The Impact of Forest Roads on Hydrological Processes and Pathways: A Review of Published Literature

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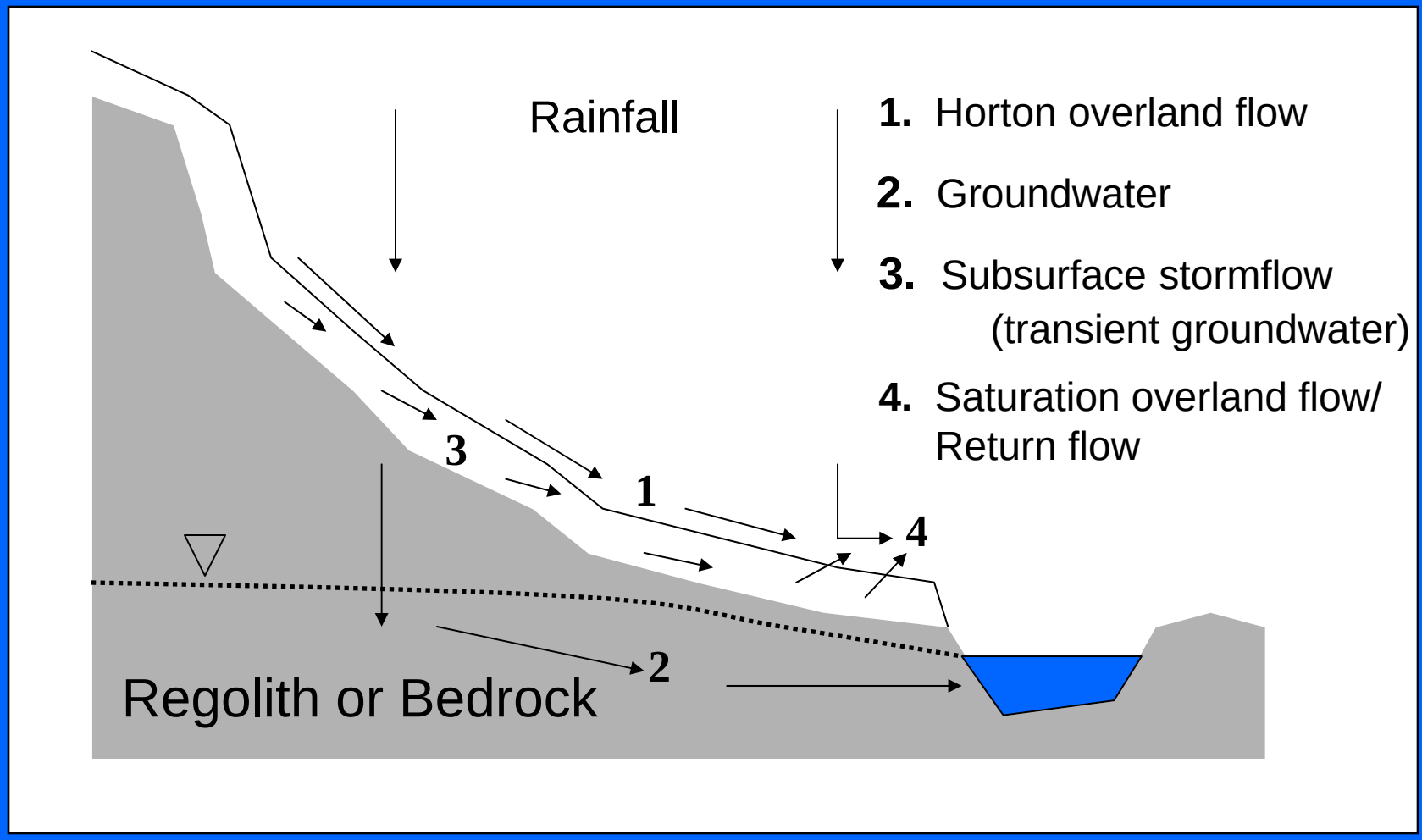
Fundamental Questions Regarding Road Hydrology

- What are the hydrological processes and pathways affected by roads?
- At what spatial and temporal scales are these processes affected?
- What can be done to mitigate the hydrologic effects of roads?

Hillslope Runoff Processes



(Dunne and Leopold, 1978)

Horton Overland Flow (HOF)

- Infiltration rate << Rainfall rate;
- Common in arid to subhumid climates;
- Thin vegetation;
- Soil disturbance (e.g. compaction);

- **NOT COMMON IN UNDISTURBED FORESTED AREAS.**

Subsurface Stormflow (SSF)

(Hillslope trench; McDonnell, 2005)

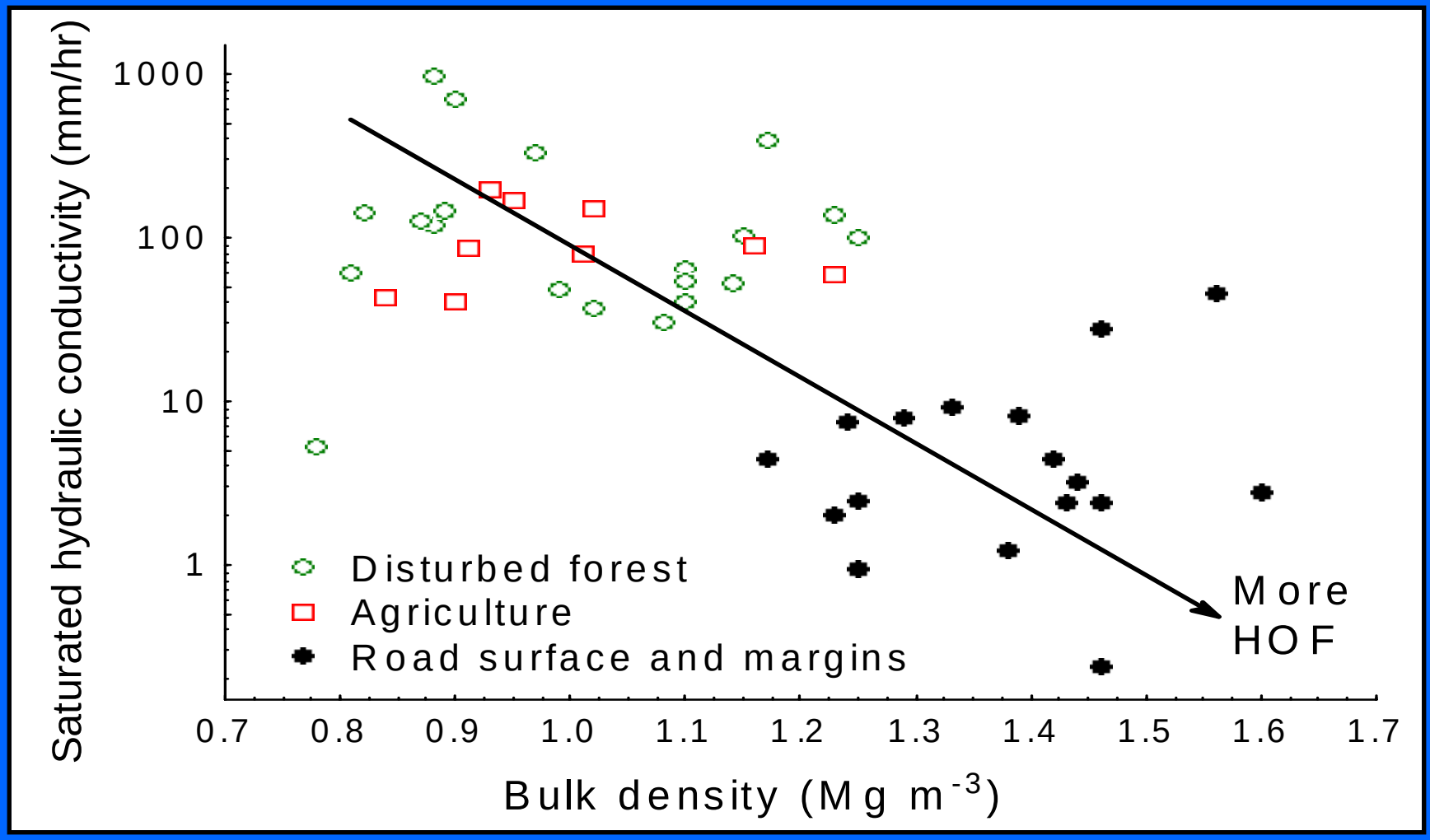
- Steep hillslopes
- Permeable soils overlying relatively impermeable bedrock or regolith
- Humid climate w/ abundant vegetation

- **COMMON IN N. CALIFORNIA AND PNW**

Road Surface Hydrology

- Highly compacted;
- High bulk densities;
- Little or no pore space.

Road Surface Hydrology - HOF

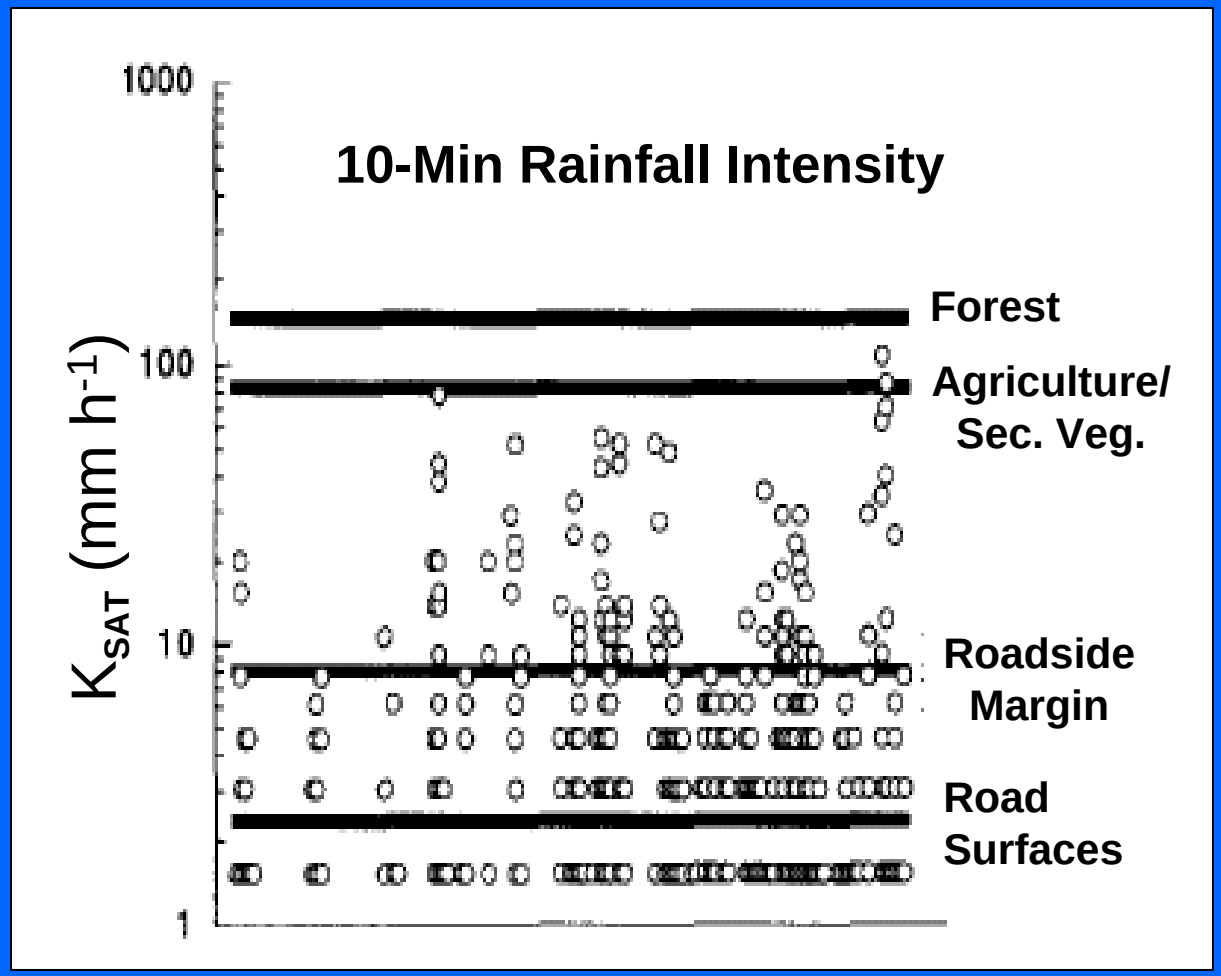


(from Ziegler, 2005)

Road Surface Hydrology - K_{SAT}

K_{SAT} (mm hr^{-1})	Location	Reference
0.0036	Oregon C.R.	Loague and Kyriakidis, 1997
0.11	N. Rockies	Luce and Cundy, 1994
0.3	NW. Washington	Reid and Dunne, 1984
2.3	Thailand	Ziegler and Giambelluca, 1997
3.0	Idaho	Luce, 1997
36.5	SE. Australia	Lane and Sheridan, 2002

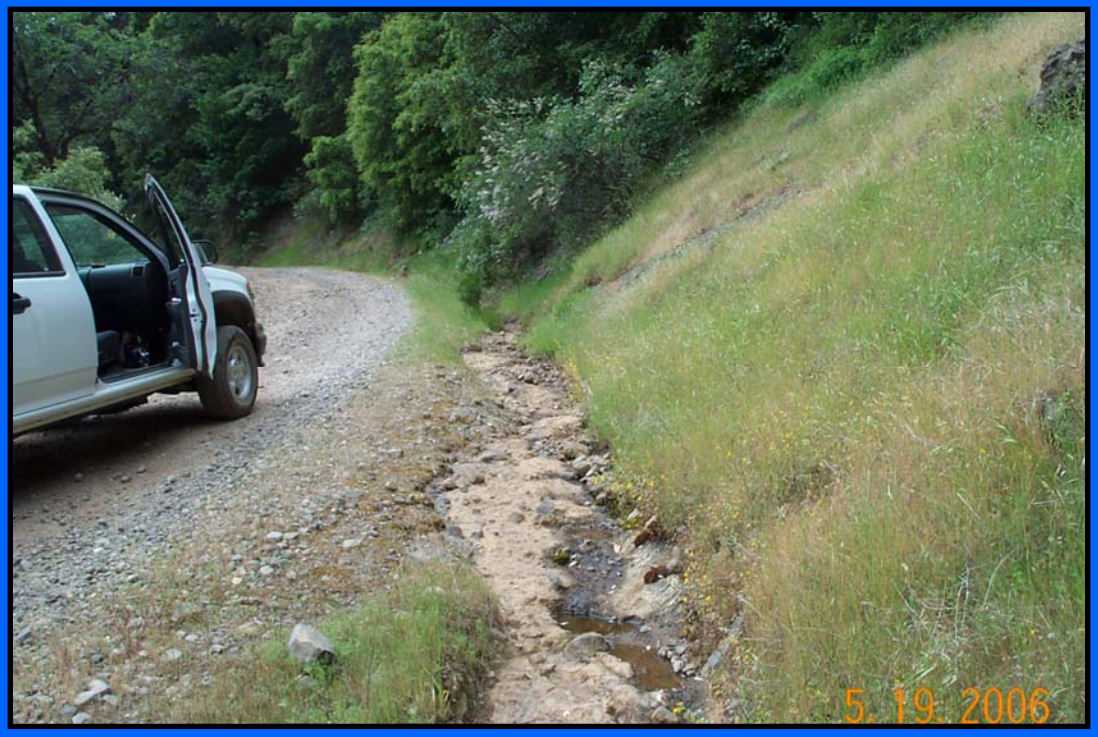
Road Surface Hydrology



- Have the potential to produce runoff during small storms;
- Abundance of HOF on road surfaces.

(Ziegler and Giambelluca, 1997)

Cutslope Hydrology

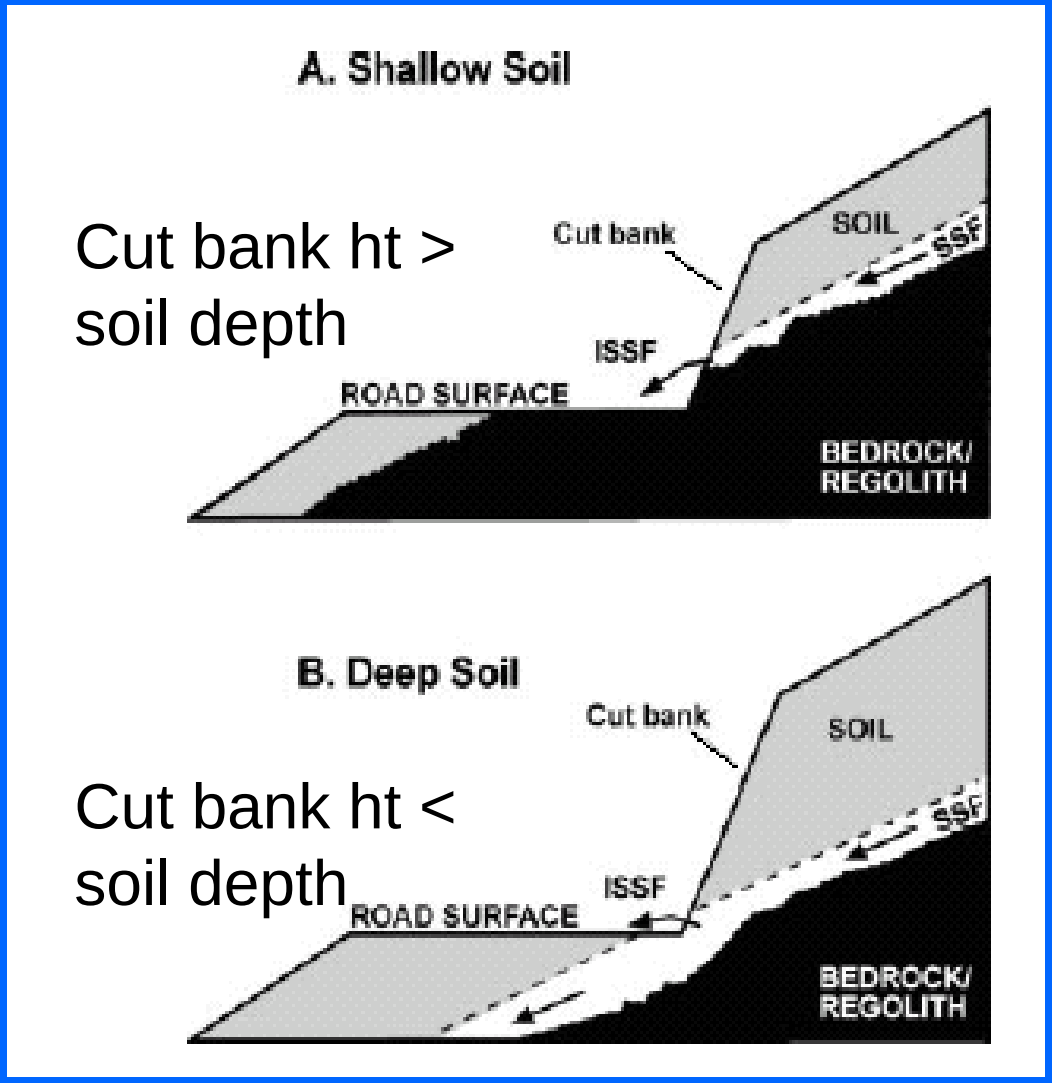


- Road cuts can expose soil/regolith interface;
- Intercepts subsurface stormflow;
- Responsible for up to 95% of total road runoff for PNW (Wemple and Jones, 2003).

Cutslope Hydrology – Impacts on Runoff Timing

- Velocity of overland flow is 10-10000 time greater than SSF (Dunne, 1978);
- Increases rising limb of hydrograph.

Cutslope Hydrology



- Cut banks intercepts SSF when the cutslope height > soil depth;
- ISSF is less likely on deeper soils, lower slopes, and ridgetops.
- Elevated pore pressures at the base of cutslope (Dutton et al., 2005)

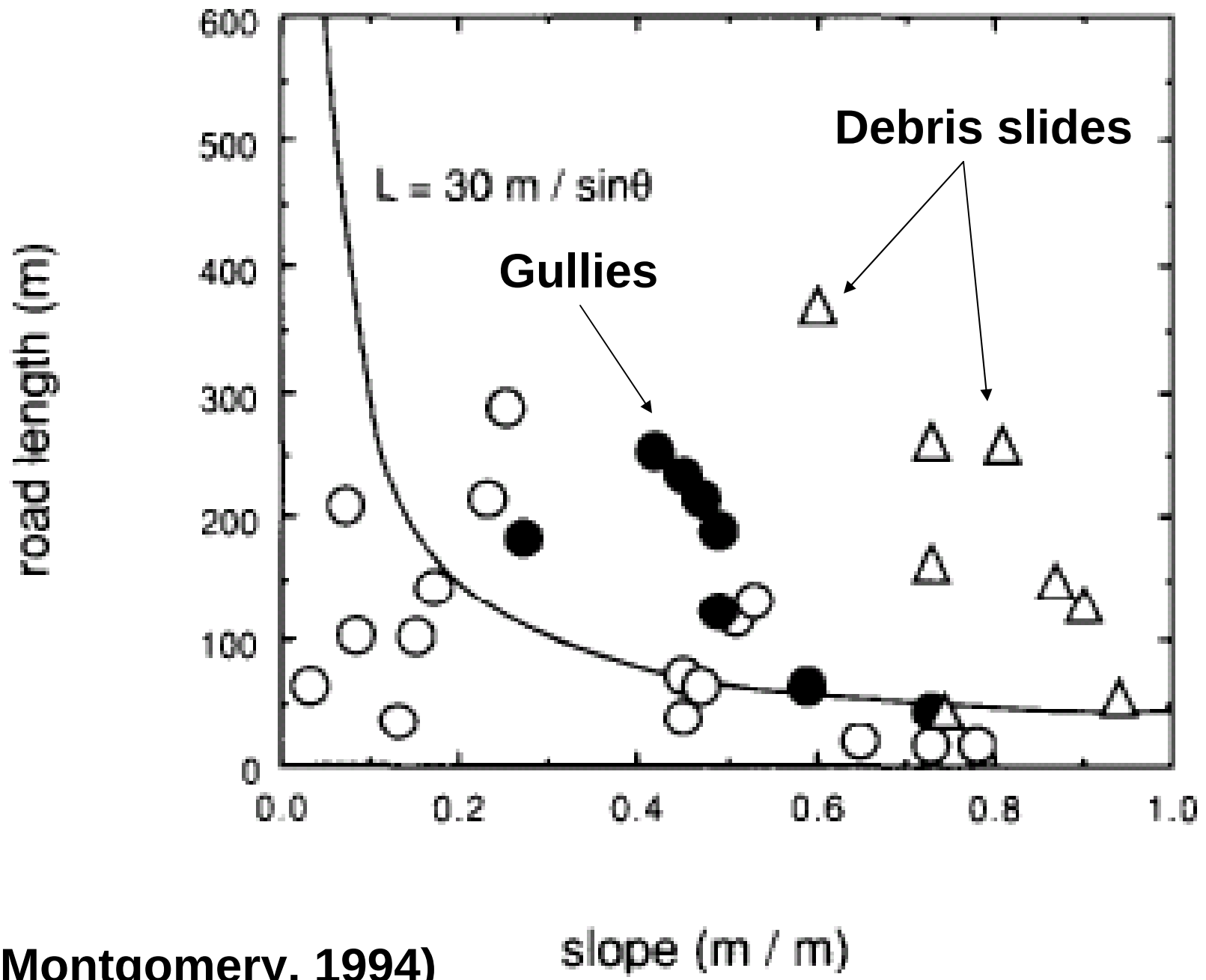
(Ziegler et al., 2002)

Road Segment Hydrology

- Road segments can intercept low order surface waters and reroute water onto the road ditch or road surface (i.e**.** piracy);

Road Segment Hydrology

- Combination of HOF, ISSF, and/or pirated water increase the likelihood of gully and landslide initiation,

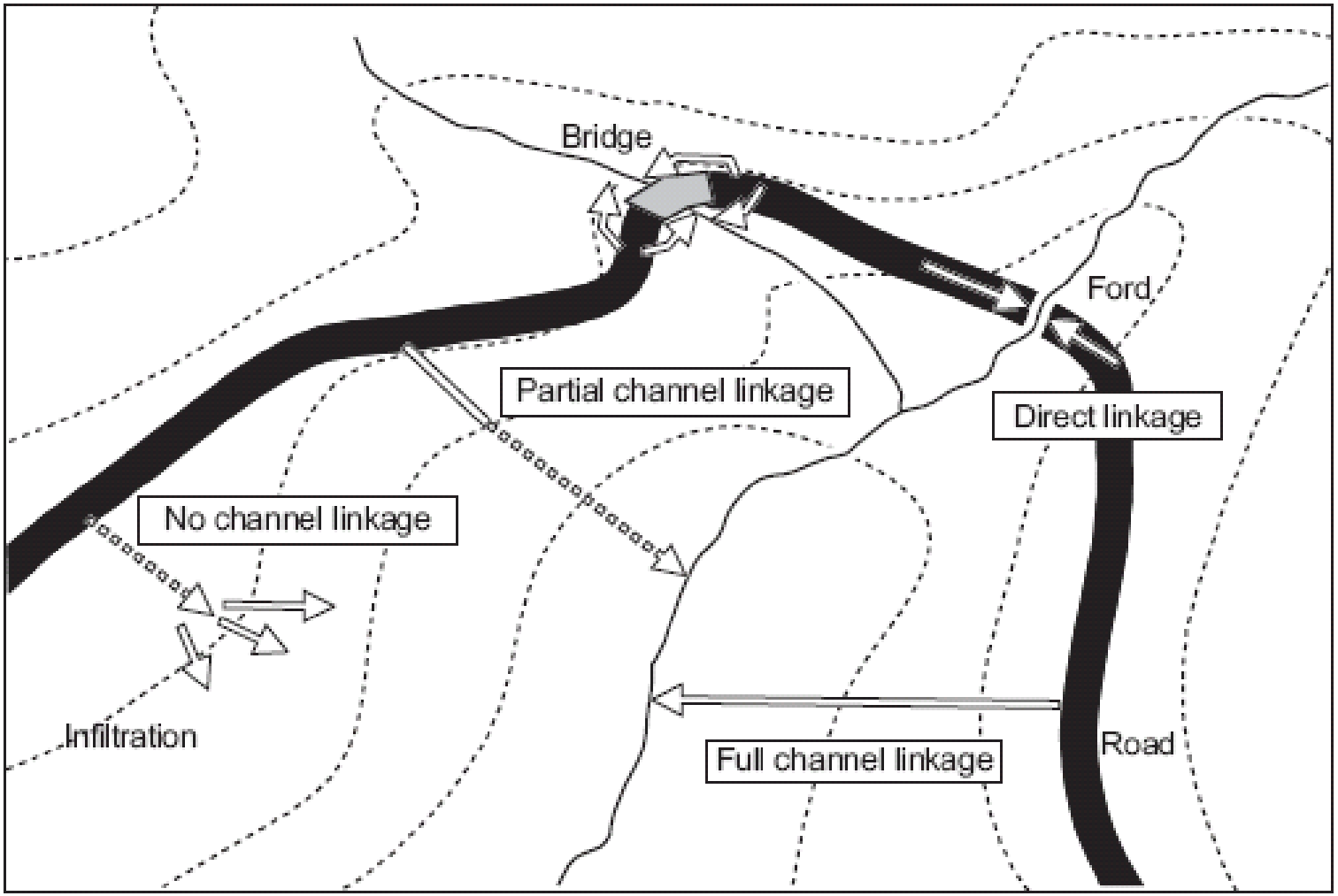


(Montgomery, 1994)

Road Segment Hydrology

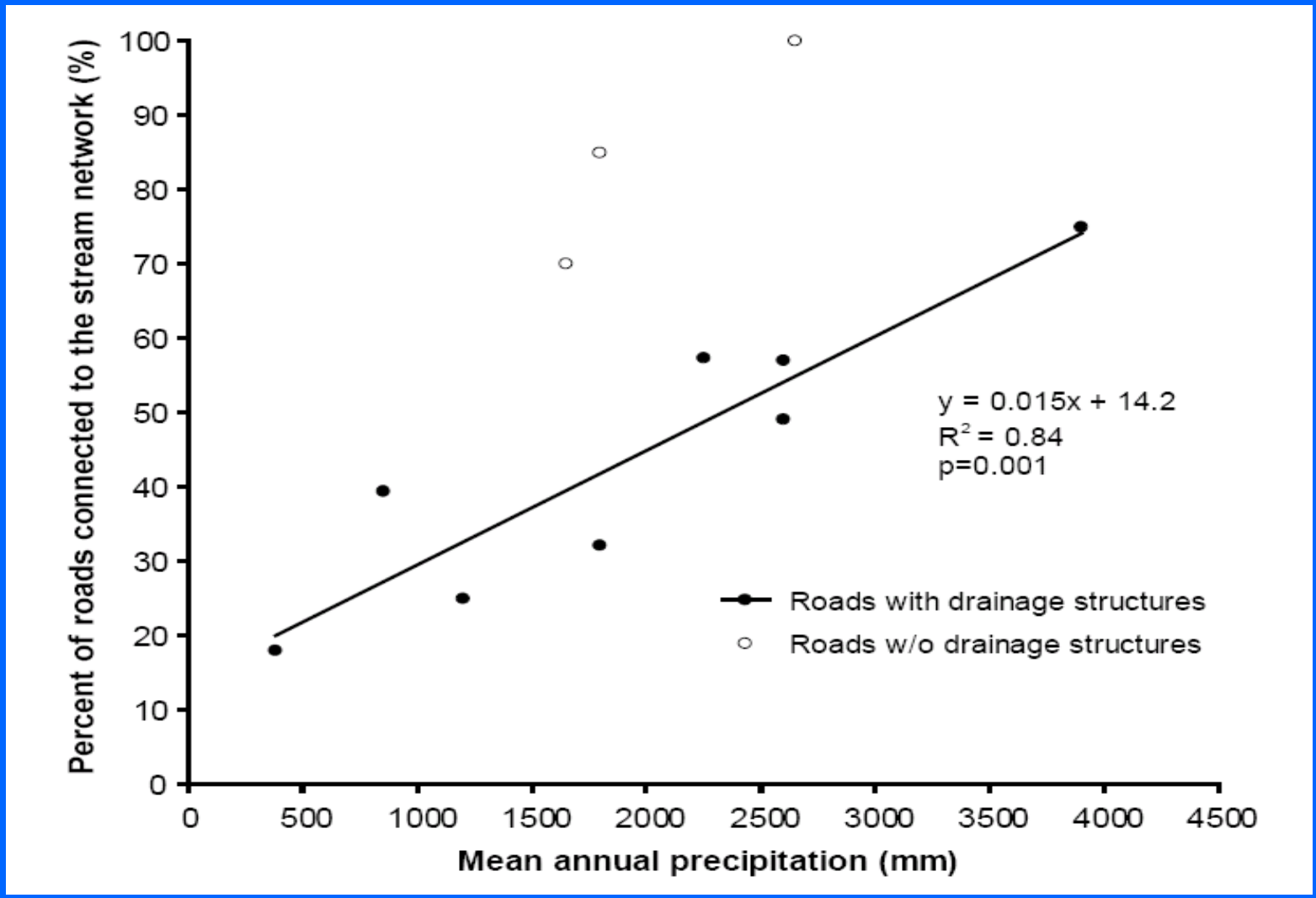
- Road segments can potentially deliver excess runoff to channel network at stream crossings

Road Segment Hydrology – Connectivity to Surface Water



(Croke and Mockler, 2005)

Road Segment Hydrology – Connectivity



(MacDonald and Coe, 2007)

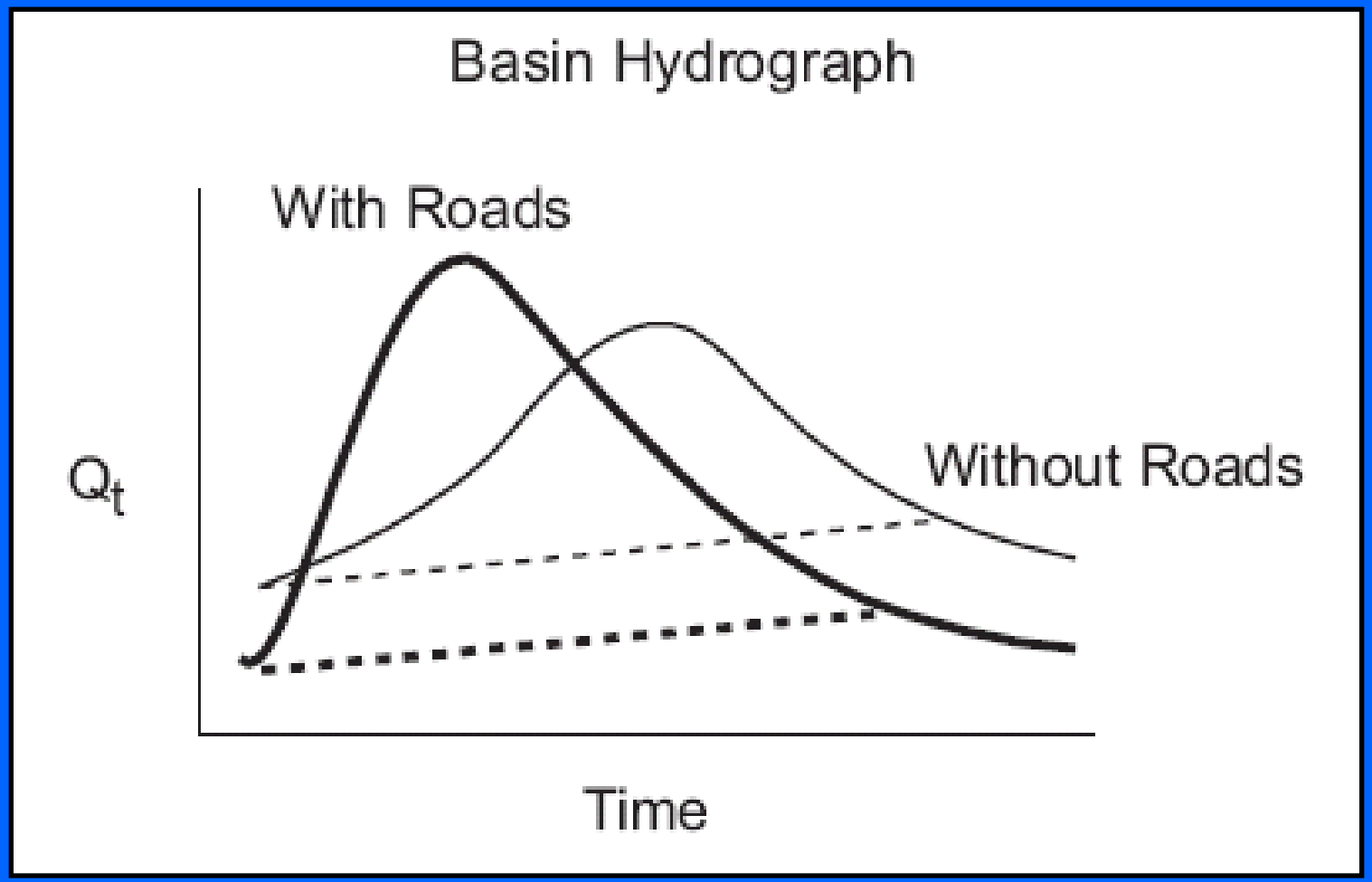
Road Segment Hydrology – Impacts to Low Order Channels

- Roads dominated by HOF can increase peak runoff in low-order channels by 10% (Ziegler et al., 2002);
- Roads dominated by ISSF can increase peak runoff in low-order channels by approximately 50% for snowmelt areas, up to 500% for rain-dominated areas (Megahan, 1972; Wigmosta and Perkins, 2001; Toman, 2004).

Road Segment Hydrology

- Only a small proportion of road segments contribute to peakflow augmentation (Wemple and Jones, 2003);
- Highly dependent upon topography of impermeable layer and hillslope position.

Watershed Impacts – Do the Hydrologic Impact of Roads Translate or Disperse Downstream?



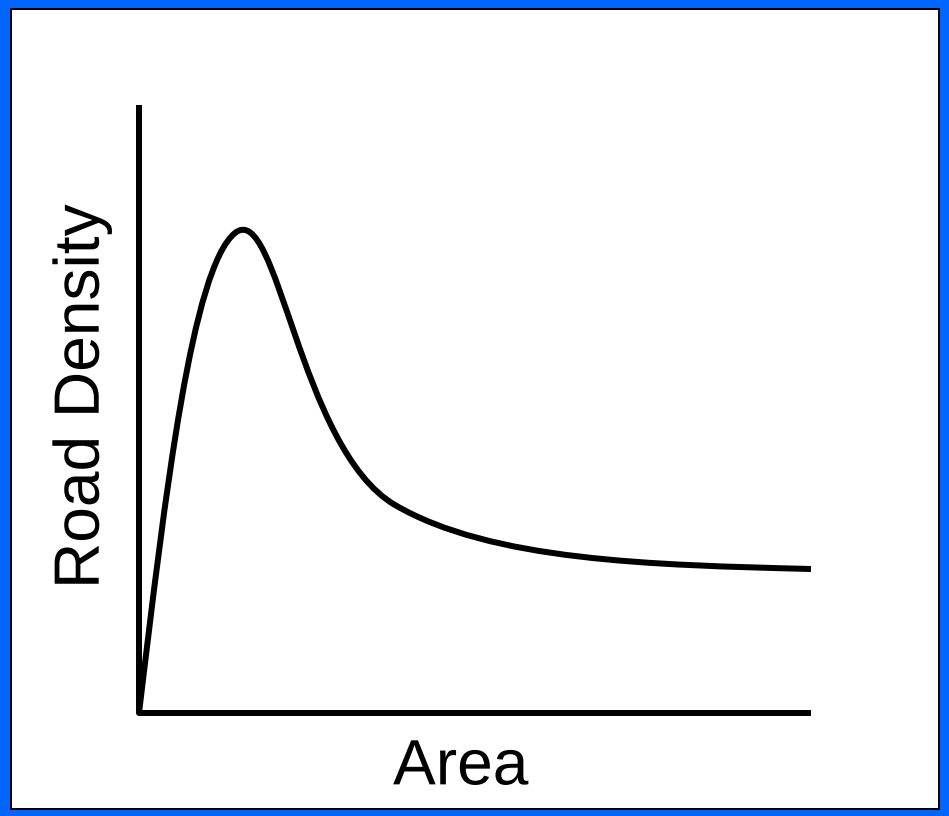
(Wemple et al., 1996)

Hydrologic Effects of Roads at the Small Watershed Scale for Paired Watershed Studies in CA & PNW

- Watershed areas ranged from 61-759 acres;

- Data from the HJ Andrews and Caspar Creek showed no increases in mean annual peak flow due to roads (Rothacher, 1973; Ziemer, 1981);

Forestry Effects on Peak Flows at the Small Watershed Scale



- No detectable effects of roads except when roads occupied more than 12% of watershed area.
- Typical road density in industrial forestland is 2-4%

Reanalysis of Paired Watershed Studies – Synergistic Effects

- Jones and Grant (1996) used a different analysis for paired watershed studies;
- Roads and harvest caused 50-100% increases in peak flow independent of peak flow size or spatial scale;
- **Interaction of roads and harvest greater than sum of parts.**

Reanalysis of Paired Watershed Studies - The Standoff

- Raised an uproar in forest hydrology community;
- Results were the product of inappropriate statistical methods???
- Jones and Grant backed off their assertions.

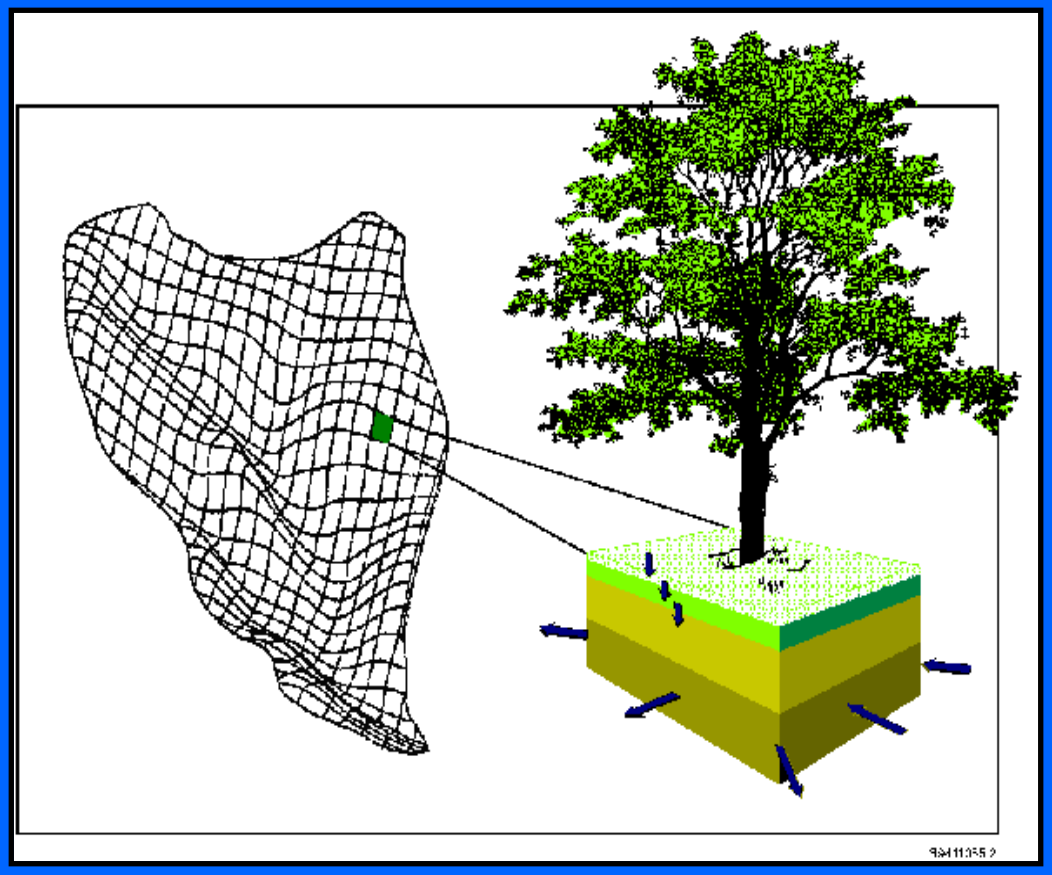
Results from Paired Watershed Studies Have LIMITATIONS

- Combination of harvest and road construction;
- Limited range of flow conditions;
- Poor pre-treatment calibration;
- Lack of treatment replication = poor statistical power.

Modeling Studies

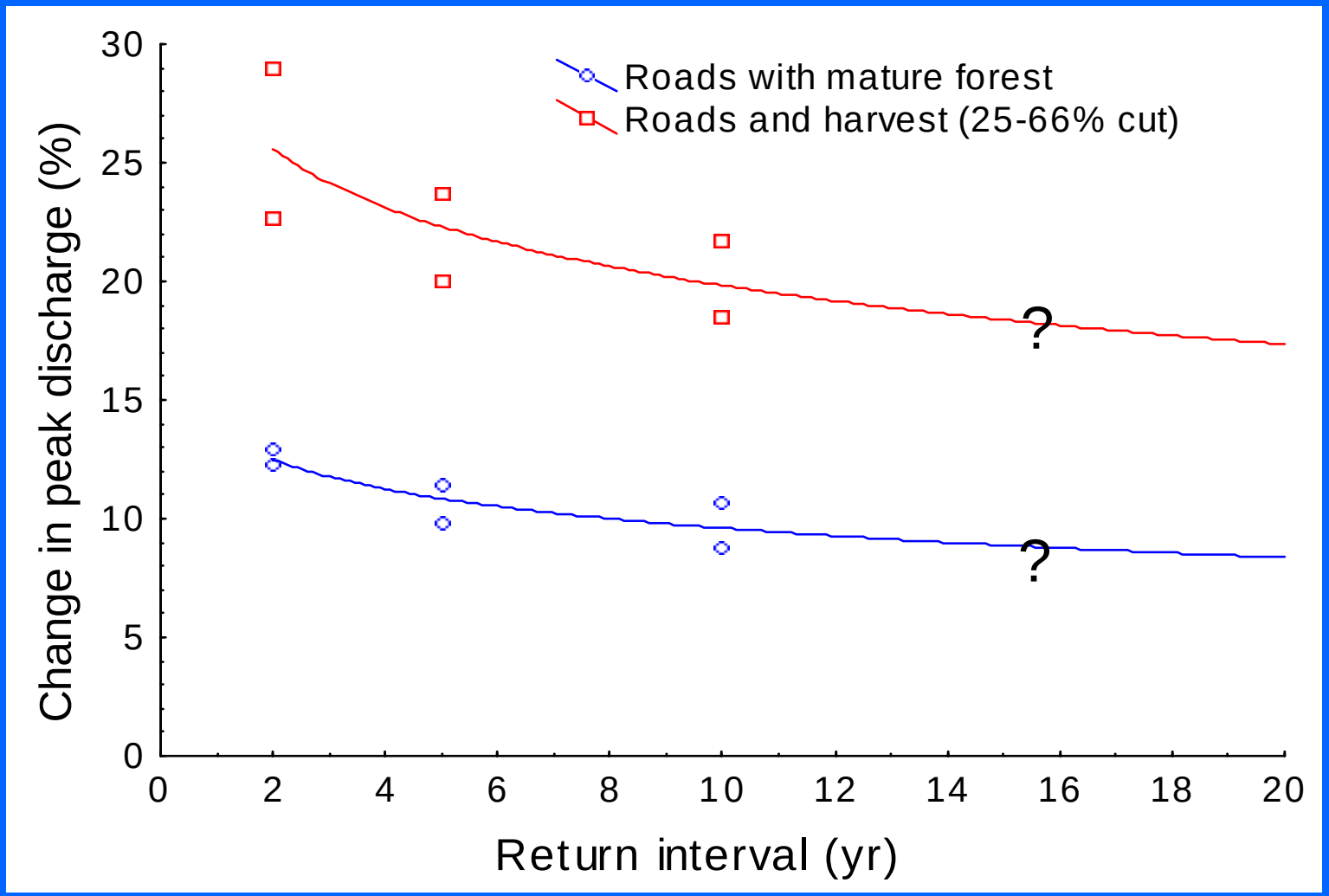
- Provide **RELATIVE** prediction of:
  - Direction of change;
  - Magnitude of change;
  - Nature of change (linear; non-linear; additive; etc)

Modeling Studies - Bowling and Lettenmaier, 2001



- Modeled two watersheds on Weyerhauser's Vail Tree Farm using DHSVM;
- Calibrated against known discharge records.

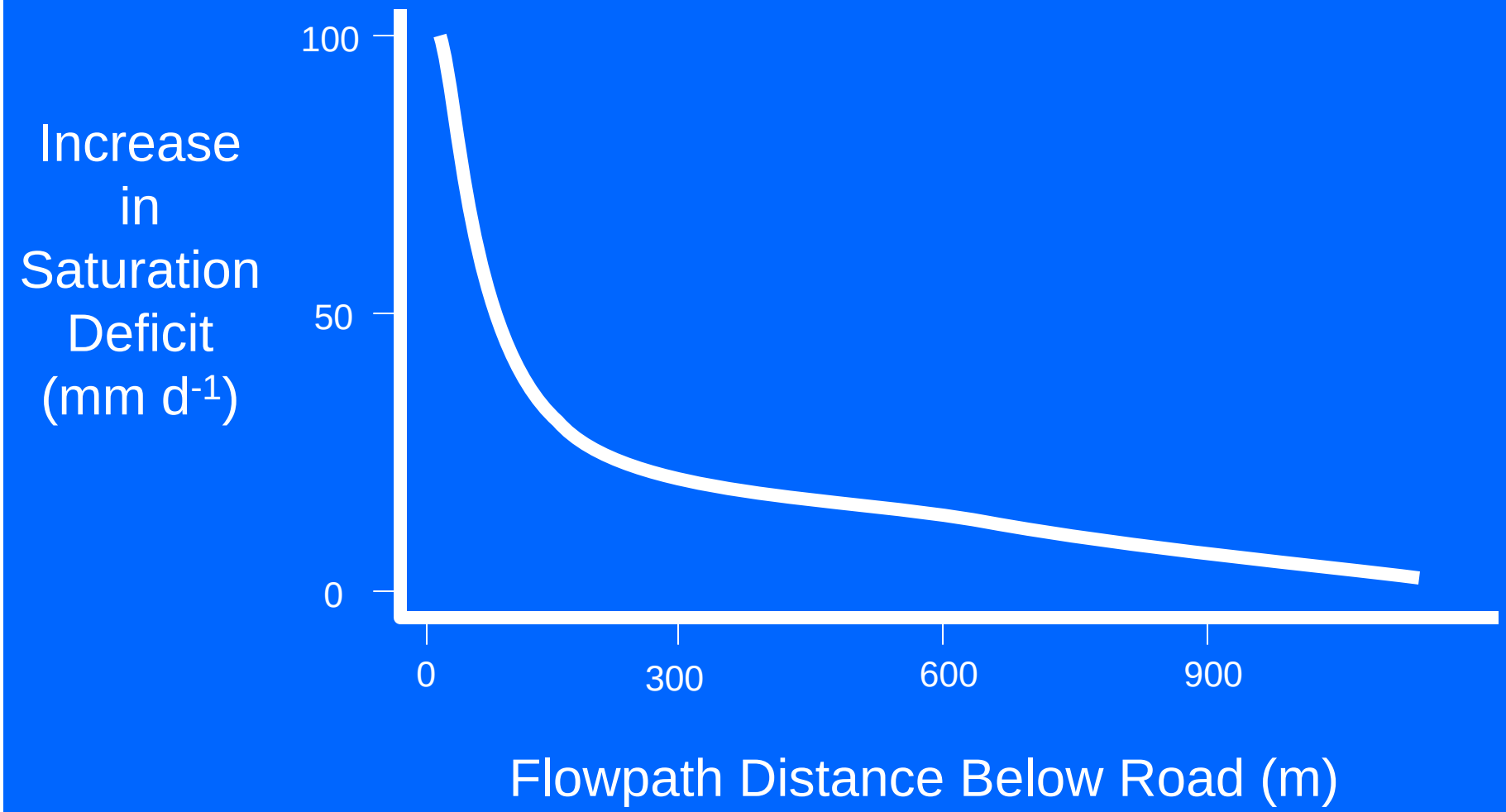
Road and Harvest Effect at Watershed Scale (0.9-1.1 mi^2)



Implications

- Effects of forest roads on peak flows equivalent to harvest;
- 11-12% increase per 2% of area disturbed by roads;
- Effects are additive rather than synergistic.
- Similar conclusions from LaMarche and Lettenmaier (2001)

Modeling Studies – Effects on Low Flows (Tague and Band, 2001)



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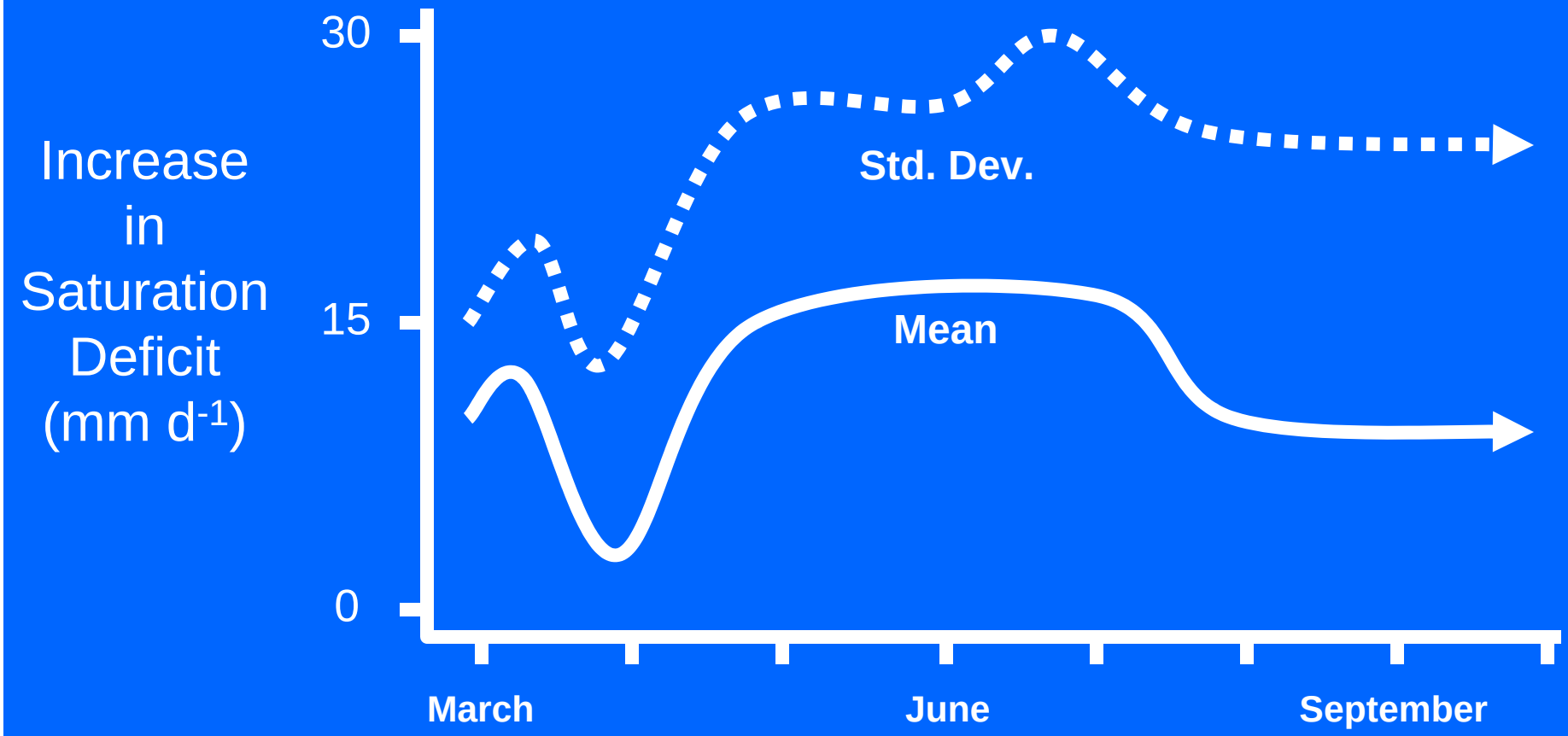


How Do We Mitigate the Hydrologic Effects of Roads?

(Wemple, 2005)

Implications for Management

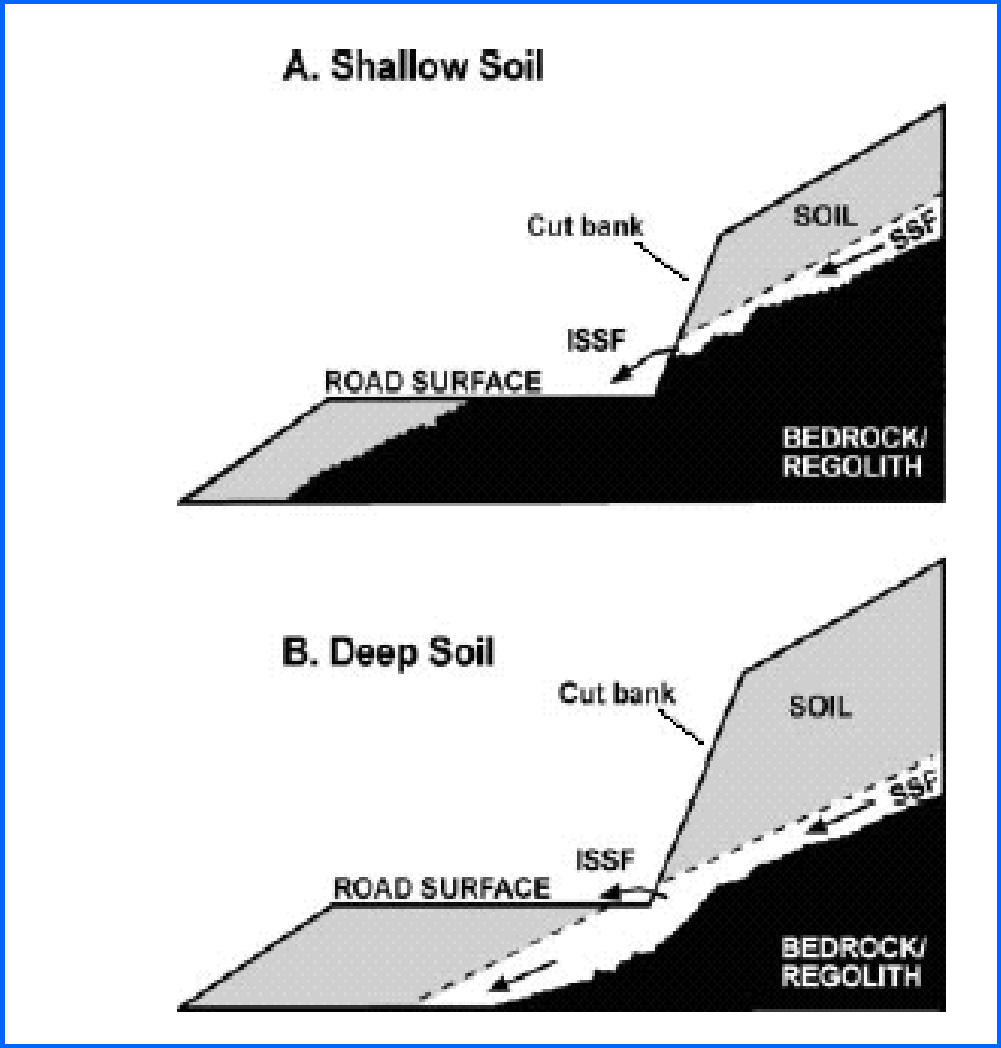
- More road runoff = more road surface erosion;
- Excess road runoff can increase the likelihood of gullying or mass-wasting below the drainage outlet;
- Sediment … sediment … sediment !!!!

Mitigation

Road ditch with intercepted groundwater

- Avoid excess stream crossings;
- Drain roads frequently;
- Minimize direct connectivity to channel network
- Minimize cutslope/flowpath interaction.

Mitigation



(Ziegler et al., 2002)

- Recognize areas where roads can intercept large quantities of SSF:
  - Shallow soils over bedrock;
  - Steeper slopes = higher cutbanks = more interception of SSF;
  - Presence of noticeable seeps or macropores.

Conclusions

- Roads can significantly alter runoff processes at the hillslope scale (e.g., plot and segment);
- Interception of SSF is the dominant mechanism of road runoff modification on steep, humid hillslopes (up to 95%);
- Magnitude of SSF interception dependent upon depth to impermeable zone, subsurface topography, and depth of road cut;

Conclusions

- Majority of road runoff is from a small proportion of the road network;
- Road runoff primarily augments rising limb of hydrograph and decreases lag-to-peak;
- Road-induced peak flows approximately equal to harvest-induced peak flows.