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Application of Geographic Information Systems to Improve the Design and Spacing of Road Cross Drain Culverts

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ABSTRACT:

Cross drain culverts are essential for managing surface runoff, preventing road erosion, and mitigating sediment impacts from forest roads on stream networks and surrounding ecosystems. This study aims to improve the design and spacing of cross drain culverts and to evaluate potential culvert locations using interactive Geographic Information Systems (GIS) tools. These tools enable the analysis of terrain features, hydrological networks, and sediment delivery volumes, facilitating accurate and informed design decisions. Results indicate that GIS-based approaches can reduce sediment accumulation and decrease maintenance and water management costs.

Keywords: Cross drain culverts, Road drainage design, Sediment transport, Forest roads, Surface runoff management, Geographic Information Systems (GIS), Sediment modeling

INTRODUCTION

Roads in steep, forested, and mountainous areas are major contributors to sediment delivery into waterways. The combination of topography and road design accelerates surface runoff and soil erosion. Most forest roads are constructed with side slopes and drainage ditches that concentrate surface flow toward stream crossings. Consequently, cross drain culverts are critical control points for sediment entering streams, making their placement and design essential for reducing the negative environmental and hydrological impacts of roads.

PROBLEM STATEMENT

When designing new roads or reconstructing existing ones, it is crucial to determine the number of culverts required and their optimal placement to minimize sediment delivery. If a culvert is positioned too far from a stream crossing, a substantial amount of sediment may reach the watercourse. Conversely, culverts placed too close may allow sediment dispersed on the forest floor to enter streams. The placement of intermediate culverts along a road alignment further affects sediment movement along the ditch and deposition at specific locations.

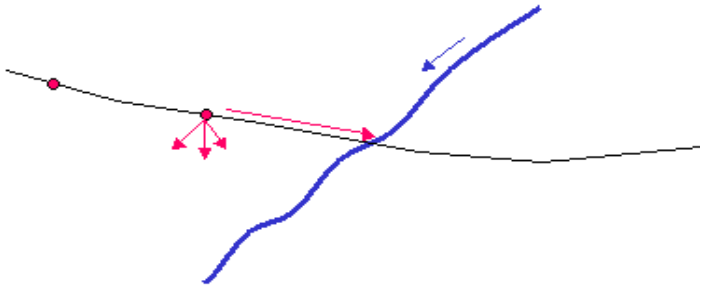

Figure 1: Sediment delivery when a culvert is placed far from a stream crossing.

Currently, computational programs estimate sediment production or simulate surface flow to trace sediment transport. While useful for analysis, these programs are not directly designed for engineering design purposes and can be time-consuming. Optimizing cross drain placement benefits from preliminary sediment analyses that consider production rates, transport potential, road network geometry, and spatial relationships with existing culverts. Immediate feedback via intuitive graphical representation accelerates design iterations, producing more efficient solutions.

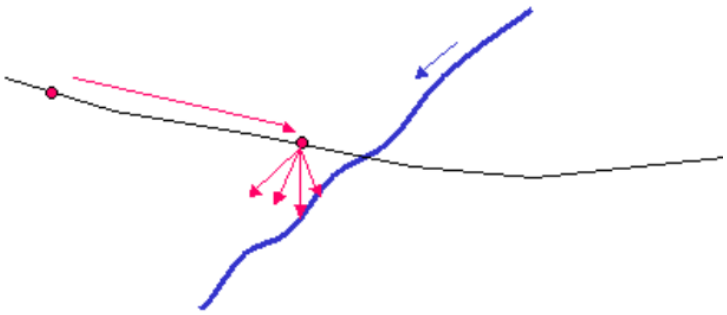

Figure 2: Sediment delivery when a culvert is placed near a stream crossing.

EXISTING TOOLS AND REGULATORY GUIDELINES

Achieving an effective road drainage design is feasible with sufficient expertise, site knowledge, and adherence to regulations. If any of these factors are lacking, computational analysis tools serve as essential decision support. This section reviews regulatory guidelines and the main software tools used for cross drain design.

Regulations

Forest management guidelines in the U.S. and Europe provide instructions for cross drain placement to minimize ditch water and surface sediment entering streams. Sediment should be dispersed onto the forest floor rather than flowing directly into waterways. Guidelines emphasize that the distance between a stream crossing and the first upslope culvert significantly influences sediment delivery, typically recommending 55–110 feet above the crossing. Culverts positioned too close may require additional measures, potentially increasing costs.

Adequate numbers of cross drains prevent ditch erosion, overflow, or scour at outlets. Minimum and maximum spacing depends on road grade and can be adjusted for side slope, stream proximity, surface conditions, road use, precipitation, and soil erosion potential. Utilization of natural swales is also recommended to avoid channeling water along ditches that may transport sediment.

SEDIMENT ANALYSIS PACKAGES

WEPP (Water Erosion Prediction Project) models erosion processes, including infiltration, runoff, soil detachment, sediment transport, deposition, plant growth, and residue decomposition. WEPP simulates specific slope profiles over time with customizable parameters.

- **X-DRAIN**: Accesses sediment yield predictions from over 130,000 WEPP simulations, with limited control over climate, soil, road slope, and stream proximity.
- **WEPP:Road**: Simulates a single road segment at a time, allowing detailed input for road surface and climate. Outputs include total sediment to streams, average precipitation, runoff, and sediment leaving eroding road sections. Optional outputs visualize erosion, deposition, forest sediment plumes, and particle sizes.

SEDMODL: A GIS-based road erosion and sediment delivery model, identifies high-risk road segments for sediment delivery using spatial data. Sediment calculations rely on Washington State DNR standards and WEPP methods. SEDMODL is flexible, suitable for preliminary screening or detailed analysis, and requires input of road attributes such as use, surface type, width, construction year, cut slope, geometry, and gradient. Known culvert locations can be incorporated as a GIS layer for more accurate calculations.

WHY AN INTERACTIVE TOOL?

Optimizing cross drain spacing requires consideration of terrain, road layout, and existing culverts. Automated optimization software is unavailable, so designers rely on sediment modelers for decision support. Current software is analysis-oriented, not interactive, requiring extensive manual edits and providing delayed feedback.

- **WEPP:Road**: Single-segment analysis requires multiple simulations for placement adjustments.
- **X-DRAIN**: Limited to uniform road conditions; cannot identify culverts with highest sediment impact.
- **SEDMODL**: Identifies potential sediment-producing segments, but manual adjustments are needed for evaluating alternative culvert locations.

An ideal interactive tool provides real-time feedback for each design step, enabling effective decision-making and optimization.

METHODOLOGY

A custom interactive GIS-based program was developed as an ArcGIS extension to support cross drain design. Users can add, move, or remove culverts while dynamically evaluating sediment impact to streams. Culverts are represented with graduated symbols proportional to sediment delivery, converting sediment minimization into a visual task that enhances user intuition without requiring extensive expertise.

The program is modular: **Data Structure – User Interface – Sediment Modeler**, interacting in real time. The data structure is a road ditch model generated from layers including roads, streams, and DEM. Optional layers (road surface, ruts, substrate, vegetation) improve

accuracy. High-resolution DEMs provide precise terrain features, enhancing surface flow modeling.

Ditch model assumptions:

1. Roads are insloped or crowned.
2. Continuous ditches exist along all roads.
3. Water flows only through culverts.
4. Culverts function without overflow.

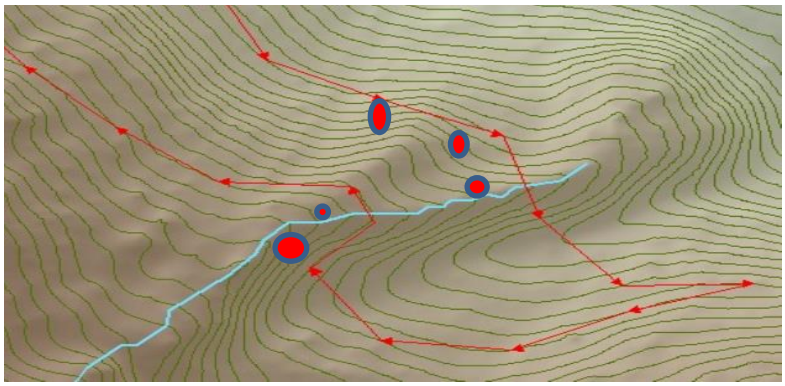

Figure 3: An example of a road showing the flow direction within the ditch using arrows; the coded circles at each culvert location indicate the amount of sediment being conveyed.

The user interface allows adjustments of flow direction and culvert operations (add, remove, move), triggering dynamic sediment calculations. The sediment modeler, based on WA DNR watershed analysis methods, allows comparison of culvert interactions and evaluation of optimal locations. Alternative sediment models can be integrated via Visual Basic interfaces.

DISCUSSION

The Interactive Culvert Spacing Tool simplifies the design process, quickly leading to optimal solutions. It also serves as an educational tool, building user intuition and professional expertise. As designers gain experience, the decision support role may diminish but remains useful for verification.

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