MINIMISING SEDIMENT DELIVERY TO RIVERS: A SPATIAL MODELLING APPROACH DEVELOPED FOR COMMERCIAL FORESTRY

Michael Horswell[1] and Nevil Quinn[2]

Sappi Forests (Pty) Ltd, P.O. Box 13124, Cascades, 3202, South Africa
Centre for Environment and Development, University of Natal, Private Bag X01, Scottsville, 3209, South Africa

ABSTRACT

Minimising sediment delivery to rivers is a significant objective in achieving sustainable land-use, especially in forestry and agriculture. In KwaZulu-Natal, South Africa, this is a particular challenge due to the frequent occurrence of erodible soils, steep slopes, and high rainfall intensities. Consequently, loss of topsoil is generally high, and results in turbid rivers with excessive deposition of sediment in lowland rivers. While the use of riparian buffers has been shown to be an effective strategy in trapping sediment, the extensive landholdings of forestry companies requires that sites should be prioritised for management intervention. Furthermore, site-specific guidelines are required that are compatible with the environmental management systems of forestry companies. This paper presents an approach that establishes priorities for management intervention based on the development of three spatial indices. While the method has been tested for a forestry land-use, the principles and approach are transferable to other agricultural landscapes.

Establishing the erosion potential for commercial forestry areas is readily accomplished through the application of the USLE-based models. The principles of the RUSLE model were applied in association with the Unit Stream Power (Moore & Burch 1986) method. This modified, spatial application of the RUSLE model results in a relative indication of soil erosion potential (Sediment Supply Index). The second index (Delivery Risk Index) provides an indication of risk across the landscape during the sediment transport phase. It is based on the following road, stream and topographic factors, road-stream adjacency, road-stream intersections, road surface erodibility, road surface condition, and terrain morphology. The final index (Sediment Attenuation Index) identifies areas likely to act as sediment traps, based on the topography in which they occur. These three indices are used conjunctively to develop integrated sediment management strategies, addressing the problem at source and during transport.

However, prioritisation of areas for management intervention using continuous surface, landscape-based indices is difficult. It is necessary to relate sediment production to the stream to which it will be delivered. To accomplish this the study area was divided into micro-catchments. The mean Sediment Supply Index per catchment was divided by the stream length draining each of the micro-catchments to derive an index of sediment loading to streams. This index is useful in identifying priorities for management intervention across the landscape. To satisfy practical application requirements, specific recommendations regarding the required buffer widths to act as an efficient, final defence against sediment delivery to the watercourses are required. The micro-catchments form the basis of the analysis for developing buffer-width recommendations. The mean slope and sediment supply for each catchment is used to develop buffer width recommendations for the streams draining the catchments, using the method proposed by Karssies and Prosser (2001). The application of the modelling results at both landscape and compartment levels enables tactical and operational management strategies to be developed.

Keywords: soil erosion modelling, sediment attenuation, GIS, buffers, forestry

INTRODUCTION

Commercial forestry, and its associated industries, are significant contributors to the economy of South Africa, accounting for 4.7% of total export earnings (Lefakane & Pata 1998). The government has an expressed intention to develop its role as a supporter of forestry, especially through social forestry and the small farmer sector (Department of Water Affairs and Forestry 1995). However, the economic contribution of forestry does have associated environmental costs; water quantity and quality impacts are particularly contentious.

Commercial forestry, in South Africa, is often situated on steeper slopes in the upper areas of catchments adjacent to first order streams. Of particular significance in South Africa is that commercial plantations are largely confined to the source areas of many of the rivers that supply the country with water. Forestry areas are exposed to disturbance at a lower frequency than traditional agriculture, although the disturbance is more severe.

The role of buffers as effective sediment traps has been established. Not only are buffers efficient in improving both water quality and quantity of instream environments, they also increase biodiversity, attenuate floods, reduce bank erosion as well as providing habitat. In plantation forestry, there is the additional benefit of these areas acting as firebreaks.

Given the acknowledged impact of plantations, the legal responsibilities of landusers, the international requirements to maintain access to markets and the need to ensure sustainability, the impact of erosion associated with commercial forestry needs to be effectively managed. There is a need for a method that integrates effective management strategies with rational, scientifically based prioritisation procedures to maximize the benefit from management interventions. This method should utilise readily available data and technology, and be easy to implement.

MANAGING SEDIMENT DELIVERY TO STREAMS

Managing sediment delivery to streams requires that the problem be addressed in three phases, at the sediment source, during sediment transport and at sediment delivery to streams. Addressing the first phase requires a method for identifying priority areas for erosion control based on the erodibility of the area. To achieve this a Sediment Supply Index is developed indicating erosion potential across the landscape. The transportation phase will be addressed by assessing the localized efficiency of sediment transport across the landscape and identifying specific natural landscape features that have the greatest potential for sediment attenuation. Two indices, the Delivery Risk Index and the Sediment Attenuation Index, are used in addressing the transportation phase. The final phase, sediment delivery to streams, will be addressed by a method for developing buffer width recommendations.

The first priority in reducing sediment delivery to streams is to control the erosion at source, preventing the mobilisation of sediment and thus eliminating the possibility of delivery to watercourses. Due to landuse activities, it is not always possible to achieve the above objective. Consequently, it is necessary to identify areas within the landscape that are particularly at risk of eroding and manage them appropriately, so as to minimise the amount of sediment that is mobilised.

The application the Universal Soil Loss Equation (USLE), and its derivatives, the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) are commonly used methods for predicting soil erosion. While more complex models that model the physical processes involved in soil erosion have been developed, they are usually implemented to improve the understanding of erosion processes, or to trace the path of pollutants across the landscape. The data requirements of these models are more extensive than those of the empirical models. The USLE-based models are used due to data paucity and the fact that they satisfy the requirements for the purposes of this exercise, which is to assess the relative risk of erosion across a landscape. The derivation of the Sediment Supply Index (SSI) is presented in Figure 1.

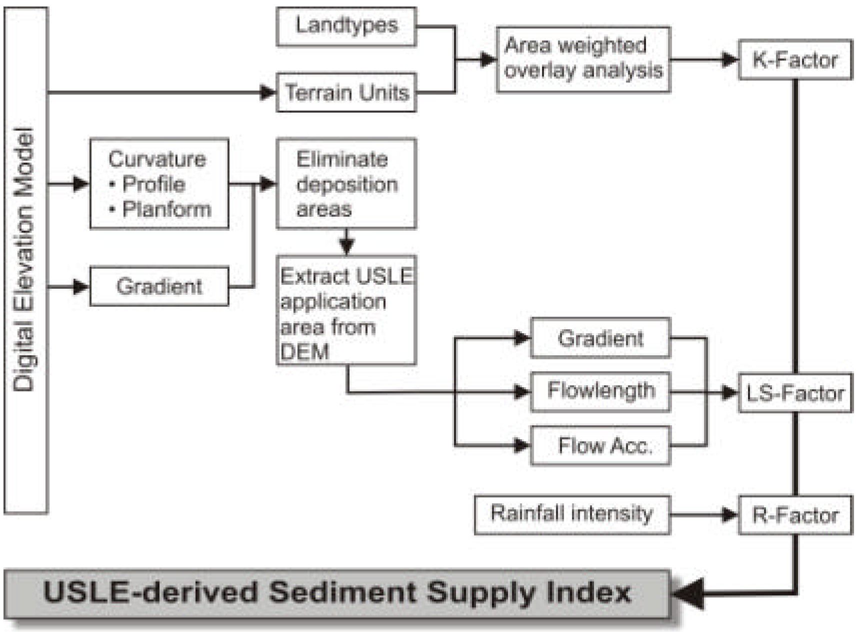

Figure 1: The process for deriving the Sediment Supply Index

The SSI is derived from the application of the USLE-based erosion prediction models, excluding the landcover and support practice factors. The reasons for excluding these factors is that commercial forestry activities regularly create areas within the landscape that are completely denuded of vegetation. Additionally, the need to avoid any implicit criticism of existing landuse practices, identified by Mander, Quinn and Mander (1993), is relevant, and may improve the acceptability of the proposed procedures to the forestry industry. Although the SSI is not a quantitative assessment of erosion, it does use predicted values for developing relative risk assessments that inform the prioritisation process.

Road-stream connectivity effectively extends the drainage network within a catchment by establishing new paths for surface flow to enter existing watercourses, and influences the efficiency of sediment delivery to streams considerably. Additional impacts relate to alterations in peak flows and the increased likelihood of road-associated sediment entering watercourses. Besides direct connectivity, i.e. stream crossings, linkages often arise when culverts, or other drainage structures, become linked to watercourses by gully formation at their outlets (Furniss, Flanagan & McFadin 1999; Mockler & Lane 1999; LaMarche & Lettenmaier 2001). Five factors that influence the efficiency of sediment delivery to streams have been identified. All the factors are related to the degree of connectivity between the road network and the stream network. The five factors are, points where streams and roads intersect; areas where roads and streams run parallel or in close proximity to one another; areas where topographic convergence creates links between roads and streams; the erosion potential of the road surface itself; the type and the condition of the road surface itself.

The Delivery Risk Index is an assessment of the efficiency of sediment transport across the landscape. Figure 2 presents the procedure for developing a Delivery Risk Index (DRI) based on modelling the factors identified above, and the specific sub-factors that represent them. It presents the primary datasets required for developing the proposed index. The procedures for combining the data to develop the five components of the index, identified above, are also presented. Methods for developing these sub-factors spatially have been investigated.

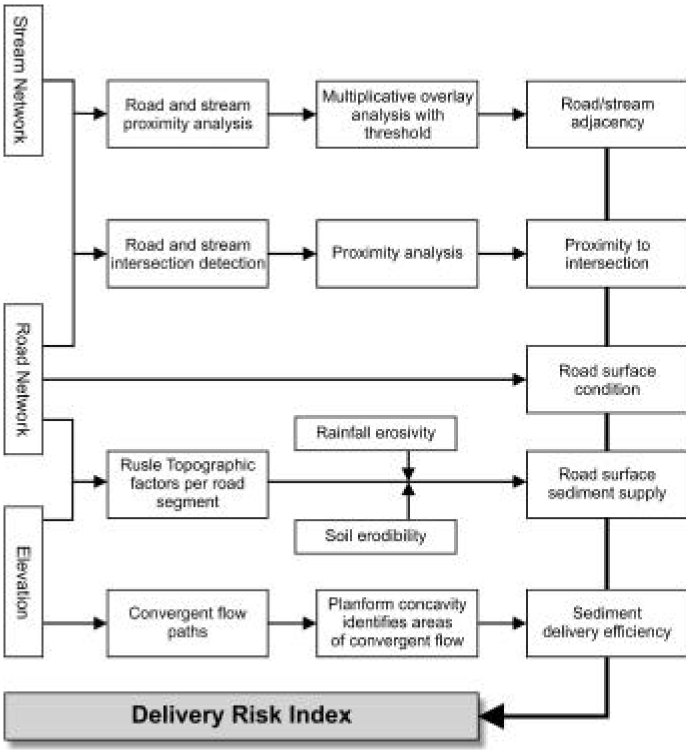

Figure 2: Process for the derivation of the Delivery Risk Index

Topographic sediment traps are areas within the landscape where the terrain morphology, gradient and surface flow patterns can be utilized to perform the service of trapping sediment. These areas may coincide with, but are distinct from riparian zones in that they are not spatially associated with the stream network. They are identified by combining the modelled characteristics of the terrain that would result in areas of low sediment mobility, these being terrain concavity and gradient. Figure 3 presents the proposed method for identifying topographic sediment attenuation features.

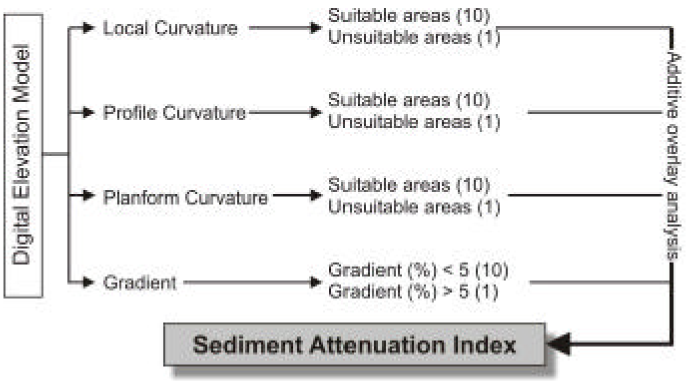

Figure 3: Process for developing the Sediment Attenutation Index

The areas suitable for sediment attenuation are extracted from the digital elevation model using the curvature and gradient criteria. Suitable areas are assigned a value of 10 for all sub-factors, while unsuitable areas are assigned a value of 1. The negative areas of the three datasets derived using the curvature function, represent concavity in the landscape while the positive areas represent areas of convexity. The range of values is determined by the ruggedness of the terrain. Areas where sediment attenuation is likely to occur, based on terrain morphology can be identified using the datasets produced which contain profile, planform and localized indices of convexity and concavity.

The final opportunity for reducing sediment delivery to streams is through the use of riparian buffer zones. The efficiency of these areas in reducing sediment delivery, across a wide range of conditions is well established. The efficiency of grassed buffers has been measured extensively and found to range between 52% and 90%, although the majority of measurements indicated trapping efficiencies of over 70% (Neibling & Alberts ,1979; Young *et al*.,1980; Magette *et al*., 1989; Dillaha *et al*., 1989) The efficiency of natural forest buffer is even greater, ranging from 85% to 99% (Cooper *et al*., 1987; Smith, 1989; Cheschier *et al*., 1991; Castelle *et al*., 1994; Gilliam, 1994; Lowrance *et al*., 1995; Hairsine, 1998). Slope effect and antecedent moisture conditions were not found to impact buffer efficiency (Ghaffarzadeh *et al*., 1992; Croke, Lane, Lacy & Fogarty, 1999). In all instances surface roughness was identified as a critical factor determining buffer efficiency. Buffer width needs to be derived by considering both the amount of sediment it is expected to trap as well as the terrain in which it occurs (Dignan, 1999; Hairsine, 1998). Particularly fine sediment is unlikely to be trapped in a buffer, and should be controlled at source (Loch *et al*., 1999).

The length of a watercourse draining a landscape unit, be it a forestry compartment or a small watershed, is an important factor in assessing the sediment risk associated with that watercourse, because the sediment load to the watercourse is determined by the length over which the mobilised sediment is distributed. A buffer width recommendation that is based on the localised sediment delivery risk can be derived using a method developed by Karssies and Prosser (2001). Results suggest that industry buffer standards (20m) are ususally adequate for sediment control The results indicate that the steep headwater streams are often inadequately protected, while the lower order watercourses are over-protected. This corresponds to Bren's (1999) observation that identified upslope convergent areas as areas that are usually under-protected. This result is controversial, as it is a direct contradiction of the Landuse and Wetland/Riparian Habitat Working Group (1999: 10) who describe first order streams as "the least sensitive watercourses in terms of hydrological processes". The research undertaken by Daniels and Gilliam (1996: 251) produced similar contradictions, "(e)phemeral riparian channels need a continuous vegetative cover to be effective filters", a condition they note to be an impossibility beneath closed canopy forest.

APPLICATION

Best practices for managing sediment delivery to streams that address erosion and sedimentation do exist. The results of the modelling procedures can be used to develop integrated and prioritised strategies for applying these management practices. The priority areas are identified by delineating areas at higher risk than the surrounding areas. Figure 4 presents an example of a site-specific sediment control strategy. The black numbers depict the compartment identifiers.

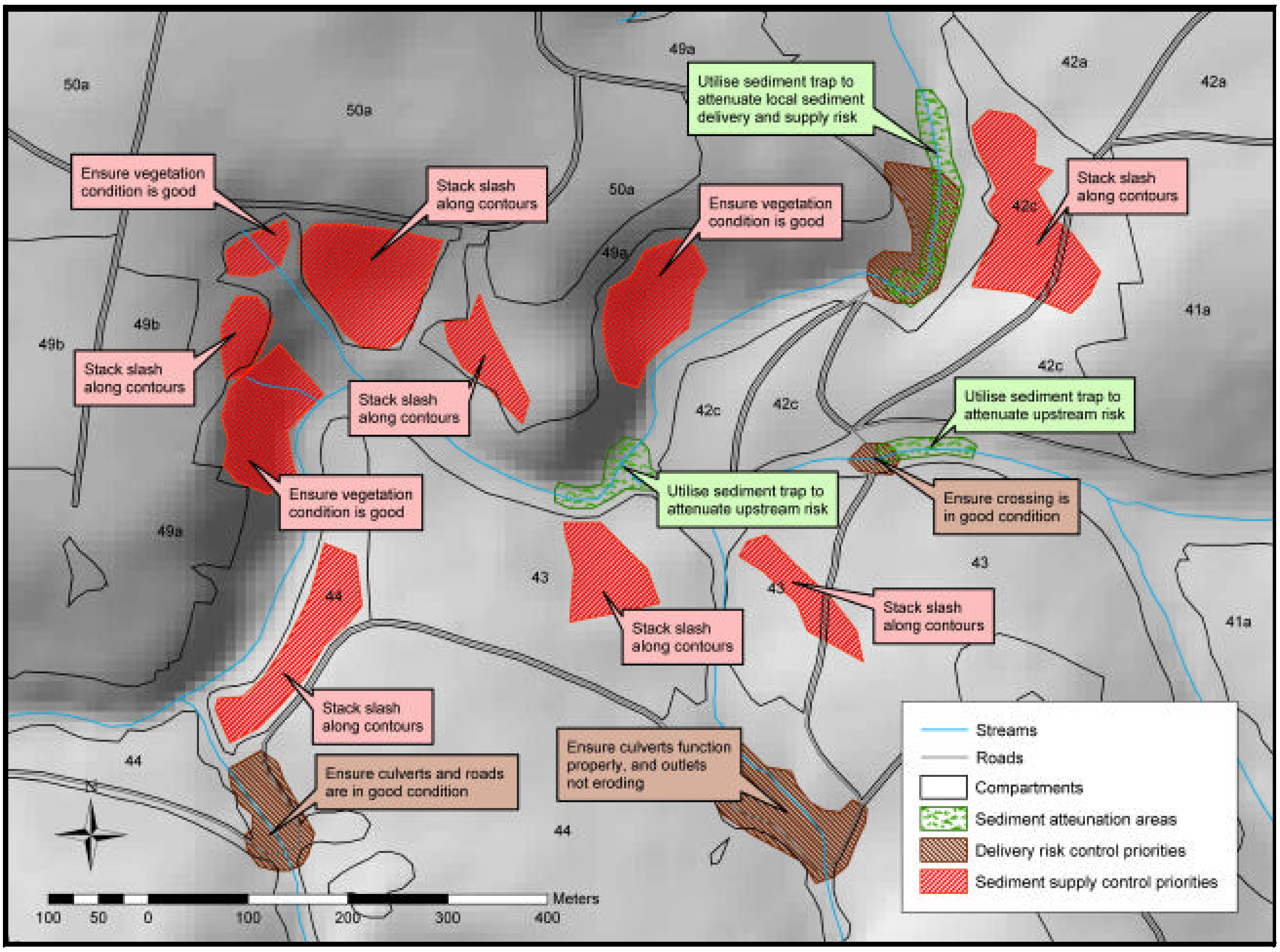

Figure 4: Example of an integrated sediment control strategy

Figure 5 depicts the recommended buffer widths, derived using the Karssies and Prosser (2002) method, for the mapped area. The blue figures indicate the buffer width in meters. It is important to note that the area occupied by riparian buffers derived using this method is considerable less than the area occupied by buffers defined using the South African standard buffer width of 20m.

CONCLUSIONS AND RECOMMENDATIONS

The research has attempted to contribute to the sustainable management of commercial forestry plantations by developing tools to identify priorities for erosion control. The results of the application of these tools can be used to make site-specific recommendations within the identified priority areas.

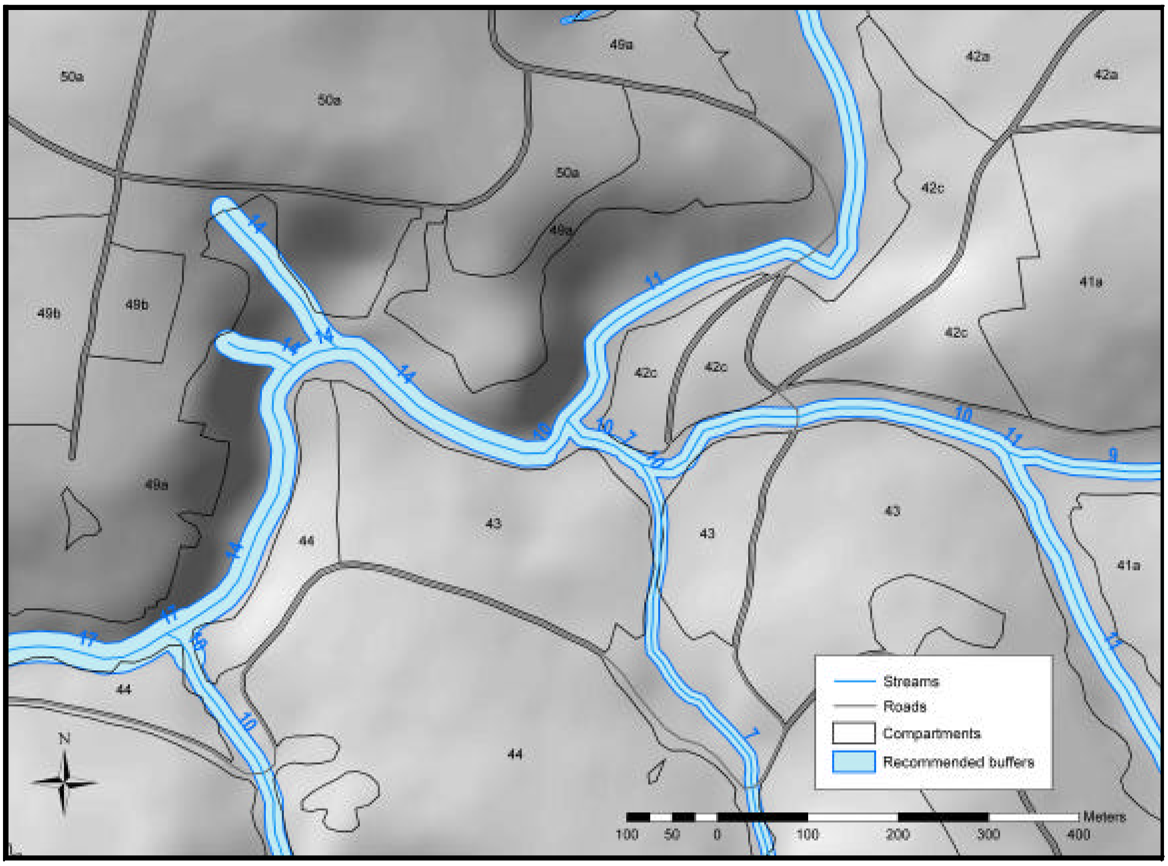

Figure 5: Buffer width recommendations

The results of the modelling undertaken correspond well to erosion observed during field trips and identified off aerial photographs. This suggests that the methods employed are suitable for identifying areas of high erosion potential, given the data constraints under which the procedure is likely to be applied. The results of the research suggest that the application of spatial modelling procedures can assist in minimising sediment delivery to rivers. The application of the results, at both landscape and compartment levels, enable tactical and operational management strategies to be developed.

REFERENCES

BREN, L.J. 1999. Aspects of the geometry of buffer strip design in mountain country. In: CROKE, J and P LANE (Eds). 1996. *Forest Management for Water Quality and Quantity:Proceedings of the second forest erosion workshop May 1999*. Cooperative Research Centre for Catchment Hydrology, Report No. 99/6. Australia.

CHESCHEIR G.M., J.W. GILLIAM, R.W. SKAGGS and R.G. BROADHEAD. 1991. Nutrient and sediment removal in forested wetlands receiving pumped agricultural drainage water. *Wetlands* 11:87-103

COOPER, J.R., J.W. GILLIAM, R.B. DANIELS, and W.P. ROBARGE. 1987. Riparian areas as filters for agricultural sediment. *Soil Science Society of America Journal* 51:416-420

CROKE, J.P., P. LANE, S. LACY and P. FOGARTY. 1999. Filter strip effectiveness: Changes due to vegetation disturbance and antecedent moisture conditions. In: CROKE, J and P LANE (Eds). 1999. *Forest Management for Water Quality and Quantity: Proceedings of the second forest erosion workshop May 1999*. Cooperative Research Centre for Catchment Hydrology, Report No. 99/6. Australia.

CROKE, J. and S. MOCKLER. 1998. Relationships between runoff and sediment yield and cover on snig tracks and general harvest areas. In: CROKE, J and P FOGARTY (Eds). 1998. *Erosion in Forests - Proceedings of the Forest Erosion Workshop, March 1997*. Cooperative Research Centre for Catchment Hydrology, Report No. 98/2. Australia.

DANIELS, R.B. and J.W. GILLIAM. (1996). Sediment and chemical load reduction by grass and riparian filters. *Soil Science Society of America Journal* 60: 246-251.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY. 1995. Forest Policy Discussion Paper. Available online: http://www.polity.org.za/govdocs/green_papers/forest1.html [11 May 2001]

DIGNAN, P. 1999. Tracing sediment flows into buffers: Causes and consequences. In: CROKE, J and P LANE (Eds). 1999. *Forest Management for Water Quality and Quantity: Proceedings of the second forest erosion workshop May 1999*. Cooperative Research Centre for Catchment Hydrology, Report No. 99/6. Australia.

DILLAHA, T.A. and S.P. INAMDAR. 1997. Buffer zones as sediment traps or sources. In: HAYCOCK, N.E., T.P. BURT, K.W.T. GOULDING, and G. PINAY (Eds.) *Buffer zones: Their processes and potential in water protection. The proceedings of the International Conference on Buffer Zones*. Quest Environmental, UK.

FORESTRY INDUSTRY ENVIRONMENTAL COMMITTEE. 1995. Guidelines for Environmental Conservation Management in Commercial Forests in South Africa. Rivonia.

FURNISS, M.J., S. FLANAGAN and B. MCFADIN. 1999. Hydrologically-Connected Roads: An indicator of the influence of roads on chronic sedimentation, surface water hydrology and exposure to toxic chemicals.

GHAFFARZADEH, M., ROBINSON, C. A., and CRUSE, R. M. 1992. Vegetative filter strip effects on sediment deposition from overland flow. *Agronomy Abstracts*, American Society of Agronomy. Madison, WI.

GILLIAM J.W. 1994. Riparian wetlands and water quality. *Journal of Environmental Quality* 23:896-900

GRAY, D.H. 1970. Effects of forest clear-cutting on the stability of natural slopes. *Bulletin of the Association of Engineering Geologists*. 7: 45-66.

HAIRSINE, P.B. 1998. Buffer zones for managing sediment movement in forestry operations. In: CROKE, J and P FOGARTY (Eds). 1998. *Erosion in Forests - Proceedings of the Forest Erosion Workshop, March 1997.* Cooperative Research Centre for Catchment Hydrology, Report No. 98/2. Australia.

KARSSIES, L. and I.P. PROSSER. 2001. Designing grass filter strips to trap sediment and attached nutrient. In: RUTHERURD, I., SHELDON, F., BRIERLEY, G. and C. KENYON (Eds). 2001. *Third Australian Stream Management Conference: The value of healthy streams*. Cooperative Research Centre for Catchment Hydrology. Australia.

LAMARCHE, J. and D.P. LETTENMAIER. 200 1. Effects of forest roads on flood flows in the Deschutes River basin, Washington. *Earth Surface Processes and Landforms* 26(2): 115-134.

LANDUSE AND WETLAND/RIPARIAN HABITAT WORKING GROUP. 1999. Wetland/Riparian Habitats: Practical field procedure for identification and delineation.

LEFAKANE, T. and R. PATA. 1998. Industry sector analysis: Forestry, South Africa. U.S. & Foreign Commercial Service and U.S. Department of State. Available online: http://www.tradeport.org/ts/countries/safrica/isa/isar0011.html [3 May 2002]

LOCH, R.J., A. CONSTANTINI, R.D. CONOLLY, T. ESPIGARES, R. GARTHE, P.D. McINTOSH, N. DUHIG and G.J. SHERIDAN. 1999. Sediment generation and management on forest roads – A Queensland perspective. In: CROKE, J and P LANE (Eds). 1999. *Forest Management for Water Quality and Quantity: Proceedings of the second forest erosion workshop May 1999*. Cooperative Research Centre for Catchment Hydrology, Report No. 99/6. Australia.

LOWRANCE, R., L.S. ALTIER, J.D. NEWBOLD, R.R. SCHNABEL, P.M. GROFFMAN, J.M. DENVER, D.L. CORRELL, J.W. GILLIAM, J.L. ROBINSON, R.B. BRINSFIELD, K.W. STAVER, W. LUCAS and A.H. TODD. 1995. Water quality functions of riparian forest buffer systems in the Chesapeake Bay Watershed. Report No. EPA 903-R-95-004; CBP/TRS 134/95.

MAGETTE, W., R. BRINSFIELD, R. PALMER and J. WOOD. 1989. Nutrient and Sediment Removal by Vegetated Filter Strips. *Transactions of the American Society of Agricultural Engineers* 32(2): 663–667.

MANDER, J.J., N.W. QUINN and M. MANDER. 1993. Umhlali River Catchment: Rehabilitation pilot project. Investigational Report No. 77. Institute of Natural Resources. Pietermaritzburg.

McCASHION, J.D. and R.M. RICE. 1983. Erosion on logging roads in northwestern California: How much is avoidable? *Journal of Forestry* 81: 23-36.

MOCKLER, S. and P. LANE. 1999. Road to stream connectivity: The relative roles of slope, discharge and soil erodibility. In: CROKE, J and P LANE (Eds). 1999. *Forest Management for Water Quality and Quantity: Proceedings of the second forest erosion workshop May 1999*. Cooperative Research Centre for Catchment Hydrology, Report No. 99/6. Australia.

MOORE, I.D. and G.J. BURCH. 1986. Physical basis of the length-slope factor in the Universal Soil Loss Equation. Soil Science Society of America Journal 50: 1294 –1298.

MOORE, I.D. and J.P. WILSON. 1992. Length-slope factors for the Revised Universal Soil Loss Equation: Simplified method of estimation. *Journal of Soil and Water Conservation* 47(5):423-428.

NEIBLING, W.H. and E.E. ALBERTS. 1979. Composition and yield of particles transported through sod strips. American Society of Agricultural Engineers Paper No. 79-2065.

SADEK, T.M., R.B. GRAYSON and C.J. GIPPEL. 1998. The impact of roads and landslides on stream water turbidity and suspended sediment in forested catchments. In: CROKE, J and P FOGARTY (Eds). 1998. *Erosion in Forests - Proceedings of the Forest Erosion Workshop, March 1997*. Cooperative Research Centre for Catchment Hydrology, Report No. 98/2. Australia.

SMITH, C. M. 1989. Riparian pasture retirement effects on sediment, phosphorus and nitrogen in channelized surface runoff from pastures. *New Zealand Journal of Marine Freshwater Research* 23, 139-146.

YOUNG, R.A., C.A. ONSTAD, D.D. BOSCH and W.P. ANDERSON. 1987. AGNPS, Agricultural non-point source pollution model: A watershed analysis tool. USDA Conservation Research Report No. 35. Washington, DC.