provide the linkage between site scale and watershed scale effects.

Annotated Bibliography

Beschta, R.L., M.R. Pyles, A.E. Skaugset, and C.G. Surfleet. 2000. Peak flow responses to forest practices in the western cascades of Oregon, USA. Journal of Hydrology. 233: 102-120.

This study analyzes the same data set studied by Jones and Grant (1996) and Thomas and Megahan (1998), but doesn't explicitly look at the hydrologic effects of roads. The authors look at small watersheds (60-101 ha) and large watersheds (62-637 km^2). However, they only analyzed peak flows greater than the 0.4-year recurrence interval.

The authors found that peak flows in small watersheds increased by 24-28% for the 0.4-year recurrence interval, 13-16% for the 1-year recurrence interval, and 6-9% for the 5-year recurrence interval. In large basins, peak-flow response was small or non-existent. These results were similar to Thomas and Megahan (1998), and were contrary to those of Jones and Grant (1996).

Bowling, L.C., P. Storck, and D.P. Lettenmaier. 2000. Hydrologic effects of logging in western Washington, United States. Water Resources Research. 36(11): 3223-3240.

Changes in streamflow were analyzed from USGS stream gauging records for 23 western Washington watersheds with basin areas ranging in size from 14 to 1600 km^2. Univariate analysis was used to explore trends in annual maximum series, annual minimum time series, and peak over threshold series. Changes in flows were not correlated with forest harvest of road construction. Trends in flow magnitude were related to the shift in the Pacific Decadal Oscillation (PDO), indicating that climatic fluctuation was the most important control on streamflow trends.

Bowling, L.C. and D.P. Lettenmaier. 2001. The Effects of Forest Roads and Harvest on Catchment Hydrology in a Mountainous Maritime Environment. In: Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. Edited by M.S. Wigmosta and S.J. Burges. Water Science and Application 2. American Geophysical Union, Washington, DC. pp. 145-164.

This study used the Distributed Hydrologic Vegetation Simulation Model (DHVSM) to simulate the effects of roads on mean annual floods for two small watersheds in western Washington (i.e. Hard and Ware Creeks – tributaries of the Deschutes River in Washington). Crest gages were installed on twelve roads segments to measure the peak stage of road intercepted subsurface stormflow (SSSF) and road generated Horton overland flow (HOF). In addition, hydrologic connectivity was assessed for the roads networks in both watersheds. Approximately 57 percent of the road segments were connected to streams in the Ware Creek catchment, and 45 percent of the road segments were connected to streams in the Hard Creek catchment. A road and channel network algorithm was developed in the DHSVM to simulate the formation of overland flow by road surfaces and the interception of SSSF by road ditches. Road runoff was routed to stream channels using a linear reservoir scheme. The model was calibrated using a 3-year dataset (July 1, 1993 to June 30, 1996). Observations of the 12 crest gages indicated that road segments can be divided into three categories related to runoff generation: 1) Roads that responded only to extreme precipitation events; 2) Roads that continued to discharge, even over extended dry periods; and 3) Roads that responded to moderate rainfall, but stop discharging after extended dry periods. Researchers estimated that only 5% of the total road runoff was produced from the road surface, with the rest coming from the interception of SSSF. Comparing modeled road discharge to measured road discharge indicated that the model generally over-predicted road segment response. The DHVSM was used to simulate the mean annual flood from October 1985 – June 1996 for three different scenarios: 1) No roads; 2) Roads; and 3) Roads interacting with harvest. The results indicated that roads increased the magnitude of the mean annual flood from 3 to 12 percent, and the ten year flood was increased from 8 to 10 percent. The results also indicated that roads could decrease the lag-to-peak by 2 to 20 hours. Coupling roads with harvest indicated an 11 to 29 percent increase in the mean annual flood, but the two effects were generally additive rather than synergistic. The increase in peak flows due to roads was approximately equal to the effects of harvest, but roads had a much higher effect per unit area than harvest. The effects of both activities declined as the flow return interval increased.

Coe, D., and L.H. MacDonald, 2001. Sediment Production and Delivery from Forest Roads in the Central Sierra Nevada, California. Eos Trans., AGU, 82(47), Fall Meet. Suppl., Abstract H51F-03.

In many forested catchments, unpaved roads are the primary sources of sediment but the effect of this sediment on downstream water resources depends on both the magnitude of the road erosion and the connectivity of the roads to the stream network. The objectives of this study were: (1) measure sediment production from unpaved roads in the Central

Sierra Nevada of California; and (2) determine the proportion of the road network that is directly connected to the stream channel network. Road connectivity was evaluated on 20 km of unpaved roads by determining the length of concentrated flow and sediment plumes, and measuring the volume of gullies induced by concentrated road runoff. In contrast to most other studies, only 20 percent of the road segments were directly connected to the stream channel network. Stream crossings accounted for 80 percent of these road segments, as road-induced gullies and sediment plumes rarely extended for more than 20 m. The length of sediment plumes was more dependent on geology than slope steepness, slope position, or vegetation type. The one road segment with a much higher connectivity was on a relatively impermeable lava cap and ran along the valley bottom. These results suggest that most of the sediment generated by unpaved roads in the study area will not be delivered to the stream network. Road crossings and sites with atypical drainage characteristics should be the focus of design and mitigation efforts.

Croke, J. and S. Mockler. 2001. Gully Initiation and Road-to-Stream Linkage in a Forested Catchment, Southeastern Australia. *Earth Surface Processes and Landforms.* 26: 205-217.

This study detailed the factors that influence hydrologic connectivity between roads and the stream network. Field surveys were done on a road system in the Cuttagee Creek catchment along the New South Wales coast of Australia. Roads were stratified by topographic position, road class, drainage type (e.g., relief culvert, mitre drain and push-out drains), and period of construction. The researchers found that 83 percent of relief culverts were fully connected to the stream network. Ridgetop roads displayed less connectivity to the stream network, with 20 percent of push-out drains and 8 percent of mitre drains showing full channel linkage. Measurements of distance from the drains to the nearest stream channel showed that the median distance of linked drains to the channel was 49 m compared with 98 m for unlinked drains ($p<0.0001$). Contributing road length and hillslope gradient were significant factors in predicting channelized vs. non-channelized flow from the drainage points. Similar results were also found using upslope contributing area. The road surveys indicated that roads increased drainage density by 6 percent. Extrapolating to the entire catchment resulted in a maximum drainage density increase of 9.3 percent.

Faustini, J.M. and P.R. Kaufmann. 2003. Regional, basin and local factors influencing the use of synoptic survey data to assess anthropogenic changes in streambed stability and fine sediment. Eos Trans. AGU, 84(46), Fall Meet. Suppl., Abstract H42E-1125.

(Abstract): To evaluate anthropogenic changes in stream bed stability or texture from synoptic stream surveys, we calculated relative bed stability (RBS*) as the ratio of the geometric mean bed surface substrate diameter to the estimated bankfull critical diameter. RBS* decreased with increasing watershed and riparian disturbance in a previous survey of Oregon and Washington coastal streams, but showed a greater apparent response in streams draining basins underlain by weak sedimentary rock than in those underlain by more resistant volcanic rocks. Systematic natural variation in RBS* (e.g., downstream trends, local variation due to channel morphology, regional differences due to geology or climate) might affect its utility as a routine assessment tool by leading to differences in the relationship between RBS* and land disturbance. To explore these issues, we sampled streams over a wide range of disturbance intensity and geologic erodibility in the northern Oregon Coast Range, eastern Oregon, and mid-Atlantic USA. In each of 17 watersheds we sampled 3 closely-spaced main stem reaches (25-50 km2 drainages in the Oregon Coast Range and mid-Atlantic USA, 250-400 km^2 in eastern Oregon) and 3 reaches each in 1 to 3 smaller tributaries to assess local variability and within-basin longitudinal trends in RBS* relative to variation between watersheds with different land use intensity. Results show that road density was correlated with the log of the expected diameter.

Harden, C.P. 1992. Incorporating Roads and Footpaths in Watershed-Scale Hydrologic and Soil Erosion Models. *Physical Geography*. 13(4): 368-385.

Although this study focused primarily on runoff generation and sediment production from footpaths and rural roads, the similarities between footpaths and roads (i.e., reduced infiltration) are important enough to make this paper worthy of addressing. In this study Harden used a portable rainfall simulator to compare runoff and sediment mobilization on paired rainfall experiments (i.e., on and off road) on sites in Ecuador and Tennessee. The data is somewhat suspect because of the small scale of the plots (15.2 cm diameter infiltration rings). When prewetting the plots the author found that all the sites on paths yielded runoff within 5 minutes, whereas only 39 percent of the non-path sites generated runoff after 30 minutes of applied rainfall. When combining the Tennessee and Ecuador datasets, Harden found that the median runoff coefficients were over 70 percent for paths, as opposed to zero for non-paths.

Harr, D.H., W.C. Harper, and J.T. Krieger. 1975. Changes in Storm Hydrographs after Road Building and Clear-Cutting in the Oregon Coast Range. *Water Resources Research*. 11(3): 436-444.

This study used a paired-watershed design to detail the hydrological effects of roads and clearcutting. Although the comparison between 'roaded' basins (i.e., road without harvest) and the control basins are limited to one year, the study showed that peak discharges for the combined fall and winter periods increased significantly when roads occupied more than 12 percent of the watershed area. The authors speculated that in basins where roads occupied more than 12 percent of the total area, 10-year peaks were capable of becoming 25-year peaks, and 25-year peaks were capable of becoming 90-year peaks. Using hydrograph analysis techniques it was also determined that quickflow (i.e. rising limb of the hydrograph) decreased and delayed flow increased significantly for one of the basins.

Jones, J.A. and G.E. Grant. 1996. Peak Flow Responses to Clear-Cutting and Roads in Small and Large Basins, Western Cascades, Oregon. *Water Resources Research*. 32(4): 959-974.

This study looked at the effects of clear-cutting and roads on peak discharge, volume, begin time, and time of peak for hydrographs in small (0.6-1.0 km^2) and large (62-637 km^2) basins in the Western Cascades, Oregon. Peak discharges were separated into seasonal (e.g., fall, winter, and spring), small (<0.125 years), and large (0.4 to 100 years) events. Rather than using the traditional ANCOVA approach of statistical analysis (i.e., testing regression slope and intercept differences in treatment vs. control), the authors used ANOVA to test for significant differences between control and treated basin. Small basins with 100% clearcutting and no roads showed a significant increase in small events (i.e., +50%), but no significant increases in large events. In small basins with roads only, mean peak discharges were 20% higher than the control and storm peaks occurred 10 hours earlier than the control. However, these differences were not statistically significant. Small basins with 25% clearcuts with roads showed a 50% increase in peak discharge along with a shorter lag to peak (i.e., 6 hours quicker). The authors stated that the hydrographs responded significantly differently to 25% clearcutting with roads than 100% clearcutting alone. The authors speculated that clearcutting and roads interact to produce larger storm peaks and shorter lag to peaks and that the major mechanism for these changes was the connectivity of the road system to the channel network. Contrary to other studies, the authors stated that these increases were independent of recurrence interval. Additionally, the authors stated that a similar percentage increase in peak discharges due to roads and clearcutting occurred during the largest storm events.

Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder. 2000. Effects of Roads on Hydrology, Geomorphology, and Disturbance Patches in Stream Networks. Conservation Biology. 14(1): 76-85.

In this paper, the authors outlined a conceptual model on how roads interacted with stream networks at a landscape scale. They proposed that landscapes consisted of a matrix of patchwork and network structures. The patchwork structures are considered the vegetation type, as influenced by soil, disturbance (natural or human), or landform evolution. The model focused on natural physical networks (e.g., streams, riparian areas, and ridgetops) and their interaction with artificial networks, such as roads. In areas without roads, matter and energy (e.g., sediment, water, coarse woody debris) follow gravitational flowpaths from the hillslope down to the channel network. Roads are capable of altering these processes by acting as: 1) Corridors for flow of water and sediment along road surfaces and ditches; 2) Barriers for flow of water and sediment; 3) Sources of water and sediment; and 4) Sinks for sediment (e.g. roads intercepting slides). The density of roads and streams provides a framework to evaluate how road design and topographic relief affect road influences on debris flows and peak flows. Although roads only disturb a small proportion of the total landscape, they can disturb a disproportionate amount of the stream network. The magnitude of disturbance from roads may reduce the abundance of stream refuges for aquatic organisms. The authors tested this conceptual model on the HJ Andrews Experimental Forest using data from previous studies. The authors outlined the conceptual model to support previous research done by Jones, Grant, and Wemple.

Jones, J.A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research.* 36(9): 2621-2642.

Jones continues her analysis of paired catchments, confining herself to basins that are 10 to 253 ha in size. Using ANOVA, she examines the effects of various treatments (e.g., harvest and roads) on peak discharges. Peak discharges were classified by seasonal category and climatic characteristics (i.e., rain-on-snow). The results indicated that in catchments with roads, the subsurface flow interception effect produced a 13-36% increase in peak discharge events greater than one year return periods. These increases persisted for decades. The author speculated that peak flow increases are especially responsive to the density of midslope roads.

King, J.G. and L.C. Tennyson. 1984. Alteration of Streamflow Characteristics Following Road Construction in North Central Idaho. *Water Resources Research*. 20(8): 1159-1163.

This paired watershed study provides mixed evidence of the effects of road construction on streamflow peak discharge. After a calibration period of 4-5 years, six watersheds were subjected to road construction ranging from 1.8 to 4.3 percent of the total watershed area. One watershed showed an increase in the flows equaling or exceeding the 25-year peak. This was attributed to subsurface stormflow interception from a road with a large upslope contributing area and high cutbanks. Unexpectedly, results from another watershed indicated a decrease in flows equaling or exceeding the 5-year peak. This watershed had the largest percentage of area in roads. The decrease in the 5-year peak might have resulted from the alternate routing of road-intercepted water out of the study watershed.

LaMarche, J.L. and D.P. Lettenmaier. 2001. Effects of Forest Roads on Flood Flows in the Deschutes River, Washington. *Earth Surface Processes and Landforms*. 26: 115-134.

This was a comprehensive and ambitious study that used the Distributed Hydrologic Soil Vegetation Model (DHSVM) to predict the effects of roads on peak flows in nine subcatchments of the Deschutes River in Washington State. A survey was done to determine connectivity between the road system and natural stream systems. The researchers found that hillslope curvature and downslope distance to the natural stream channels were the most significant ($p<0.05$) variables in predicting hydrologic connectivity between road segments and streams. Using these variables in a statistical model, the researchers predicted that 24 percent of the ditch relief culverts were connected to the stream network. Once these sites were incorporated into the GIS, runoff was routed using the DHSVM. The model predicted that forest roads alone would increase runoff from 2 to 10 percent for the mean annual flood, and from 3 to 12 percent for the 10 year event. These increases in floods increased with flood return period. Previous fieldwork done at the road segment scale indicated that roads located below recent harvest units were capable of producing more runoff than roads located below mature forest. However, the model showed that roads and harvest were independent at the catchment and subcatchment scale. The authors speculated that this was a scaling issue.

Lane, P.N.J. and G.J. Sheridan. 2002. Impact of an unsealed forest road stream crossing: water quality and sediment sources. Hydrological Processes. 16: 2599-2612.

Turbidity monitoring, rainfall experiments, and runoff simulation experiments were performed for a newly constructed rocked road crossing in the Central Highlands of Victoria, Australia. Rainfall and runoff experiments were used to obtain the unsaturated hydraulic conductivity (K_{SAT}) for the road surface, fillslopes, and road verges (i.e., untravelled surfaces at the base of the cutslope or the top of the fillslope). The K_{SAT} values were 36.5 mm hr^{-1} for the road surface, and between 32.7 to 50.4 mm hr^{-1} for the fillslopes, and 11.6 to 23.2 mm hr^{-1} for the road verges. The K_{SAT} values were roughly 10 times higher than those reported in other studies. The researchers postulated that the high K_{SAT} values were due to the very coarse gravel on the travel surface and the minimal compaction of the road verge and fillslopes.

Lewis, J., S.R. Mori, E.T. Keppeler, and RR. Ziemer. 2001. Impacts of Logging on Storm Peak Flows, Flow Volumes and Suspended Sediment Loads in Caspar Creek, California. In: <u>Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas.</u> Edited by M.S. Wigmosta and S.J. Burges. Water Science and Application 2. American Geophysical Union, Washington, DC. pp. 85-126.

This study fit models to 11 years of storm peak flows, flow volumes, and suspended sediment on a network of 14 stream gaging stations in the North Fork of Caspar Creek, a 473-ha second-growth forest of redwood and Douglas-fir located in coastal Northwestern California. The catchment was logged in accordance with the California Forest Practice Rules, complete with riparian buffer zones of 15 to 46 m. Independent variables included the areal extent of roads and landings, areal extent of roads within 150 feet of the stream channel, and number of road stream crossings. Road variables were not significant in predicting increases in storm peak flows or flow volumes. However, the areal extent of road cuts and road fills was the most important variable for predicting suspended sediment loads. Soil compaction from roads comprised less than 3 percent of the catchment area, with most of the roads located near ridgetops. The authors speculated that since roads and harvest were not applied as separate treatments, it was too difficult to statistically distinguish their effects.

Luce, C.H. and T.W. Cundy. 1994. Parameter Identification for a Runoff Model for Forest Roads. *Water Resources Research*. 30(4): 1057-1069.

This paper provides some useful information on road runoff at the highly controlled plot scale. The authors performed rainfall simulation on six different road plots across a range of soil types. The simulations were done on 1 m^2 and 5 m^2 plots at varying antecedent moisture conditions. Conductivity, sorptivity, depression storage, and roughness factor values were chosen for a physically based overland flow model using two automated parameter estimation algorithms. Hydraulic conductivities for the road surfaces ranged from 5 x 10-5 mm hr^{-1} to 8.82 mm hr^{-1}, with a mean of 0.11 mm hr^{-1}. The model was successful in reproducing field-measured road surface hydrographs. However, the authors speculated that high errors (i.e., percent error in volume and percent error in peak flow) were associated with spatial variability, especially with dry antecedent moisture conditions. The errors were reduced as soil moisture increased.

Luce, C.H. 1997. Effectiveness of Road Ripping in Restoring Infiltration Capacity of Forest Roads. *Restoration Ecology*. 5(3): 265-270.

This study explores the effectiveness of ripping and mulching for road restoration in the Idaho Panhandle. Saturated hydraulic conductivities (K_s) were measured on an unripped road, a ripped road, and a ripped/mulched road for two different soils during three simulated rainfall events. The first soil was derived from metasedimentary parent material and had high rock fragment content and high fine content. The second soil was derived from Idaho batholith granitics and was sandy, with some rock fragments, and low fines. Ripping on the metasediment-derived soils was done using 4-foot deep rippers, whereas ripping on the granitic soil was done using 2-foot deep rippers. The K_s for unripped roads ranged from 0-12 mm/hr for both soil types. After ripping, the K_s significantly increased to 22-35 mm/hr for metasediments and 7-25 mm/hr for granitics.

These values were modest compared to the K_s of 60-80 mm/hr for lightly disturbed forest soil. K_s decreased by 50% for ripped granitic soils following additional rainfall. K_s decreased for ripped metasediment soils, but the decrease was not significant. The addition of mulch prevented the decline in K_s for metasediments, but only moderately for granitics. The study indicates that the incorporation of organic material is crucial to maintain high infiltration capacity on ripped roads.

MacDonald, L.H., R.W. Sampson, and D.M. Anderson. 2001. Runoff and Road Erosion at the Plot and Segments Scales, St. John, US Virgin Islands. *Earth Surface Processes and Landforms*. 26: 251-272.

This is a case study addressing the dominant processes affecting road runoff and sediment production. The paper describes runoff and sediment production from three vegetated hillslope plots, four road surface plots, and two cutslope plots on St John in the US Virgin Islands. The vegetated hillslope plots produced small amounts of runoff during two hurricane events, with runoff coefficients less than 3 percent. Most road plots produced runoff during storm events with at least 6 mm of precipitation. During the largest storm events some of the road runoff reservoirs overflowed, resulting in underestimates of runoff. Significant relationships were established between total storm precipitation and road plot runoff for all road surface plots and for one of the cutslope plots. Storm energy was significant in predicting runoff for two of the road surface plots and one of the cutslope plots. Reported runoff coefficients of 4 to 12 percent for the road plots were less than those reported in other studies. The authors speculated that these lower values might be attributed to the high degree of fracturing in the bedrock below the road surface, thereby promoting more infiltration. They also theorized that road age and traffic might influence infiltration rates. Runoff coefficients for the cutslope plots ranged from 4.2 to 8.1 percent. In addition, 13 m^3 of water was applied 10 m uphill from a cutslope plot resulting in a runoff coefficient of 2.5 percent during dry antecedent moisture conditions. This particular experiment showed that the interception of subsurface stormflow by road cutslopes was an important process.

Megahan, W.F. 1972. Subsurface Flow Interception by a Logging Road in Mountains of Central Idaho. In: Csallany, S.C., T.G. McLaughlin, and W.D. Striffler. Eds. Proceedings from the "National Symposium on Watersheds in Transition"; American Water Resources Association, Fort Collins,CO: 350-356.

This is the definitive paper on subsurface stormflow (SSSF) interception by logging roads, and is particularly relevant to areas in which subsurface stormflow is the dominant runoff process. The author studied two first order Idaho basins that were bisected by insloped logging roads. Runoff was collected in troughs across road cutslopes that bisected two small watersheds. In addition, piezometric response, soil moisture content, and snow water equivalents (SWE) were measured for the contributing areas upslope of the road cuts. SSSF intercepted by the cutslopes varied from 14 to 21 percent of the total precipitation over a two-year period. The difference between years was associated with SWE and snowmelt rates. When compared to the stream flow of perennial streams directly downstream from the road segments, SSSF interception accounted for 32 and 37 percent of the total catchment runoff. The author points out that the excess water might be passing below the cutslopes through rock joints and fractures. The author also makes an estimate of road surface runoff using a runoff coefficient of 0.75 and compares it to SSSF interception. The conclusion is that SSSF interception produced 7.3 times more water than the road surface. This might be an underestimate due to the high runoff coefficient used for the road surface.

Megahan, W.F. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. *Water Resources Research*. 19(3): 811-819.

(Abstract): Many of the environmental impacts of logging and wildfire are caused by changes in the hydrologic response of slopes after disturbances. This study was conducted to evaluate changes in inflow, storage, and outflow for 3-year periods before and after clearcut logging and wildfire on two steep, granitic, microwatersheds in Idaho. Clearcutting alone and clearcutting plus wildfire increased annual peak snow water equivalent and snowmelt rates an average of 41% and 30%, respectively. The greater volume and rate of snowmelt caused respective increases in the peak piezometric rise and in total piezometric storage, amounting to 47% and 27%. Accordingly, the total volume of subsurface flow intercepted by the roadcut was increased 96% and was accompanied by 27% greater peak flow rates. None of the above responses were detectable on an adjacent watershed that was burned by wildfire alone. Evapotranspiration was reduced on both watersheds after clearcutting or wildfire, as indicated by increases in the unsaturated soil water content at the end of the growing season amounting to 44 and 72%, respectively. Accelerated mass erosion on clearcut slopes, and accelerated surface and mass erosion on roads and in channel below roads, can result from such changes.

Montgomery, D.R. 1994. Road Surface Drainage, Channel Initiation, and Slope Instability. *Water Resources Research*. 30(6): 1925-1932.

This study related road drainage characteristics with shallow landsliding and overland flow induced channel initiation. Surveys done in the southern Sierra Nevada indicated that upslope drainage area and local slope are useful in predicting channel initiation by road drainage points. Less drainage area is needed to initiate channels from road-related drainage as opposed to natural drainage. Field measurements done on the Olympic Peninsula in Washington State showed that road drainage points with short segment lengths (i.e. <150 m) and low hillslope gradients (<20%) did not initiate channels. Road drainage points with relatively high segment lengths (i.e. >150 m) resulted in channel initiation, whereas high hillslope gradients (<60%) and relatively high segment lengths (<150 m) resulted in landsliding. Similar results were found on Mettman Ridge in Southwestern Oregon. The author stated that all road erosion features resulted in connectivity to stream network.

Reid, L.M. and T. Dunne. 1984. Sediment Production from Forest Road Surfaces. *Water Resources Research*. 20(11): 1753-1761.

This paper details culvert runoff rates and sediment concentrations from eight insloped gravel-surfaced road segments and two paved road segments in the Olympic Peninsula of Washington State. In addition, the eight gravel-surfaced road segments were stratified by traffic intensities ranging from heavy use to abandoned. Applying the unit-hydrograph method, using 15-minute storm durations, the authors found that all storms with rainfall intensities greater than 0.5 mm hr^{-1} generated runoff on the gravel road surfaces. Using four well-defined storms and comparing total precipitation with total runoff, it was found that the average infiltration rate of the gravel-surfaced segments was 0.8 mm hr^{-1}. Rainfall simulation experiments indicated that infiltration rates stabilized with the first 3 to 5 minutes of precipitation. A third infiltration estimate of approximately 0.3 mm hr^{-1} was calculated by using 11 periods of uniform precipitation intensity and constant discharge. Using these three estimates of infiltration, an average infiltration capacity of 0.5 mm hr^{-1} was calculated for the gravel-surfaced road segments. The average infiltration rates on paved roads were 0.2 mm hr^{-1}. Abandoned gravel roads had infiltration rates of 0.7 mm hr^{-1}, although this was not found to be significantly different than the higher traffic intensities. Additionally, in the study area 75 percent of the road-generated runoff was routed directly to streams.

Sidle, R.C., S. Sasaki, M. Otsuki, S. Noguchi, and A.R. Nik. 2004. Sediment pathways in a tropical forest: effects of logging roads and skid trails. Hydrological Processes. 18: 703-720.

This study evaluated the contribution of unimproved logging roads and skid trails to surface erosion and sediment delivery in a tropical forested watershed in Malaysia. Researchers found that all logging road discharge points were hydrological connected to the stream. However, 78% of the roads were delivering sediment to the streams. The study highlights the importance of properly engineering roads to reduce hydrologic connectivity.

Tague, C. and L. Band. 2001. Simulating the Impact of Road Construction and Forest Harvesting on Hydrologic Response. *Earth Surface Processes and Landforms*. 26(2): 135-152.

This paper used the Regional Hydro-Ecological Simulation System (RHESSys) to detail the effect of forest roads on hydrologic response over different spatial and temporal scales. The study focused on road-induced impacts not addressed in other studies such as: 1) the hydrologic effects on areas below the road which receive less recharge due to the redirection of flow into ditches; and 2) outflow and soil moisture response in cases in which road culverts drain into areas not hydrologically connected to the stream. These road-induced changes can affect runoff production, soil moisture, and ecological processes such as transpiration. The authors calibrated the RHESSys with watersheds in the HJ Andrews Experimental Forest. In watersheds with roads and no harvest, annual outflow increased from 0.5 to 1.7 percent relative to undisturbed areas, with a decrease of 0.1 to 1.6 percent in evapotranspiration. Harvest and roads combined to cause a 6.3 to 8.0 percent increase in outflow, with a 6.7 to 8.6 percent decrease in evapotranspiration. These differences were most dramatic during the summer months, when a reduction in evapotranspiration may have ecological effects on forest health and productivity.

Thomas, R.B. and W.F. Megahan. 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. Water Resources Research. 34(12): 3393-3403.

This paper presented an analysis of the dataset from Jones and Grant's 1996 paper and the results tell a remarkably different story. Thomas and Megahan dispute the lumping of peak flows into small (< 0.125 years) and large (0.4-100 years) categories, arguing that bankfull in many mountain streams occurs in 11 to 100 year recurrence intervals. Analysis of covariance (ANCOVA) is used, rather than ANOVA, to determine if the regression slopes of the treated watersheds are significantly different from the control. Thomas and Megahan found that while the combination of clearcutting and roads was significantly different from the control for the first 9 years after harvest, the differences were not as dramatic as the 100% clearcut. Also, these differences were not significantly different from the pre-treatment levels. No treatment effects were detected more than 10 years after harvest and Thomas and Megahan speculated that effects would last longer if the road/harvest interaction hypothesis, brought forth by Jones and Grant, were correct. Thomas and Megahan stated that the pretreatment calibration period (i.e., 3.5 years) was too short, watershed treatments were not replicated, and the reliability of the hydrograph data was suspect. Taking this into account, Thomas and Megahan felt that the conclusions made by Jones and Grant could not be substantiated.

Veldhuisen, C. and P. Russell. 1999. Forest Road Drainage and Erosion Initiation in Four West-Cascade Watersheds. *TFW Effectiveness Monitoring Report:* TFW-MAG1-99-001.

This report looked at the magnitude and controlling factors on road-induced gully initiation and landslides for four watersheds in western Washington. These watersheds represented a wide range of geologic and climatic settings. Four to five road segments were chosen for each watershed or WAU, with each segment ranging from 0.5 to 2.2 miles in length. The presence and characteristics of erosion features were assessed at each road drainage site (i.e., cross-relief culvert), in addition to other local variables such as hillslope gradient, hillslope form, and ground surface roughness. Approximately 50% of the drainage structures had no erosion features associated with them. Thirty-five percent of the drainage sites had gullies present, and 15% of the drainage sites were associated with landslides. Sixty-three percent of the gullies delivered sediment to the channel network, whereas 80% of the landslides delivered sediment to the streams. Slopes of 60% or greater had substantially higher rates of gullying. The interception of shallow-groundwater seeps by roadside ditches was an important causal mechanism for gully initiation on hillslopes with less than 60 percent slope. Road contributing length was an important factor on slopes of 60-79%. However, the presence of seeps was the most important factor for gully initiation for slopes less than 60 percent. Gully initiation was independent of road contributing length for slopes of 80% or greater. The authors concluded that the present Washington Forest Practice Rules for drainage spacing specifications are insufficient for preventing road-induced gully initiation.

Wemple, B.C., J.A. Jones, and G.E. Grant. 1996. Channel Network Extension by Logging Roads in Two Basins, Western Cascades, Oregon. *Water Resources Bulletin*. 32(6): 1195-1207.

This paper should be read in conjunction with the Jones and Grant (1996) paper. The paper presented a conceptual model on how roads affect the volume of water for quickflow. The effect of roads on flow routing and timing were also addressed. In addition, the authors performed field surveys and GIS road analysis to determine the extent of hydrologic connectivity between the road system and the stream network. More than 57 percent of the surveyed road lengths were connected to the stream network. This resulted in an estimated 36 to 39 percent increase in drainage density. A model was developed to predict the occurrence of gullying below road drainage points. The researchers found that the road segment length, hillslope gradient, and their interaction adequately predicted the occurrence of gullying ($p<0.01$). Gullies were more prevalent below roads on slopes greater than 40 percent, independent of road segment length. The authors used the data on hydrologic connectivity and channel extension as indices to predict changes in peak flows for Lookout Creek and Blue River. They found that the timing of road system development corresponded to the timing of observed changes in peak flows for the two catchments as hypothesized by Jones and Grant (1996).

Wemple, B.C., F.J. Swanson, and J.A. Jones. 2001. Forest Roads and Geomorphic Process Interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms. 26: 191-204.

This paper documents the geomorphic impacts of roads following a major flood event in the Cascade Range, Oregon. Approximately 348 km of roads were inventoried in the Lookout Creek and Blue River basins following a 30 to 100 year return period storm. (100-year return period storm were low elevation storms, whereas higher elevations were a 30-year return period storm). Geomorphic features were categorized as mass-wasting or fluvial (e.g., features formed by particle-by-particle transport of sediment by overland flow or channelized flow). Fluvial features accounted for 22 percent of all geomorphic features. Approximately 50 percent of the fluvial features were caused by plugged culverts, resulting in bedload deposition behind the culverts. Thirty-nine percent of the features were caused by stream diversions, and 12 percent of the features were caused by incised ditches. The results indicated that fluvial and mass-wasting features interact to form “disturbance cascades”. An example of this is when several road induced debris slides transform into a larger debris flow.

Wemple, B.C. and J.A. Jones. 2003. Runoff production on forest roads in a steep, mountain watershed. Water Resource Research. 39(8):

Set in the same location as the Earth Surface Processes and Landforms article (Wemple, 2001), this study attempted to answer two site-scale hydrologic questions related to runoff production on roads and catchment scale hydrologic response:

1) Can the relative magnitude and timing of road runoff be predicted using independent site variables?
2) Do road segments produce storm hydrographs whose magnitude and timing contribute to higher peak flows and quicker lag-to-peaks?

To answer these questions, 12 cross relief culverts within Watershed 3 (WS3) of the HJ Andrews Experimental Forest were instrumented with weirs, crest gage recorders, and pressure transducers. In addition, runoff was continuously recorded at WS3, a 101 ha, second-order drainage. The 12 road segments drained 14% of the subcatchment draining to WS3. Rainfall and runoff events were recorded for each site for six months. Independent site variables such as road surface area, upslope contributing area, slope length, slope gradient, soil depth, and cutbank height were measured for each installation. Theoretical predictions of subsurface stormflow (SSSF) interception were generated using a model for kinematic SSSF on inclined slopes. Thirty-three precipitation events were recorded during the study, with maximum storm depths ranging from 9-259 mm, average storm intensity ranging from 0.7-4.5 mm/hr, and maximum storm intensity ranging from 1.8-12.2 mm/hr. The year was much wetter than average, with one storm producing the peak flow of record (i.e., 45 years). Results indicated that road-induced HOF produced between 1 and 7% of the measured runoff. Measured runoff was generally consistent with predicted runoff. Unit area runoff from road segments was higher than unit area runoff from WS3 for half of the sites. Road sites with shorter lag-to-peaks produced the highest unit-area peak runoff. Peak runoff from the road sites became increasingly synchronized with peak runoff at WS3 as event size increased. Road segments whose culverts discharged near channel heads were more likely to contribute significant fractions of the peak at WS3, and peaked earlier than WS3. Over 95% of the road runoff was from intercepted SSSF, and the magnitude of SSSF interception was correlated reasonably well with precipitation intensity. Controlling for hillslope length (i.e. distance from road to ridgetop), road segments whose road cuts intersected the entire soil profile were most likely to produce runoff. Roads draining slopes with shallow soils had rapid runoff response, typically preceding or coinciding with the peak at WS3. Roads segments whose cutbank depth was a fraction of the soil depth produced primarily baseflow and contributed only to the falling limb of the hydrograph. Roads constructed on slump benches produced no measurable runoff. This study provides useful information on the linkages between segment and watershed scale response. An especially interesting point is that a small fraction of road segments may be responsible for the majority of augmented runoff.

Wigmosta, M.S. and W.A. Perkins. 2001. Simulating the Effects of Forest Roads on Watershed Hydrology. In: Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. Edited by M.S. Wigmosta and S.J. Burges. Water Science and Application 2. American Geophysical Union, Washington, DC. pp. 127-144.

The DHVSM (discussed in previous summary of LaMarche and Lettenmaier 2001) was used to simulate the effects of forest roads on streamflow characteristics for the Carnation Creek catchment on the west coast of Vancouver Island, British Columbia. The model was calibrated using data from October, 1972 to September, 1973, but generalized only one vegetation and soil type across the entire catchment. Despite this limitation, the model could explain 89 percent of the variability in timing for the rise, peak, and fall of the hydrograph. Results indicated that the road network might increase the contributing area of some channel segments and decrease the area draining to others. The simulations showed that while total runoff volumes were not altered, lag-to-peaks were shortened, and runoff magnitude was increased. The authors speculate that road-induced overland flow has little effect, and that effects become significant once subsurface stormflow is intercepted by the road cutslope.

Wright, K.A., K.H. Sendek, R.M. Rice, and R.B. Thomas. 1990. Logging Effects on Streamflow: Storm Runoff at Caspar Creek in Northwestern California. Water Resources Research. 26(7): 1657-1667.

The authors of this paper investigated whether road construction or selective harvesting in Northwestern California increased total storm volumes, quick flow volumes, peaks flows, or altered lag times. Their results showed that road construction did not significantly alter the magnitude or timing of storm volumes, quick flow volumes, or peak flow. The authors speculated that since roads occupied only 4.5 percent of the watershed, compared to the 12 percent threshold given by Harr et al. (1975), few effects could be detected. The authors also noted that 88 percent of the road network was within 61 m of the main channel. They hypothesized that roads in close proximity to the stream channels had less of an impact in rerouting subsurface stormflow (SSSF) because the majority of SSSF was probably unchanged throughout much of its path to the stream channel.

Ziegler, A.D. and T.W. Giambelluca. 1997. Importance of Rural Roads as Source Areas for Runoff in Mountainous Areas of Northern Thailand. *Journal of Hydrology*. 196: 204-229.

This study modeled the runoff contribution of rural native surface roads, forest land, and agricultural land in Thailand on a catchment scale using a physically based model for overland flow. Saturated hydraulic conductivities were estimated for roads and adjacent lands (i.e. forest and agricultural land) using a disc permeameter. The saturated hydraulic conductivities (K_s) for road surfaces ranged from 0.2 mm hr^{-1} to 5.1 mm hr^{-1}, with a median value of 2.3 mm hr^{-1}. The K_s for forest land varied from 52.3 mm hr^{-1} for disturbed forest to greater than 1666 mm hr^{-1} for undisturbed primary forest. Rainfall intensity exceeded Ks on the road surfaces on approximately 50 percent of the 710 rainfall periods. Overland flow was simulated for the 25 largest precipitation events in the dataset. It was determined that 100% of the modeled storm events produced runoff on road surfaces as opposed to only 24% of the storm events producing runoff on forest and agricultural land. The authors also determined that while occupying only 0.22 percent of the total catchment area, road surfaces contribute a greater percentage of total overland flow during smaller events than the adjacent land types. During larger storm events the forested and agricultural areas become a variable source of overland flow and their inputs overwhelms the input of road-induced overland flow.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca. 2000. Partioning Total Erosion on Unpaved Roads into Splash and Hydraulic Components: The Roles of Interstorm Surface Preparation and Dynamic Erodibility. *Water Resources Research*. 36(9): 2787-2791.

This study separates road runoff into splash and hydraulic components. Road plots in Thailand and Hawaii were subjected to high energy rainfall impact (i.e., splash) as well as a low energy application of water (i.e., hydraulic). The authors found that splash treatments produced runoff quicker than hydraulic treatments. Splash treatments also had higher runoff coefficients than hydraulic treatments. Steady state infiltration values were also significantly lower for splash treated sites. The researchers attributed this to sealing of the soil surface through rainfall impact.

Ziegler, A.D., T.W. Giambelluca, R.A. Sutherland, T.T. Vana, and M.A. Nullet. 2001. Horton overland flow contribution to runoff on unpaved mountain roads: A case study in northern Thailand. *Hydrological Processes*. 15: 3203-3208.

Road runoff was monitored on a 165 m road segment in northern Thailand. Soil moisture probes were installed above and below the road segments to detect rise in the water table. The soil was derived from granitic parent material, with soil depths in excess of 2.5 m. In order to detect the presence of intercepted SSSF, the oxygen isotope signatures of stream water, rainwater, and road runoff were measured during natural precipitation events. Soil moisture data indicated that water percolated downward, rather than rising up from below. This indicated that a perched water table did not occur, resulting in no SSSF interception by the road cut. Isotope signatures also confirmed that road-induced HOF was the dominant road runoff process. The study suggests that deeper soils are more prone to HOF rather than intercepted SSSF. The study also suggests that tracer studies may be useful when exploring the linkages between road segment runoff and streamflow.

Ziemer, R.R. 1981. Storm Flow Response to Road Building and Partial Cutting in Small Streams of Northern California. *Water Resources Research*. 17(4): 907-917.

This paper details a paired basin study from the Caspar Creek drainage in the redwood/Douglas-fir region of coastal Northern California. After a four year calibration period approximately 19 hectares of road were constructed in the South Fork of Caspar Creek and parts of the basin were partial cut. The construction of roads resulted in no detectable change of any storm flow parameter. However, roads occupied only 5 percent of the basin and Ziemer speculated that effects were not detected because the surface area of roads and landing were small in comparison to the basin area.