Improving Cross Drain Culvert Spacing with GIS Interactive Design Tool

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ABSTRACT - Reducing forest roads sediment impact on the stream network requires a well-designed cross drain system. Washington State regulation has specific guidelines for cross drain design. To help in the process, several computerized sediment analysis packages are currently used to evaluate potential culvert locations with limited applicability. A specialized decision support tool, with an intuitive process flow and a friendly interface is introduced.

PROBLEM

Forest roads are held responsible for a large part of the increased quantities of sediment delivered to streams. The majority of the forest roads in mountainous regions are insloped with a side ditch. Most of these roads deliver sediment at stream crossings; therefore a wise placement of cross drains is essential for reducing road impacts on stream networks. When designing a new road or rebuilding an old one it becomes important to know how many cross drains are needed and where should they be placed in order to minimize sediment delivery. If a cross drain culvert is placed too far up the road from the stream crossing then a significant amount of sediment will still be delivered (Figure 1a). Conversely if the culvert is too close to the stream crossing part of the sediment dispersed onto the forest floor may still reach the stream (Figure 1b). Furthermore, the placement of intermediate culverts along the road alignment governs the amount of sediment moving along ditch and the sediment dispersed at specific locations.

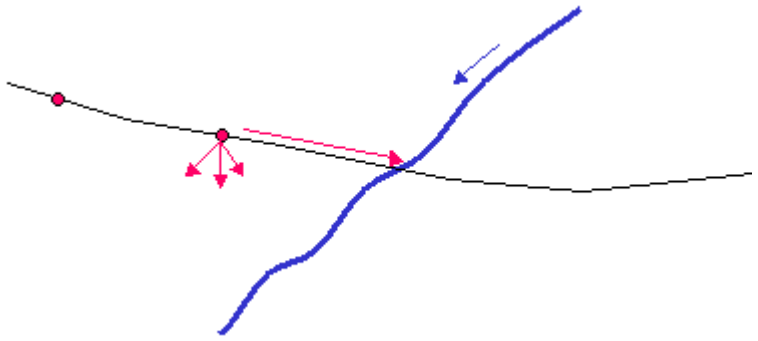

Figure 1a. Sediment delivery when culvert is too far from stream crossing.

Computer programs that estimate sediment production or generate overland flow patterns to trace sediment to streams are currently in use, but they are not design oriented and are generally slow. Cross drain culvert placement could be improved, using a preliminary analysis of sediment delivery at each probable location involving sediment production, delivery potential, the geometry of the road network, and relationships to other existing cross drains. The instant evaluation of a placement decision, displayed in an easily understood graphic manner, can simplify design loops and quickly lead the design process on a proper path. A specialized

computer program to assist in cross drainage design would be a valuable addition to the current collection of road design tools.

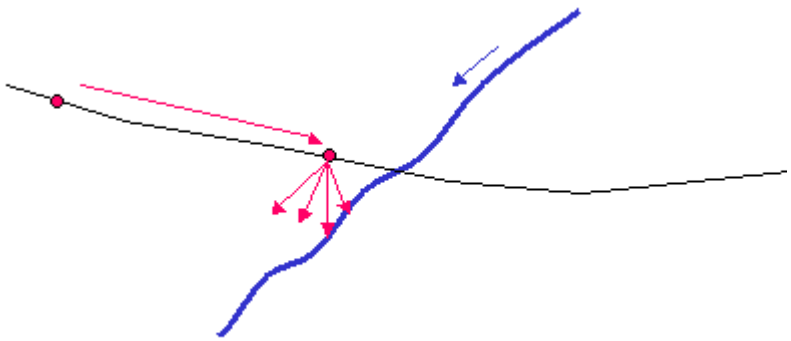

Figure 1b. Sediment delivery when culvert is too close to stream crossing.

EXISTING TOOLS AND REGULATIONS FOR CROSS DRAIN CULVERT DESIGN

Generating a suitable solution for a road drainage system can be a relatively easy task if the designer is experienced, familiar with the terrain, and stays within the bound of the particular rules and regulations. If all these factors are not met the designer can call upon computerized analysis tools to help in the process. Design functional requirements and constraints as stated by the current forest road design regulation are reviewed below. Some existing software tools are also described.

Regulation

The Washington State Forest Practice Board Manual has specific instructions for cross drain culvert placement. Designers have to minimize entry of ditch water and surface sediment into streams by dispersing sediment onto the forest floor. It is specified that the distance between a stream crossing and the first upslope cross drain is an important factor influencing the volume of sediment delivered and it is recommended that a culvert should be installed 50 to 100 feet above all stream crossings (Forest Practice Board Manual). In some of these cases where culverts are too close to a stream crossing, diverted sediment could still reach the stream network. The manual recommends either avoidance of such situations or implementation of additional measures. These additional measures could significantly increase the cost of road. Furthermore a sufficient number of cross drains should be installed in order to prevent ditch scour, over flowing cross drain capacity or erosion at cross drain outlets. There are specific rules for the minimum and maximum distance between culverts as a function of road grade. These distances can be adjusted with side slope, average distance above streams, road surface condition and use, precipitation, and soil erosion potential factors. The manual requires designers to make use of natural swales that the road crosses in order to avoid rerouting water along the ditch, where it can pick up and transport sediment (Forest Practice Board Manual).

Using these guidelines it is possible to design a functional cross drain system, but the process relies heavily on the user experience. For a more rigorous analysis of the sediment production and delivery from forest roads a few specific software tools exist. Some of the better-known sediment modeling programs are WEPP and SEDMODL.

Sediment Analysis Packages

WEPP is a simulation program, originally developed for agricultural purposes as a replacement for USLE (Elliot et al., 1999). It is a complex program that models the processes that lead to erosion, including infiltration and runoff, soil detachment, transport and deposition, plant growth and residue decomposition. WEPP works with a given slope profile and runs simulations over a specified period of time under a multitude of customizable parameters. The Forest Service Moscow Lab has developed a set of specialized interfaces in order to simplify WEPP use for erosion and sediment delivery from forest roads. X-DRAIN is a basic interface to accessing predicted sediment yields from over 130,000 WEPP simulations (Elliot et al., 1999). The user has limited control over climate, soil, side slope and distance to streams parameters. Road geometry and distance to streams are considered uniform all along the analyzed road segment. The total sediment yield in lb/year is presented on a tabular form for a fixed number of combinations of road gradient and cross drain spacing values. WEPP:Road is meant to be more refined sediment modeler capable of modeling one road segment at the time. It accepts road surface information, and more customizable climate information. The modeling can be done over a period of time and the sediment yield to the stream network in lb is reported as a single number with the additional average precipitation, runoff, and the amount of sediment leaving the eroding portion of the road prism. There is also the option of an abbreviated hillslope output presenting a distribution of erosion and deposition, the presence of a sediment plume in the forest, and the particle size distribution of sediment delivered to the channel (Elliot et al., 1999).

Geographic Information Systems have become a standard in environmental modeling. Their capacity of modeling overland flow is what makes them indispensable to spatially distributed phenomena involving streams and water routing. SEDMODL is a GIS based, road erosion and delivery model developed by Boise Cascade Corporation in cooperation with the National Council on Air and Stream Improvement. The model identifies road segments with a high potential for delivering sediment to streams in a given watershed. It uses spatial information to determine the proximity of the roads to the stream network. Sediment delivery is then calculated for the roads that drain to streams using methods derived from the Washington Department of Natural Resources Standard Method for Conducting Watershed Analysis and WEPP. The program is designed as a flexible, multipurpose tool that can be used both for screening purposes or a more detailed sediment analysis. For more reliable results a set of specific road attributes is required. They can include: road use, surface type, road width, construction year, cutslope height, road geometry type, and road gradient. If culvert locations are known they can be inputted as GIS layer and will affect sediment computations accordingly (Sedmodl Technical Documentation).

WHY AN INTERACTIVE TOOL

Optimizing cross drain culvert spacing takes into account a composite sum of factors including terrain information, road layout, and existing culvert locations. Short of using an automated optimization software package, the feedback the user receives during the design process, as a validation of a placement decision, is essential to quickly producing a good solution. Since automated optimization tools are not currently available road designers are restricted to using various sediment modelers functioning as decision support tools. The existing sediment modeling software packages are not interactive design oriented. They were created as analysis packages and if used for cross drain culvert design they do not give instant feedback to the user during the placement process. They require lots of manual data editing, proving slow and relatively unproductive.

For example, as WEPP:Road considers only one road segment at a time, using it to determine best locations and optimal spacing of a road drainage system would require multiple simulations for each potential culvert movement. The length, distance to the stream network and possibly other factors of all road segments affected by the change would have to be manually recalculated and the sediment delivery analysis rerun. This could become a very inefficient, time consuming procedure if applied repeatedly, like in the case of long roads with multiple cross drains.

XDRAIN can only be used for roads with uniform conditions across, being limited to a constant road grade and considering culverts to be uniformly spaced. Users can't tell which one of the culverts has more potential to deliver sediment and it is impossible to know what placement would possibly reduce sediment impact to streams.

SEDMODL automatically identifies and displays road segments that are probable to deliver sediment based on, among other factors, a GIS layer of known culvert locations. If trying to find the best possible locations for existing culverts or revise the number of culverts to reduce sediment impacts, the culvert layer has to be modified manually and the model rerun. This process, as in WEPP case, is not design friendly and can become ineffective if repeated many times.

From the perspective of cross drain culvert design, an ideal decision support tool would evaluate each design step as it is proposed such that a user could easily tell the effect of his/hers decision and improve upon it.

METHOD

To address the problem of cross drain culvert spacing, we have developed a custom computer program. The program is an interactive design tool capable of providing instant decision validation. It is implemented as an ArcGIS extension that seamlessly integrates with the standard ArcGIS package, providing a familiar interface and ease of use. Users have the ability to add, move and remove cross-drain culverts while dynamically getting an evaluation of the sediment impact to the stream network from each of the culverts in the analyzed network. The culverts are represented on the computer screen with graduated symbols proportional to their sediment delivery, thus transposing the question of minimizing sediment delivery to a question of minimizing symbols on screen. This technique does not require highly trained personnel and builds intuition for the involved phenomena.

The program is structured on a modular frame: Data Structure – User Interface – Sediment Modeler. All these modules actively interact with each other at run time to compute and display the sediment impact related to each user action of adding, removing or moving culverts.

The Data Structure is essentially a road ditch model. This model is generated from a multitude of input layers when the program is started. The necessary layers are a road layer, a stream layer, and a digital elevation model. Optional data such as: road surface, road ruts, parental material, and side slope vegetation are also considered if present. Although the program works with any digital elevation model, best results are obtained with a high resolution DEM. Using these, it is possible to more precisely identify terrain features, which in turn results in more accurate modeling of surface flows, the basis of stream – road interaction.

The ditch model makes the following assumptions:

1. The roads are either insloped or crowned
2. There is continuous ditch on every road in the network
3. Water flows along the ditch and spills out only at culverts
4. Culverts are functional and do not spill over

An essential characteristic of the ditch model is its flow direction. This is automatically computed and stored before any operations on culverts can be performed, and it is displayed with arrows to make it easily noticeable where sediment could be routed (Figure 2).

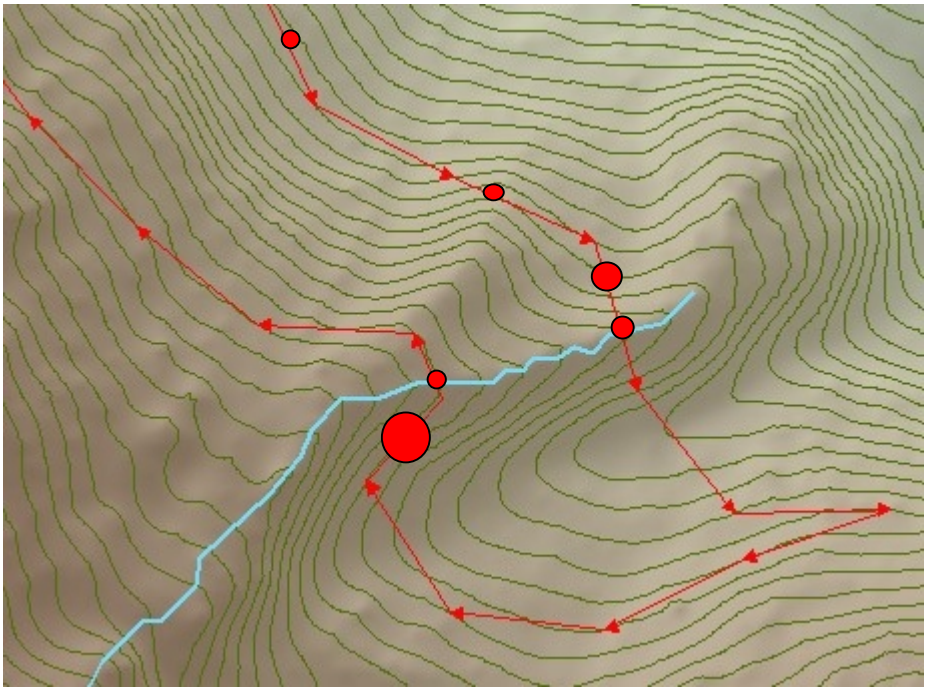

Figure 2. Sample road with flow direction along ditch indicated by arrows; sediment delivery at each culvert location is represented by graduated circles represent.

The user interface includes of a set of tools that can: split, merge and flip flow direction of road segments. Using these tools may become necessary when working with a coarser elevation model that may misrepresent flow direction along certain parts of the road network. In such cases a user may need to intervene and set the correct flow direction to align with the original road design. The program also provides specific tools for culvert operations: add, move and remove. Operating any of these tools triggers all sediment calculations. The user interface extracts relevant data out of the data structure and passes it to the sediment modeler, which will then return its results to be displayed on the screen.

The Sediment Modeler is a simple modeler based on the WA DNR Manual for Conducting Watershed Analysis. Whereas this model may not be the best available, it does provide sufficient information to compare interaction among cross drain culverts and evaluate locations on the road network. It is implemented as a separate ArcGIS extension in order to give user the ability to plug in a sediment modeler of choice. A more detailed sediment modeler could

relatively easily be plugged in by implementing our publicly available set of Visual Basic interfaces.

DISCUSSION

The Interactive Culvert Spacing Tool introduced above is meant as a specialized tool to assist in cross drain culvert design. Arguably, a simpler sediment modeler such as this paired with a well-thought, friendly user interface can simplify the design process, quickly leading to optimal solutions. The Interactive Culvert Spacing Tool is in essence a learning tool. It has the potential to build user intuition, thus contributing toward the necessary professional experience. In time, as users develop specific road design skills the tool's decision support role may diminish but could still be used for verification purposes.

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