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MODELING THE HYDROLOGICAL CONNECTION OF FOREST ROADS AS A SOURCE OF SEDIMENT TO STREAMS

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ABSTRACT

The essential viability of fluvial systems and their water quality is extremely sensitive to pollution including loading by sediments. Any agricultural or industrial land in a catchment, which drains into streams and rivers, may affect the quality and quantity of the water in the fluvial system. Improvement and adjustments to the land use management system may therefore help alleviate any negative effects on the water and river systems. In forests, unsealed roads have long been recognised as the main source of sediment delivery which results from management (Croke *et al*., 1999, Anderson *et al.,* 1976 and Patric, 1976). Forest roads closest to watercourses are more likely to pollute water than the ones located far away from the streams because of their shorter flow path and delivery length. Calculating the actual flow length and understanding and modelling the characteristics of the delivery pathway from the outlet of the drainage systems of forest roads to streams is one of the most important aids to managing roads against negative impacts.

The aim of the study presented in this paper was to predict which locations on a road would be most likely to contribute sediment to streams. The method was to calculate and model the flow path and length of runoff delivery, including the possible distance of flowing runoff, from the source of runoff and sediment to the stream network using GIS models. The system was developed using actual data from Stromlo Forest ACT, Australia as a case study site. The results have shown that the flowlines model did not always accurately predict the distance to stream from some points. The reason was related to the behaviour of the flowlines model, which predicted the flow to take a lengthy zigzag path along the streamlines rather than joining the stream. The flowpath model, which uses a flow direction grid to define the distance from the drains to the streams, gave more accurate results compared with other models; and the distance to streams that was measured in the field.

1 INTRODUCTION

Land use management systems, especially forest engineering activities such as timber harvesting and forest roads formation have long been recognised as the main sources of sediment affecting the quality and quantity of water in fluvial systems. Forest road managers always are concerned about the condition of the roads during forestry activities such as timber transportation. Because of that, road maintenance has been mostly focused on draining the road surface and keeping the roads serviceable. However, over the past two decades, concern by the public and scientists about the effects of forest roads on soil and in - stream water quality, have made managers more concerned about the off-site effects of forest roads. Sheet erosion is a common problem for almost all unpaved forest roads. This problem will not harm the in - stream water quality unless the flow reaches the stream. Therefore, the off-site effects of the roads are mostly related to the connectivity of the road and stream based on the possibility of the runoff flow reaching to the stream from the outlet of the road drainage systems. New technology such as GIS software and the capability of computers help the scientist and managers to determine this probability by modelling the flow.

GIS software has become one of the most important tools for developing geographical, geological and hydrological models and watershed management systems. *The National Research Council of USA* (1999) reported that GIS is a powerful new tool for the collection, storage, management and display of map-related information that can provide decision-makers with interactive tools to better understand and judge how the actions of management might affect a natural system. In watershed management systems, it is very important for researchers and managers to identify the possible sources of impacts (e.g. soil erosion) to streams. Wilson *et al.* (1999), argued that GIS has allowed users to predict essential values and data at any point within the watershed and to run both traditional and new models more efficiently by partitioning entire watersheds into smaller sub-watersheds. They also reported that most of lumped parameter models such as MODFLOW, HEC2, and SWAT have been linked to GIS to predict surface and ground water flows. These applications and assessments take many different forms and are applicable to many different areas such as forest roads as well as water quality issues.

Digital Elevation Models (DEMs) are useful GIS layers that can be used for automatic delineation of flow and stream networks and watershed analysis. They can be used to create terrain attribute maps, data and finally to determine channel and drainage density using GIS software. Calculation of flow direction and upslope areas using DEMs are a major part of hydrologic modeling. The procedure is based on representing the flow direction, derived from DEM, as an input by determining the steepest downwards path after partitioning of flow among eight potential pathways to a neighboring (D8) grid cell. Gallant and Wilson (2000), Tarboton (1997), and Moore *et al*. (1991) argued that calculating the flow direction from DEM is necessary in hydrologic modeling to determine the flow path of the water, sediment and/or contaminant. Flow direction is also used for calculating upslope contribution and specific catchment's area, which are the two most important distributed terrain attributes, which determine flow and sediment transportation.

Since the 1990s when the use of terrain attribute analysis in GIS was developed by Moore and Wilson, watershed assessment and management has improved dramatically. These authors and others have pioneered and developed viable GIS applications, computer programming and mathematical support. The calculations they have developed, have contributed to watershed and surface water modelling and management (Lyon (2003) cited from Maidment and Djokic, 2000). GIS has been used to vary model inputs and compare model outputs, such as forest engineering systems, with field data in the hope of improving the scientific basis of key water quality management plans.

Modeling, calculating, predicting and/or estimating the level of road -to -stream linkage (distance) can provide a suitable tool to manage the streams and roads against on-site and off-site impacts of runoff generated from the road prism. Runoff and flow behaviour originated from the road prism towards streams should be well represented in order to define the level of connection between the road and the stream. Although erosion and sediment production are common outcomes from road construction and maintenance, these will not cause any problem to streams if there is no road to stream connection. To establish if this is so, it is important to know where the runoff will flow (the direction), where it may concentrate (based on the flow direction and contribution area draining a specific drainage system) and finally where it is most likely to link to watercourses.

Finding the key to reducing soil erosion which may lead to sediment delivery to an adjacent stream resulting in water quality degradation is essential if forest road systems are to be managed effectively. One of the main aims of this paper is to answer the question, 'how can the spatial analysis and visualization capability of GIS can be used to improve parameter estimation or determination related to forest road management systems?' This paper also discusses the possibility of automating the calculation of the road-to-stream linkage (distance) using GIS network analysis, flowlines and flowpath GIS analysis functionality applications.

2 METHODS

The map of the entire region included the case study area (Stromlo Forest, ACT, Australia) has been digitized and the watershed and catchments areas have then been separated from the original map for further study (Figure 1). Stromlo Forest and the adjacent area are a small part of the Murrumbidgee catchment area draining to the Molonglo River. A Digital Elevation Model (DEM) was created using ANUDEM and ArcInfo. DEM was then analysed and terrain attribute maps such as slope, aspect, curvature, Compound Topographic Index (CTI), Stream Power Index (SPI) and upslope contribution area were derived from the DEM and have been used as input for model application. The entire Stromlo Forest Management Area (SFMA) as a small watershed has been delineated using DEM analyses in order to create stream networks, sub-catchments or sub-watersheds and their exact position on the ground estimated. The watershed was delineated using basin and hydrologic modelling extension in the ArcView, ArcInfo commands and also TauDEM WinMap.

The hydrologic modelling and watershed delineation processes are shown in Figure 2. The DEM of the study area was used as an input layer. The first step is to fill in the sinks (areas which will not drain anywhere) in the elevation grid. Cells that do not drain anywhere may, become a problem to the process of building a drainage network system that defines the flow path. The next step is to create a flow direction network. from the filled DEM Flow accumulation is used to identify the downstream cells. These were used to create the stream network, stream order, stream length and points of reach. The watershed outlet or "pour point" was created using flow grid and reach point inputs, finally this layer was used for creating the watersheds (Figure 2). Watershed areas, mean of elevation, mean of slope, stream flow length and high and low positions of the stream were also calculated by the watershed delineation process.

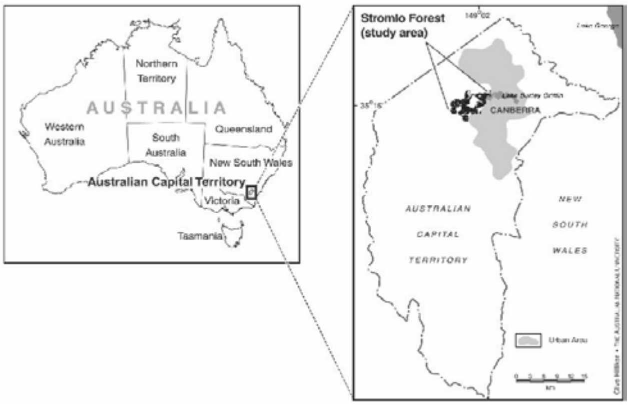


Figure 1: Location of the study area

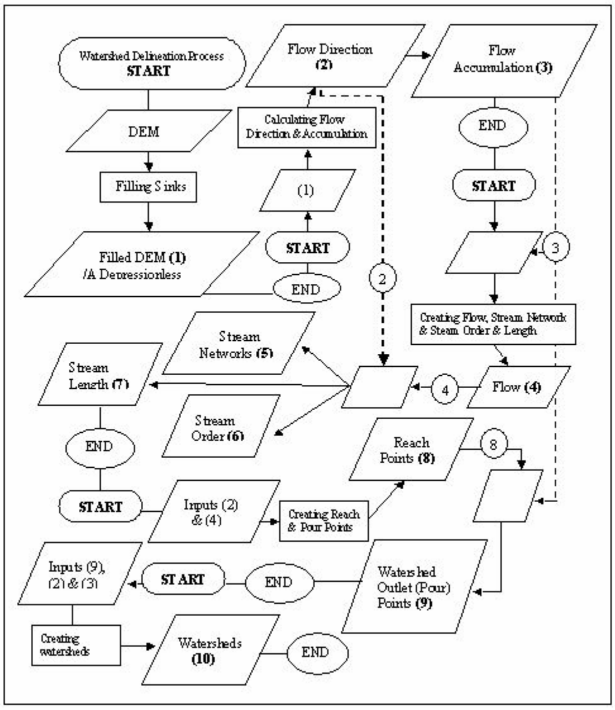


Figure 2: The hydrologic modeling and stream-watershed delineation flow chart

The location of the forest road prisms and drainage systems such as miter drains and culverts has been gathered from the field using GPS and then transferred into ArcGIS and stored as a GIS databases and layers. Data was been stored in multiple files and all data contains a unique coordinate system that identifies the position of each data point in the field (Stromlo Forest). A database of individual files, which contains drains, road layout, and characteristics of the terrain, was developed and complemented by adding some data extracted from the terrain attributes of the related terrain layers.

The distance between road drainage systems and streams was calculated using ArcInfo commands and algorithms to determine the connectivity of road and stream. The ArcInfo commands have been written in Arc Macro Language (AML) using some algorithms such as Patricle-track (the particle tracking algorithm) and coding the function of water movement behaviour on the ground (Takken, 2003). The processes of calculating the distance are shown in Figure 3. The stream coverage and stream grid were created from the existing stream network (from the watershed delineation process) using ArcInfo and were then used as other input layers. The field data related to the road drainage systems, that have been previously stored as multiple files, were used as drain point vector input layers, separately for culverts, miter drains and rills and gullies.
The ArcInfo *NEAR* method has been used for determining the distance between the outlet of road drainage systems (point) and streams (line). The arc *NEAR* model determines a point-to-arc, point-to-node and point-to-point distance. The locations of the road drainage systems (point coverage) and stream network (line coverage) have been used as input layers. The distance was computed from each outlet drainage point to the nearest streamline. The output includes the all of the attributes from the input point coverage, which will be copied during the process, and the calculated distance that will be added during the application. The *NEAR* application process, therefore, will not affect the input files and their coordinate precision.

The *FLOWLINES* program has been written, based on the particle-tracking algorithm that is known as 'particle-track', and the grid function and code (Takken, 2003). This model predicts the direction and future location of a flow, based on the local velocity field by interpolating the nearest grid (e.g. elevation grid) cell centers. The output of this model is a line coverage file within flowlines. The flowlines start at the outlet of drain and flow all the way down until they reach the edge of the grid (DEM) and join a streamline. These flowlines intersect with streamlines using sflines code (Takken, 2003). The output of these processes is a distance file that includes the length of flowlines from the outlets of the drains to the stream using the stream coverage within a buffer zone. A FLOWPATH model has been written, based on the grid function and flow direction (Takken, 2003). The model uses the flow direction grid to define the distance from the outlet of the drain to the stream. The program calculates the flowpath starting from the grid cell at the outlet of the drain and then follows the flow direction down the grid until it reaches a grid cell that has a streamline. The distance between drain and stream is the length of the calculated flow path that has been written by the model in the end of the process (it has been named GRIDPATH).

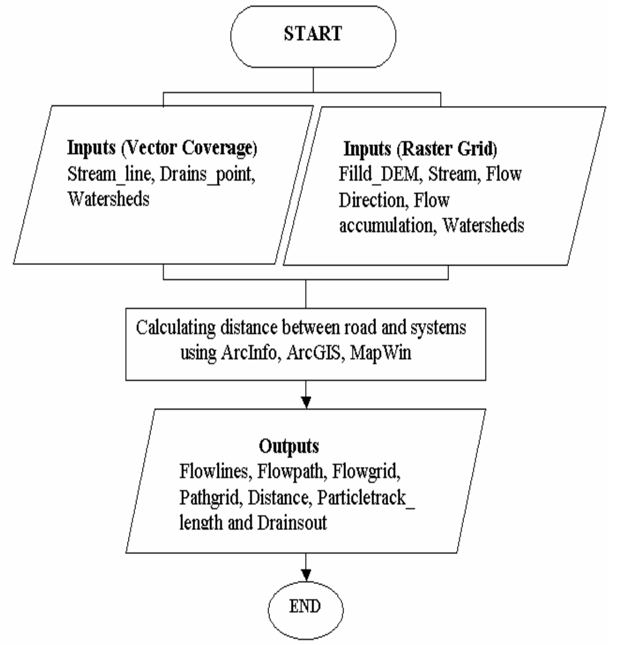


Figure 3: GIS_ Based flow chart model

The distance has also been calculated using the TauDEM extension for ArcGIS and WinMap by a network analysis process. A DEM grid file was used as input file and the distance was calculated using watershed delineation, network and DEM analysis. The distance between each drain to stream has been extracted from the grid output using ArcInfo commands and AML (it has been named DISTMW4). The process of calculating the connectivity between drain and stream in the DISTWASH model is almost the same as most of the models, which are mentioned above. DEM, flow direction, stream networks and watershed grid have been used as input layers and the output layers was a grid file from which the distance data can be extracted using ArcInfo commands based on the location of the drains.

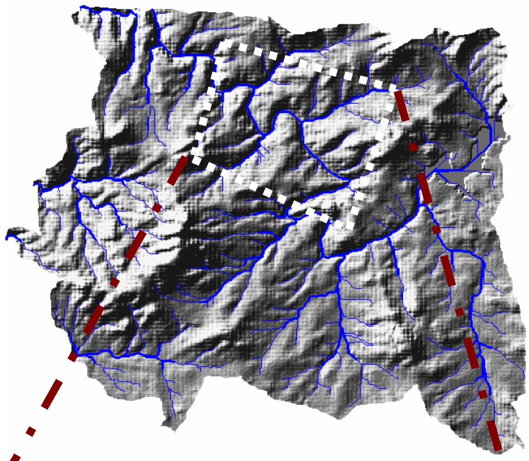
In order to compare and assess the results of the different estimation procedures, GPS was used on a random sample (about 1/3) to measure actual the field road drainage to stream path lenghts. The visible evidence of the flow path from the outlet toward the stream enables the author measure the actual flow distance on the ground. Measurement of flow pathswas based on the topography, slope direction, depression and any other evidence that showed where water would have flowed from the outlet down to the stream. The results of the models were compared with the distance obtained in the field using regression and sensitivity analysis.

3 RESULTS AND DISCUSSION

The results of this study show that an accurate DEM with good positioning of the stream is necessary when correctly determining the distance between the outlet of the drain and streams. Accurate flow direction is also important as it used both as raster (grid) and vector files for creating other output files. The accuracy and correct determination of the direction of the flow is mostly related to the accuracy of the input file (DEM). The reliability with which the downslope cells or flow accumulation is determined, is very important for positioning the stream network, and is mostly related to the accuracy of the direction of the flow. The level of accuracy of the road-to-stream connectivity is related to the level of the accuracy of stream network positioning. Some outputs of the watershed delineation process are shown in Figure 4. As can be seen from this Figure, the stream is laid down in the correct position on the DEM and the sub-watersheds are calculated from the stream network.

As mentioned previously, this study compared several alternative methods of estimating the distance between the outlets of the drain and the stream from a DEM. The results of the different methods were compared with the measured distance from the field. The comparison has shown that two models (Flowpath and Flowlines) predicted the distance more accurately than others, based on correlation analysis (Figure 5 and 6). Figure 6 shows the correlation matrix between distance to stream as determined from the field measurement (FIELDDIS) and six other potential indicators. The best prediction is clearly gridpath (correlation coefficient r = 0.93, r^2 = 0.86 and p = 0.000) (see Figure 5 and 6 and Table 1 and 2).

The flowlines algorithm was not worked accurately for some of the drain points; the flowlines could not reach the stream properly for nearly 5% of the point coverage. Some flowlines were correctly located from the outlet of the drains and the path to the stream was correctly simulated, but they did not join the stream grid cell correctly. The flowlines followed a lengthy zigzag path along the streamline (Figure 7). However, for most drains the flowlines are calculated drains correctly. The points (about 30) in which the flowlines predicted the wrong movement and direction have been taken out (before correlation test) from the analysis and comparison process because of uncertainty of the results. The PTRALEN distance (the result of flowlines and sflines) has the second best level of correlations (r: 0.87, r^2 = 0.75 and p = 0.000) (compared with distance determined from field measurements) after taking out the drains that had anomalous prediction (Tables 1 and 2).



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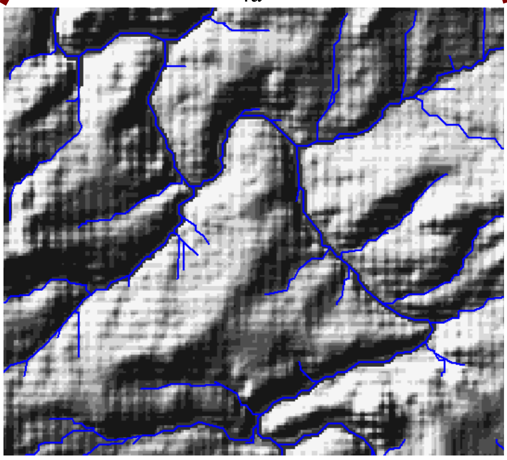

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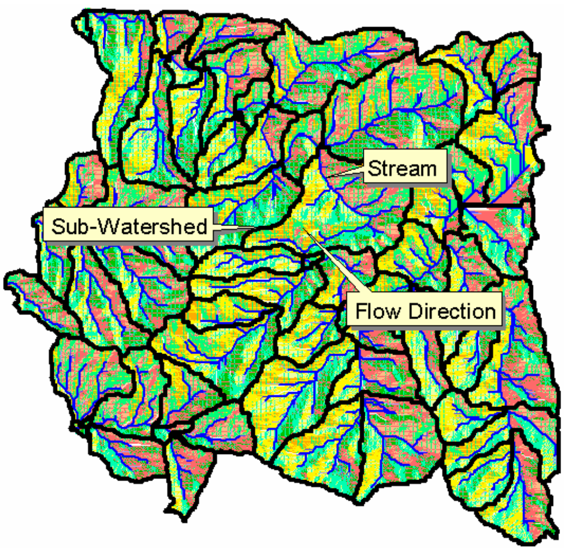

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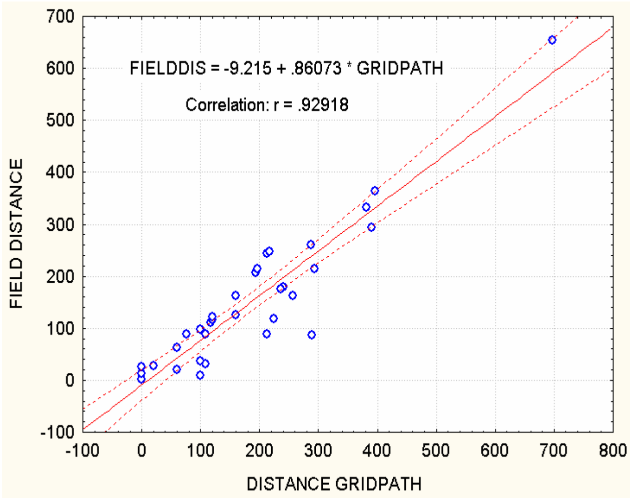
Figure 4: Watershed delineation results, hillshade DEM and stream position on the surface (a & b) and sub-watershed (c)



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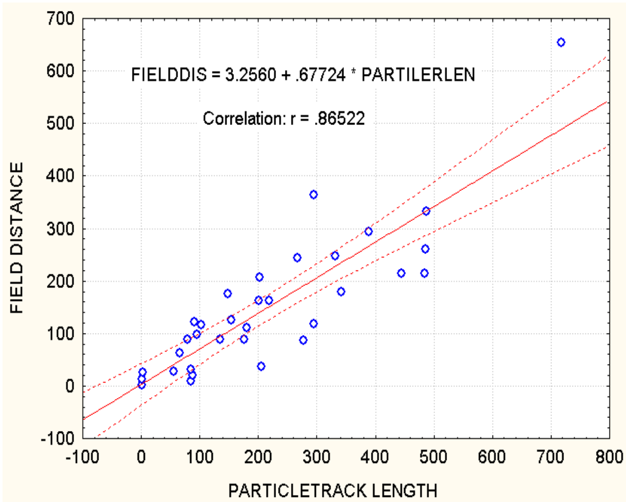

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Figure 5a & b: Regression and correlation comparison between predicted distances (Distance Gridpath (a) and Particletrack length(b)) and field-determined distance (Field Distance)

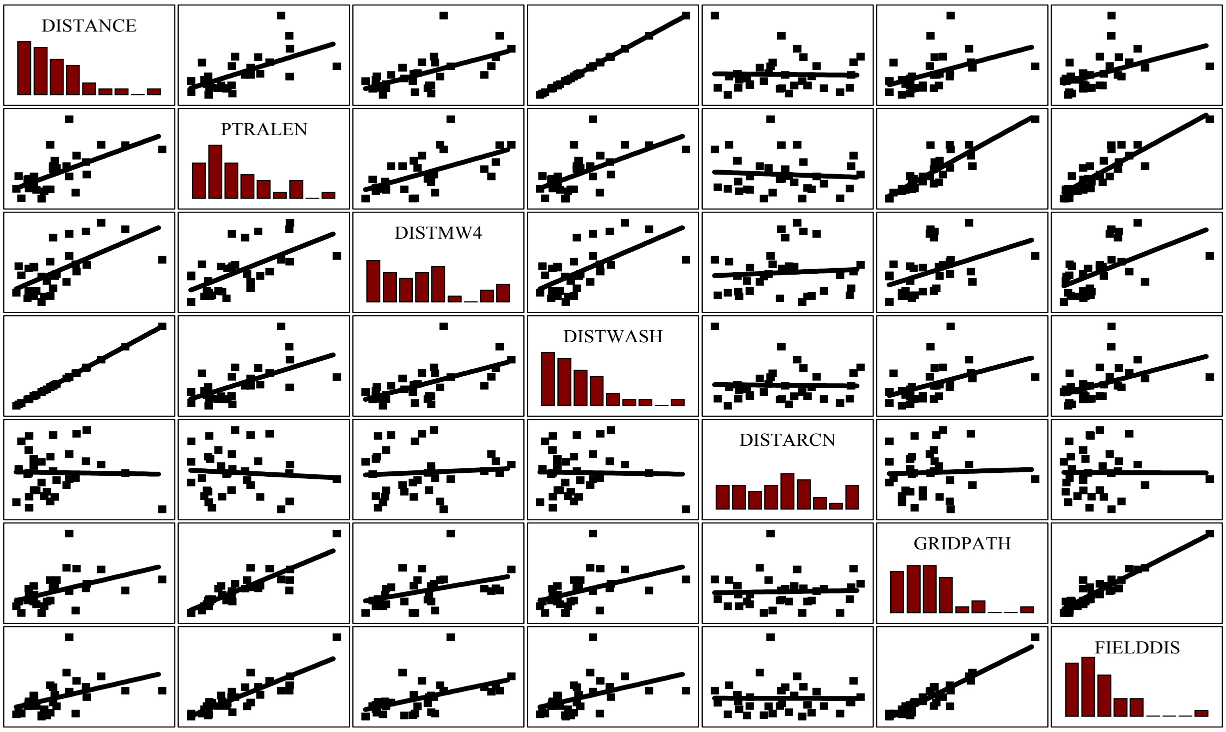

Figure 6: Correlation matrix between the field distance and predicted distances

Table 1: Correlation results between field distance and predicted distance using different models

MODELS	Field Distance	GridPath	PtraLen	Distance	NEAR	DistMwin	DistWash
FIELD DIST	1.00						
GRIDPATH	0.93	1.00					
PTRALEN	0.87	0.88	1.00				
DISTANCE	0.45	0.46	0.62	1.00			
NEAR	-0.005	0.04	-0.08	-0.02	1.00		
DISTMWIN	0.53	0.43	0.61	0.62	0.08	1.00	
DISTWASH	0.45	0.46	0.62	1.00	-0.02	0.62	1.00

Table 2: Summary of Statistical results (Parameters Estimation and Effect Test)

FIELD DISTANCE								
Models	R	R^2	Effect test		Parameter Estimates			
			F Ratio	Pro.F	t Ratio	Pro.t	Mean	St.dev
GridPath	0.93	0.86	195.9	0.00	14.0	0.00	186	143
PtraLen	0.87	0.75	92.31	0.00	9.61	0.00	218	169
Distance	0.45	0.21	8.07	0.008	2.84	0.008	317	251
Near	-0.01	0.00	0.001	0.98	-0.03	0.98	173	72
DistMwin	0.53	0.28	11.97	0.002	3.46	0.002	526	397
DistWash	0.45	0.21	8.07	0.008	2.84	0.008	317	251

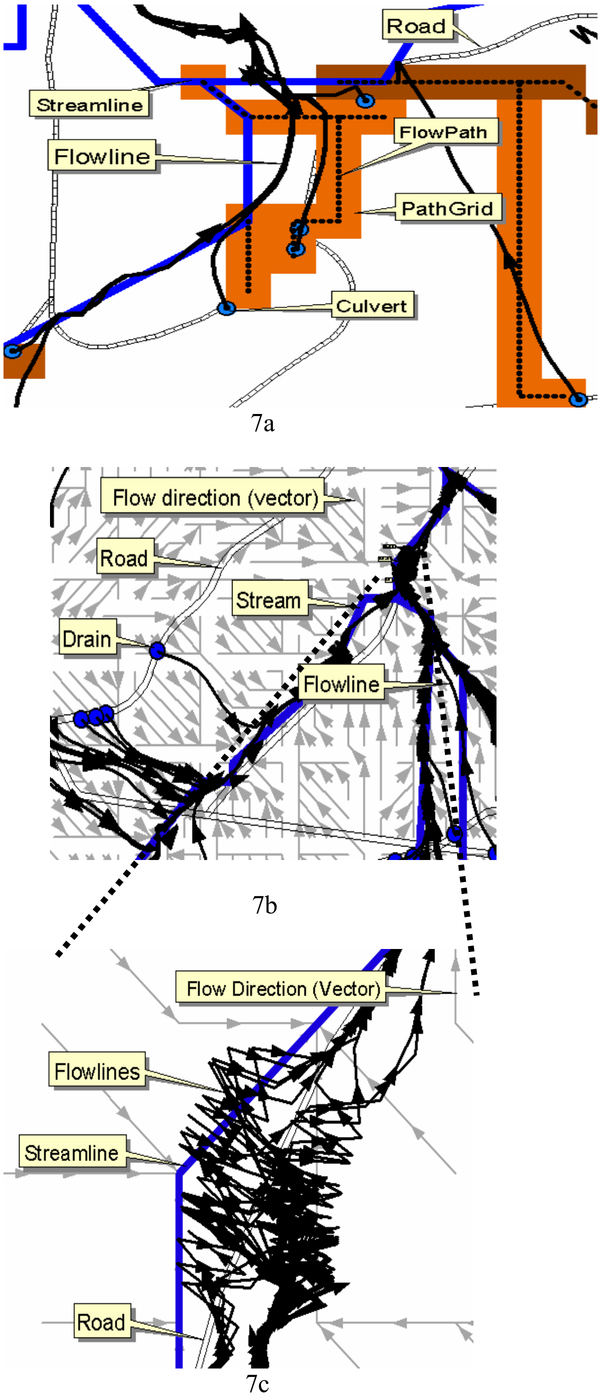

Figure 7: Indicates the Flowlines calculated from the outlet of drains to stream and their wrong prediction along with a lengthy zigzag flow along the streamline (7b & 7c), and movement comparison among Flowpath, Gridpath and flowlines (7a)

4 CONCLUSIONS AND FURTHER WORK

The increasing availability of computer programming and GIS datasets has encouraged the development of GIS_ based modelling techniques. This study shows that using a GIS in combination with mathematical (algorithm) and hydrological models is very useful for determining the level of road-to-stream connectivity by calculating the distance between the outlet of drain and stream. Hydrologic modelling and/or stream delineation play an important role in forest road management, especially in managing the road to stream hydrologic connection. Furthermore, the paper describes the development of an automated road-to-stream distance calculation using GIS_ Based model application (computational algorithms). The results of this (automated distance calculation) are very useful for managing the roads in order to prevent stream water deterioration and hydrologic connectivity, and will also reduce the amount of field work and therefore reduce the cost of evaluations. The results of this study have also identified a method of calculating the distance between road and stream much more accuracy than other applications when compared with the field measured distance. Further work will involve: using the prediction of road-to-stream distance to determine connectivity, improving the delineation of the watershed and finally testing the model system by comparing predicted with actual results determined from the field.

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