

**SPATIAL MODELLING TO ESTABLISH
PRIORITIES FOR EROSION CONTROL
IN COMMERCIAL FORESTRY PLANTATIONS**

by

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ABSTRACT

Commercial forestry is recognized for both its economic contribution as well as its environmental impact. Of particular concern, is the soil erosion and sedimentation of watercourses associated with forestry plantations. Environmental laws regulate many of the activities of the forestry sector. It is critical that the forestry sector ensure that its operations are compliant with the legal requirements that govern its use of natural resources. In pursuing legal compliance it is necessary to ensure that erosion control strategies are developed so as to ensure the positive effects of any interventions are optimised. The identification of areas that are particularly at risk to erosion or contribute to sediment delivery is an essential component in prioritising areas for management interventions.

Establishing the erosion potential for commercial forestry areas is readily accomplished through the application of existing models. Process based erosion models generally have greater data requirements than the empirically derived USLE-based models. Given the paucity of data available, the latter approach was adopted. Two methods of topographic sub-factor derivation were investigated, those associated with the RUSLE (Renard, Foster, Weesies & McCool 1991) and the Unit Stream Power method presented by Moore and Burch (1986). Since no existing methods identifying delivery risk areas existed, a method was developed based on principles and factors identified in the literature. Additionally, methods for identifying topographic assets, in terms of sediment attenuation, were developed. From these models three indices were derived; sediment supply, delivery risk and sediment attenuation.

Thereafter, the mean Sediment Supply Index was divided by stream length for small catchments defined within the landscape to derive an index of sediment loading to streams. This index is used to identify priorities for management intervention across the landscape. The mean slope and sediment supply is used to develop buffer width recommendations for the streams draining the catchments, using a method developed by Karssies and Prosser (2001). Using the three indices in conjunction it is possible to make on-site and off-site erosion control recommendations as well as identify and exploit any natural features that can be utilized in erosion control.

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PREFACE

The research described in this dissertation was carried out at the Centre for Environment and Development, University of Natal, Pietermaritzburg, under the supervision of Dr Nevil Quinn and Dr Trevor Hill.

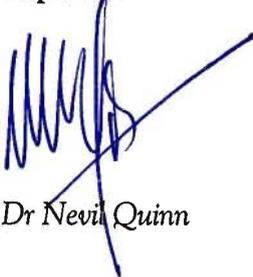
This dissertation represents original work by the author and has not otherwise been submitted in any form for any degree or diploma at any other university. Where the work of others has been used it has been duly acknowledged in the text.

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CHAPTER 1: OVERVIEW

1.1 INTRODUCTION

This chapter provides an overview of the forestry industry in South Africa. It introduces the issues of soil erosion and sediment attenuation in commercial forestry areas. The potential role of buffers in managing sediment delivery to streams will be presented. This chapter will examine the availability of applicable data sources, both nationally and industry specific. It will introduce the major regulatory bodies, standards and industry norms governing environmental management in the commercial forestry sector in South Africa. Finally, it will present the aims and objectives and outline the scope of the study as well as the structure of the dissertation.

1.2 COMMERCIAL FORESTRY IN SOUTH AFRICA

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). In 2001 this amounted to 1.8 billion rand (US Department of State 2001). The potential of social forestry to contribute to the upliftment of impoverished rural communities has been recognized as an important factor in rural development. 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). Figure 1.1 depicts the extent of commercial forestry in KwaZulu-Natal and Mpumalanga, the primary forestry provinces in South Africa. The data presented is from the National Landcover database (Thompson 1997).

However, the economic contribution of forestry does have associated environmental costs; water quantity and quality impacts are particularly contentious. The consumption of water by commercial plantations has been the focus of a considerable amount of research and debate (Versveld, Le Maitre & Chapman 1998). As will be shown in Chapter 2, available literature suggests that soil erosion and the sedimentation of watercourses are among the most significant environmental hazards associated with commercial forestry activities.

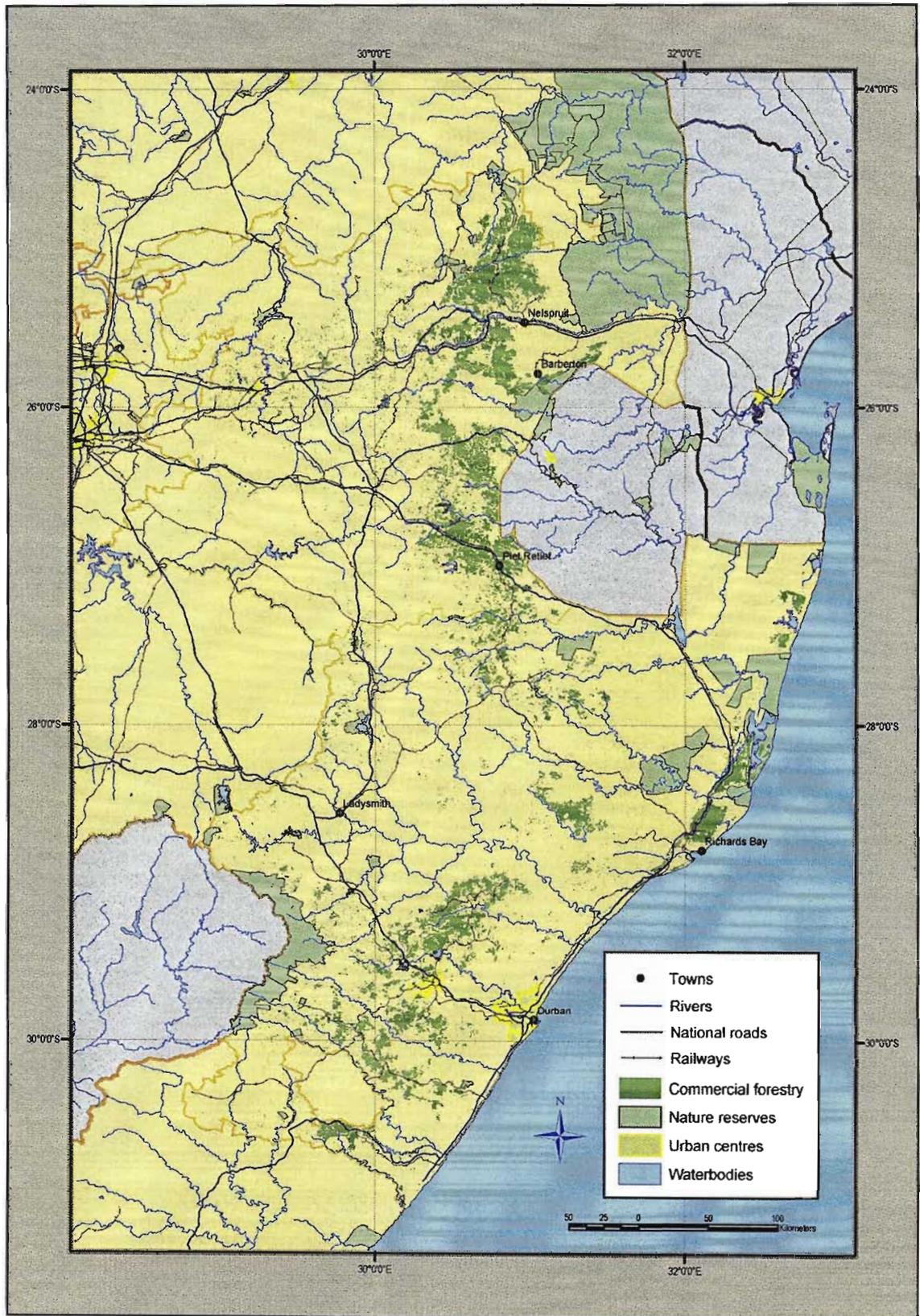


Figure 1.1: Commercial forestry areas in KwaZulu-Natal and Mpumalanga (Thompson 1997)

The Guidelines for Environmental Conservation in Commercial Forestry in South Africa issued by the Forestry Industry Environmental Committee (1995) acknowledge that soil loss is one of the undesirable impacts of forestry, and the Forest Policy Discussion Document (DWAF 1995) explicitly requires that sustainable forest management include protection of water resources and soils. The African National Congress Agricultural Policy Document (1994) acknowledges that commercial forestry has been implicated in increased soil erosion. It is evident that an awareness of the associated economic benefits and the environmental costs is influencing national policy regarding commercial forestry.

Interventions to improve, or preserve, the quality and quantity of water contributed by these upper catchments are most likely to succeed if they can be focussed on specific problematic sites, so as to maximize the efficacy of the interventions. This dissertation will address the issue of water quality as related to sediment delivery to streams; it will not directly consider any issues related to the water consumption of plantations.

1.3 SEDIMENT PRODUCTION IN FORESTS

While models for soil erosion have been developed and successfully applied, typically the basis for these models is in the traditional agricultural environment (O'Shaughnessy, Fogarty & Croke 1998). These authors suggest that there are specific conditions relating to commercial forestry that need to be addressed in an evaluation of the impacts relating to soil erosion. An understanding of erosion processes as they relate to commercial forestry is required, so that the potential benefits of forestry can be optimised without compromising the sustainability of the industry by depleting the resources on which it depends. Commercial forestry, in South Africa, is often situated on steeper slopes in the upper areas of catchments adjacent to first order streams. Areas of forestry are exposed to disturbance at a lower frequency, although the disturbance is more severe than traditional agriculture. 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. Both the forestry industry and national interests are acknowledged in the need to manage soil erosion in forestry areas, given the sensitive nature of these areas and the disturbances to which they are exposed.

The extensive networks of roads, often unsealed, associated with commercial forestry areas are a significant sediment source in these areas. For example, Sadek, Grayson and Gippel (1998) report that catchments with unsealed roads produced 10 to 100 times more sediment load per unit area compared with undisturbed catchments. Peak hourly average turbidity during storm events was four to six times that in undisturbed catchments. The temporary lack of vegetation cover during plantation regeneration also contributes to increased sediment loads, although the effect is eliminated once total groundcover is restored to between 40 and 50% of the pre-disturbance levels (Croke & Mockler 1998). In northwestern California, McCashion and Rice (1983) found that roads were responsible for 61% of the soil volume displaced by erosion in logging areas and that the average erosion rate on roads was 17 times the average rate for logging areas. The incidence of mass soil movements has been shown to increase in clear-cut areas throughout the world (Gray 1970).

1.4 EXISTING LEGISLATION AND PROTOCOLS

Recent legislation promulgated in South Africa, places the onus for environmental management on the landowner. Over and above the provisions contained in the Constitution (Act No. 108 of 1996), acts relating to the forestry industry are the National Forests Act (Act No. 84 of 1998), the National Environmental Management Act (Act No. 107 of 1998), National Water Act (Act No. 36 of 1998) and the Conservation of Agricultural Resources Act (Act No. 43 of 1998). This legislation is the implementation of the principles contained in the policy documents mentioned above.

Additionally, the environmental performance of the South African forestry industry is governed by the Forestry Stewardship Council (FSC) and ISO 14001 accredited management systems. These international systems require regular auditing of the environmental performance of forestry companies. The requirements of these management systems are implemented through internal Best Management Practices (BMPs). Fulfilment of the requirements of these environmental management systems maintains the South African forestry industry's access to international markets. Consequently, any methods arising from this research need to comply with the requirements of these systems and

practices, if they are to be acceptable to the forestry industry. The specific requirements of the legislation and self-regulatory mechanisms will be discussed in Chapter 2.

1.5 THE ROLE OF BUFFER ZONES

Many definitions of buffer zones have been proposed. Simplistically, buffer zones are defined as “a transition zone between areas managed for different objectives” (World Resources Institute 2001). The role of buffers, be they simple vegetated filter strips, forested riparian zones or wetland systems as effective sediment traps has been conclusively established (Castelle, Johnson & Conolly 1994). Not only are buffers efficient in improving both water quality and quantity of instream environments, there are additional benefits arising from the responsible management of riparian areas, such as increasing biodiversity, flood attenuation, reducing bank erosion and habitat provision. In plantation forestry there is the additional benefit of these areas acting as firebreaks. Establishing appropriate buffer widths and selecting the type of buffer feature to be created is critical to the efficacy of the buffer zone in achieving the desired objectives.

1.6 AIMS AND OBJECTIVES

Given the acknowledged impact of plantations, the legal requirements controlling forestry activities, 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 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 existing data and available technology, and be easy to implement.

The aim of this research is to develop a system for prioritising areas for management interventions to control sediment production and delivery in commercial forestry plantations. The first focus of the research is to develop a process that could assist in identifying priority areas for erosion control based on the erodibility of the area. Assessing the localized efficiency of sediment delivery to streams is the second focus. Identifying specific natural landscape features that have the greatest potential for sediment attenuation

is the final focus. Methods of integrating the results of the three foci to establish management priorities will be investigated.

The explicit objectives of the research are:

- (i) To present the current understanding of erosion in commercial forests, both locally and internationally
- (ii) To review the potential of riparian buffers zones as sediment control mechanisms
- (iii) To develop a method of identifying areas of high erosion potential in commercial forestry areas
- (iv) To develop a method for assessing the risk of sediment delivery to streams in commercial forestry areas
- (v) To integrate the information obtained from the above four objectives into a method for identifying priority areas for managing sediment delivery in commercial forestry areas
- (vi) To implement the developed methodology in a case study
- (vii) To evaluate the utility of industry standard, and nationally available, datasets in applying the proposed methodology
- (viii) To identify shortcomings in the proposed methodology and further research needs

1.7 STRUCTURE OF THE DISSERTATION

This introduction has highlighted the issues to be addressed in the subsequent chapters of this dissertation. Chapter Two will present a more detailed discussion of sediment production and control in forests. This chapter will examine the legal requirements and industry regulations that govern the forestry industry in South Africa. It will identify the key contributing factors, and introduce the prevailing erosion control principles. Chapter Three will present a method for identifying areas of sediment supply. Chapter Four presents methods for assessing the influence of road-stream interaction as it relates to sediment delivery, as well as a method for identifying areas within the landscape likely to act as sediment traps. The discussion of the utility of the approach described in the preceding chapters will be the focus of Chapter Five. It will examine the applicability of the modelling

results in establishing management priorities. This chapter will present ways of improving the methods and will demonstrate how the work undertaken can be applied practically. The sixth chapter will assess how successful the research has been in terms of the stated objectives. It will re-examine the methods proposed in Chapters Three and Four, identifying further research and development needs.

CHAPTER 2: SEDIMENT PRODUCTION AND CONTROL IN FORESTS

2.1 THE PROBLEM OF SOIL EROSION

Human beings, in fact all land based organisms, are dependent on soil for their livelihood to a greater or lesser degree (Daily, Matson & Vitousek 1997). Soil, they argue, is one of a nation's most important assets, built up over hundreds to hundreds of thousands of years, and potentially wasted away over very few. The services supplied by soils include buffering and moderation of the hydrological cycle, physical support of vegetation, retention and delivery of nutrients to plants, disposal of waste and dead organic matter, renewal of soil fertility and regulation of major element cycles. The loss of such a valuable resource has significant impact; this loss is known as soil erosion.

Soil erosion is defined as the natural process of removal of topsoil by water and wind (Goudie *et al.* 1994). The severity of soil erosion by water, the focus of this dissertation, is influenced by the topography of the landscape (gradient, slope length), the erosivity of the precipitation, the energy of the overland flow of water, the vegetation cover, the erodibility of the soil itself and any specific erosion prevention measures that may be in place (Lorentz & Schulze 1995). This natural process is frequently exacerbated by the landuse activities of humankind; particularly it is associated with cultivation. Soil erosion impacts can be either on-site or off-site.

On-site impacts of soil erosion are primarily associated with the loss of topsoil and associated soil fertility, the impact on landuse sustainability, the loss of the natural seed bank and the secondary impacts of fertilizer application. The offsite impacts of soil erosion are driven by the delivery of sediment to watercourses and waterbodies. High sediment loads impact on the aquatic environment in four ways (Dallas & Day 1993; Lovett & Price 1999):

- (i) Gross loss of habitat
 - Sediment fills pools and substratum spaces reducing available habitat
 - Sedimentation can lead to anoxic conditions

- (ii) Smothering of stream life
 - Eggs of substratum breeding fishes are smothered
 - Respiration of fish and invertebrates is adversely affected
 - Dissolved oxygen levels are altered by the decomposition of buried detritus
- (iii) Scouring of streams
 - Reduces the algal food resource
 - Affects the ability of filter-feeders to feed
- (iv) Increased turbidity
 - Photosynthetic processes are affected
 - Visual predators ability to hunt is compromised
 - Water temperature may decrease

The above list excludes impacts associated with increased frequency of flooding, deterioration of recreational and navigational waterways, and damage to structures for water storage, conveyance and treatment (Daily, Matson & Vitousek 1997). Sediment is considered the largest single polluter of rivers and the second most significant polluter of lakes in the United States of America (Dillaha & Inamdar 1997).

Pimentel *et al.* (1995) state that soil erosion is a major threat to the sustainability and productivity of agricultural activities, with arable land being lost globally at a rate of over 10 million hectares per year. According to Oldeman, van Engelen and Pulles (1990) approximately 2 billion hectares (17% of the earth's vegetated surface) have been degraded by human induced changes. The global estimates of direct costs associated with soil erosion are estimated at 250 billion dollars annually, and an additional 150 billion dollars in offsite costs. In the United States of America topsoil loss is estimated at 4 billion tons per year, from the 160 million hectares of cropland (an average loss of 25 t.ha⁻¹.yr⁻¹). The on-site economic losses exceed 27 billion dollars. The total economic costs including on-site and off-site damage costs, as well as erosion prevention expenses are over 44 billion dollars annually. In contrast, the cost of control measures is estimated at 8.4 billion dollars (Pimentel *et al.* 1995).

In South Africa estimates of soil erosion appear lower than in the USA, ranging between three and ten tons per hectare per year under intensive cultivation, although extremes of $120 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ have been reported (Verster, du Plessis, Scholms & Fuggle 1998). These authors estimate average soil regeneration to be $0.31 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. Although erosion rates are relatively low, erosion is widespread in South Africa. Over 30% of South Africa experiences erosion at rates in excess of $4 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. Over 3 million hectares have been rendered unproductive in South Africa due to erosion, and 60% of the total area is threatened by soil erosion, "... this may well be the greatest environmental problem facing South Africa ..." (Verster, du Plessis, Scholms & Fuggle 1998: 191). At an even smaller scale it is estimated that 80% of KwaZulu-Natal is affected by water induced soil erosion, and between 10% and 25% of the province may be irreparably degraded (Gordon-Lennox 1996).

2.2 SOIL EROSION IN FORESTS

In South Africa, plantation forestry is associated with the cultivation of exotic tree species, most commonly, *Eucalyptus* spp., *Pinus* spp. and *Acacia mearnsii*. Plantation forestry is associated with low frequency, but high impact disturbance. Soil losses associated with plantation harvesting and site preparation are reported at $7.1 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Gordon-Lennox 1996), more than double the national average soil loss of $3 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Verster, du Plessis, Scholms & Fuggle 1998). In South Africa, rotation lengths are short, ranging between seven and 35 years, depending on the envisaged timber product for example, pulp, paper or saw logs. Essentially, landscape units ranging in size from a few hectares to over 100 hectares, will be regularly denuded of vegetation, although larger scale removal of vegetation may occur in the event of forest fires.

A study by Scott (1997) found that while clearfelling had little effect on sediment production, erosion increased significantly after wildfires. This is attributed to the increased water repellency of the soils after a fire, as well as the loss of the organic matter that usually covers the forest floor. Water repellency promotes the generation of overland flow, heightening the risk of erosion. In another study Scott, Versfeld and Lesch (1998) report a tenfold increase in suspended sediments, associated with clearfelling activities. The differing findings regarding the impact of clearfelling in these two studies may be

attributable to the on-site management practices immediately after clearfelling. However, with regard to wildfires, a fourfold increase in the amount of suspended sediments associated with clearfelling is reported by Scott, Versfeld and Lesch (1998).

Over and above the removal of vegetation, there are a number of activities that effect the erosion potential within each harvesting unit including soil disturbances (e.g. skidder tracks, temporary harvesting roads, compaction due to machinery) and the burning of waste material.

Forestry in South Africa has high road densities associated with the plantations. Industry guidelines suggest an optimum of 1 km of road per 40 hectares, although this is seldom achieved in reality (G. Naidoo *pers. comm.* 2001). This high density of roads, usually unsurfaced, provides an extremely efficient delivery mechanism for sediment delivery to streams. Luce and Black (1999) found that roads with high levels of associated vegetation disturbance produced seven times more sediment than roads with low levels of disturbance of adjacent vegetation. This suggests that particular attention needs to be paid to managing sediment delivery from general harvesting areas, or compartments, to adjacent roads.

Depots, or landings, are a further contributor to the production of sediment in forestry areas. Depots are temporary collection areas for timber from compartments that are inaccessible to long-haul vehicles. These areas are highly disturbed with high heavy-traffic loads, and are permanently denuded of any vegetation or cover. Ninety-eight percent of all soil erosion occurring in Tennessee forestry areas can be attributed to roads, extraction tracks and depots (Tennessee Department of Agriculture 1993). These factors, the periodic removal of all vegetation cover, the impact of actual harvesting activities and the associated road infrastructure, can be categorized into two basic activities, harvesting and extraction. The impacts of these activities, as they relate to soil erosion, are the compaction of soil and the loss of vegetation cover.

2.2.1 Influence of soil compaction on erosion rates

Broadly speaking, soil structure is a combination of soil particles, water and air spaces (pores). Compaction occurs when the pore space between the particles is reduced. Since

large pore spaces facilitate the movement of water into and through the soil, the reduction of these spaces decreases both the infiltration and drainage capacity of the soil (Daily, Matson & Vitousek 1997). This, in turn, will increase runoff leading to increased erosion. Figure 2.1 presents the impact of soil compaction schematically.

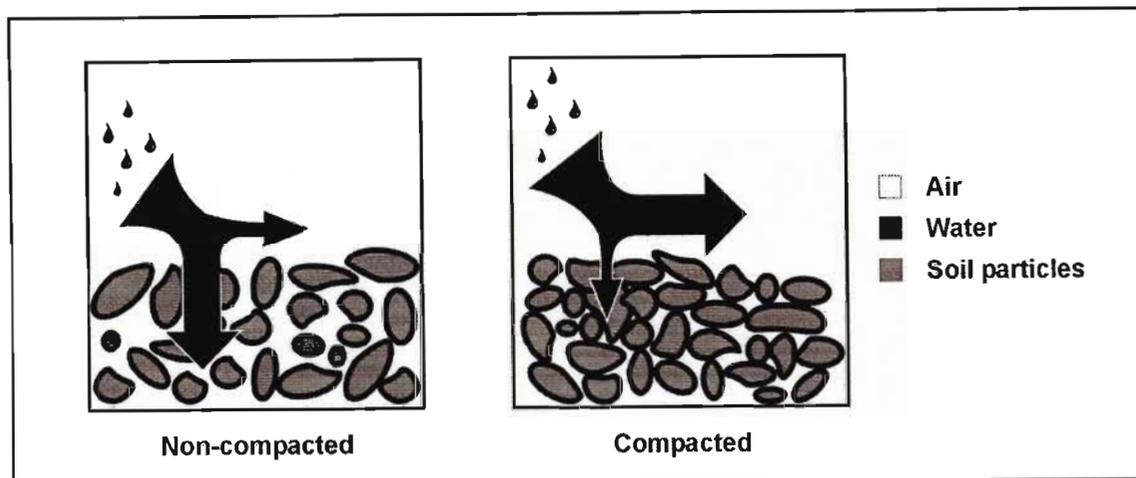


Figure 2.1: Schematic representation of the influence of soil compaction on infiltration

Soil compaction can be the result of natural processes or anthropogenic disturbances as presented in Table 2.1.

Table 2.1: Causes of soil compaction

Cause	Description
Raindrop impact	Natural cause of compaction, as is evidenced in 'soil crusting'
Tillage operations	Repeated tillage at a constant depth will create compacted layers just below the depth of tillage
Wheel traffic	The most significant cause of compaction, the weight of agricultural equipment significantly compacts soil
Minimal crop rotation	Different rooting systems of different crops help to attenuate compaction Repetitive preparation and planting cycles increase soil compaction

In forestry, areas of compaction are linked with high traffic volumes specifically, and are consequently associated with roads, extraction tracks and depots. The impact of compacted surfaces on runoff and sediment production was investigated by Croke, Hairsine, Fogarty, Mockler and Brophy (1997) in New South Wales, Australia. For a range of simulated rainfall conditions, they measured the amount of sediment and runoff produced on extraction features (roads and tracks) and the general harvesting area across a range of soil

types. Long-term sediment yields were found not to differ significantly across soil types, although granite derived soils showed higher levels of on-site erosion prior to revegetation. Most importantly is that runoff and sediment production were significantly higher on the extraction features than on the harvesting area, across all soil types. On average, the extraction features produced seven times more surface runoff and 20 times more sediment than the general harvesting area. High sediment yield from compacted surfaces, roads, tracks and depots, have been confirmed in other studies (Table 2.2).

Table 2.2: Key findings Australian researchers regarding sediment production from forest roads and its management

	Key findings	Authors
Runoff generation	<ul style="list-style-type: none"> Runoff coefficients of 54% to 99% were observed on forest roads Extraction tracks runoff coefficient can be as high as 80% 	Croke, <i>et al.</i> (1999) Lacey <i>et al.</i> (1999)
Sediment production	<ul style="list-style-type: none"> Catchments with unsealed roads produce 10 to 100 times as much sediment as undisturbed catchments Extraction tracks produce up to seven times more runoff than general harvesting areas Extraction tracks produced 30 to 40 t.ha⁻¹.yr⁻¹ in wet years, and 5 to 9 t.ha⁻¹.yr⁻¹ in dry years, compared with 0.5 t.ha⁻¹.yr⁻¹ in undisturbed areas Erosion rates on extraction tracks were 70 t.ha⁻¹.yr⁻¹ and erosion rates on log landings (depots) were 120 t.ha⁻¹.yr⁻¹ Sediment concentrations were five to eight higher on the larger roads than on the feeder and abandoned harvesting tracks Peak average hourly turbidity values were four to six times higher in disturbed catchments Sediment sources are either poorly managed harvesting areas or road surface 	Sadek <i>et al.</i> (1998) Croke (1998) Lacey (1998) Wallbrink <i>et al.</i> (1998) Croke <i>et al.</i> (1999) Sadek <i>et al.</i> (1998) Dignan (1999)
Recovery	<ul style="list-style-type: none"> After five years runoff from extraction tracks reduced to only double that of the general harvesting areas Freshly disturbed areas likely to produce more sediment than old disturbed areas (sediment depletion factor) Initial increases in sediment associated with harvesting decrease despite ongoing harvesting activity 	Croke (1998) Lacey <i>et al.</i> (1999) Wilson & Lynch (1998)
Management	<ul style="list-style-type: none"> Gravelling road surfaces can reduce sediment generation by more than 500% and grassed roads (50% cover) reduced sediment generation by over 400% 	Loch <i>et al.</i> (1999)

2.2.2 Influence of vegetation loss on erosion rates

The cause of soil erosion is the detachment of soil particles from the land. Whether it be erosion by wind or water, vegetation cover plays a role in reducing the likelihood of detachment by reducing the efficiency of the contact between the erosion agent and the erodible surface.

Water erosion starts when raindrops hit the bare soil. The greater the force of this impact, the greater the resultant erosion will be. Intercepting the rainfall before it strikes the ground reduces the potential of the impact to induce erosion (Schulze 1995). Tall trees intercept the rain effectively, but due to tree height the force of raindrops, once they reach the ground is not significantly reduced. For optimum reduction, vegetation needs to intercept the rainfall close to the ground. In plantation forestry, the ground below the tree canopy has little live vegetation, but is often covered by a mulch of vegetative matter (litter) that acts as an effective damper of rainfall impact. Versfeld, van Wilgen, Bosch and Kruger (1994) suggest that forestry may reduce erosion in degraded areas, but qualify this statement by noting that this has not been adequately researched in South Africa. Figure 2.2 illustrates the effect of vegetation cover on surface runoff, and highlights the importance of vegetation condition and type in buffer design and maintenance.

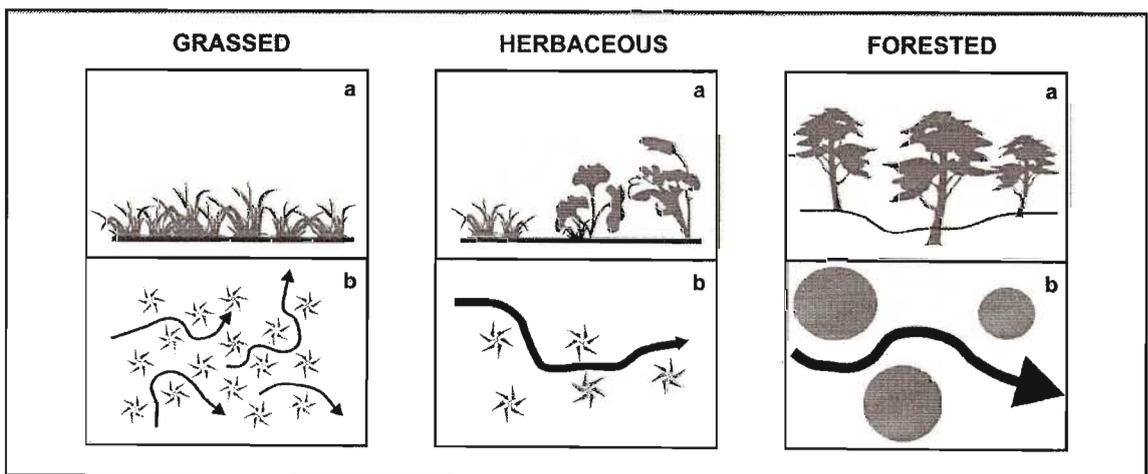


Figure 2.2: The effect of different vegetation types on the erosivity of surface runoff.

Once soil particles have been detached and suspended, it is the surface flow of water that becomes the erosion agent, scouring the land surface as it moves across it. In areas of convergence, this scouring action may become heightened resulting in the formation of

rills, and in the long term, the onset of gully erosion (Donahue, Miller & Shickluna 1983). Gully erosion within forestry areas is recognized as a significant risk, as has been shown in Australian research (Table 2.3).

Table 2.3: Key findings associated with gully erosion and management in forestry areas

	Key findings	Authors
Gully onset	<ul style="list-style-type: none"> • Forestry activities increase the risk of gully erosion for approximately one year after harvesting • Gullies often originate at road drain outlets • Gully development at road discharge outlets play a critical role in sediment delivery to streams 	Prosser & Soufi (1998) Dawes & Croke (1999) Croke <i>et al.</i> (1999)
Management	<ul style="list-style-type: none"> • Soil disturbance in areas that concentrate flows should be avoided at all cost • Gullies need to be treated within a year of onset 	Prosser & Soufi (1998) Prosser & Soufi (1998)

Reducing the velocity of the surface flow affects sediment carrying capacity. Again, vegetation cover is important in achieving this by increasing the surface roughness of the land. This process assists in removing the particles out of suspension and reducing the potential off-site impacts of an erosion event. It is evident that the loss of vegetation cover is a significant factor affecting both the production of sediment and the control thereof.

2.3 LEGAL REQUIREMENTS AND POLICY TO CONTROL SOIL EROSION

The laws of the country of operation, as well as policy documents containing the principles to which the forestry companies should adhere, control the forestry industry.

2.3.1 Legal requirements

In South Africa, there are a number of acts relating to the forestry industry and its impacts on the environment. The principles, duties and obligations imposed by legislation on the forestry industry regarding its role in soil erosion and water pollution will be presented. Acts that impact or affect the industry, outside of the issues raised above will not be discussed.

2.3.1.1 *The Constitution of the Republic of South Africa*

The Constitution (Act No. 108 of 1996) enshrines the South African Bill of Rights, which includes an environmental right:

“Everyone has the right-

- (a) to an environment that is not harmful to their health or well being; and*
- (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that-*
 - (i) prevent pollution and environmental degradation;*
 - (ii) promote conservation;*
 - (iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.”*

The constitution not only governs the behaviour and obligations of the state relative to its citizens, it is applicable to relationships between individuals. “Land users are therefore obliged to ensure that their activities do not unreasonably infringe on the Constitutional rights of others” (Winstanley 2000: 10).

2.3.1.2 *The National Water Act (Act No. 36 of 1998)*

The preamble of the act identifies as one of the act’s key objectives the protection of the quality of water resources. Specifically, this involves the reduction and prevention of pollution and degradation of water resources. The legal obligations of landowners or users, with regard to water pollution are:

“19(1) An owner of land, a person in control of land or a person who occupies or uses the land on which-

- (a) any activity process is or was performed or undertaken; or*
- (b) any other situation exists,*

which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or recurring.”

These measures may include:

- “(a) cease, modify or control any act or process that is causing pollution;*
- (b) comply with any prescribed waste standard or management practice;*
- (c) contain or prevent the movement of pollutants;*
- (d) eliminate any source of pollution;*
- (e) remedy the effects of pollution;*
- (f) remedy the effects of any disturbance to the bed and banks of a watercourse.”*

Two components of pollution are highlighted in the act, firstly, any alteration of the physical, chemical or biological properties of a water resource that reduces its fitness for any reasonable beneficial use, and secondly, the alteration of these properties to make it harmful to any potential users, including the resource itself. The provisions in the act for cleanup costs require that the polluter must pay. These provisions are retroactive. This means that landowners, or landusers, may be held liable for the rehabilitation of streams that may have become degraded as a result of their current or historic landuse practices, in addition to the control of the pollution source.

2.3.1.3 *The Conservation of Agricultural Resources Act (Act No. 43 of 1998)*

This act endeavours to ensure that the productive potential of the land is retained. Relative to this dissertation, it regulates the control and remediation of soil erosion by water. Landusers are obliged to prevent erosion from occurring in Section 4.

“Every landuser shall ... protect the cultivated land on his [sic] farm unit effectively against excessive soil loss as a result of erosion through the action of water”

The act lists specific measures for the prevention of erosion, including the management of surface runoff, conservation tillage, crop rotation, minimizing the fallow (unvegetated) periods, efficient livestock management and the use of crop residues as mulch. Additionally, landusers are responsible for the restoration and reclamation of eroded land (Section 13).

It is important to note that this act has also given rise to the recent promulgation of regulations relating to the control of alien and invasive plants, which are of particular relevance to the plantation forestry industry in South Africa. It requires that buffer zones be created between watercourses (Section 15b:9) and Category 2 plants, to which all South African commercial forestry species belong.

“Unless authorised thereto in terms of the National Water Act, 1998 (Act No. 36 of 1998), no land user shall allow category 2 plants to occur within 30 meters of the 1:50 year flood line of a river, stream, spring, natural channel in which water flows regularly or intermittently, lake, dam or wetland”

2.3.1.4 Other legislation affecting the commercial forestry industry

The National Environmental Management Act (Act No. 107 of 1998) is applicable to the forestry industry in that it provides the framework for co-operative environmental governance, both between relevant government departments and between national authorities and the industry itself. The final act relevant to the commercial forestry industry is the National Forests Act (Act No. 84 of 1998). This Act governs aspects of indigenous forest protection as well as commercial forestry development, in particular it promotes the development of community forestry as an economic empowerment means for previously disadvantaged communities.

2.3.2 Industry policy and self-regulation

The main mechanism by which the forestry industry self-regulates is through the adoption of third-party certification schemes, mainly ISO 14001 certified management systems and Forestry Stewardship Council (FSC) accreditation. The adoption of these schemes maintains the access of certified or accredited companies to international markets. This section will examine the principles contained in the public environmental policy statements of the two major forestry companies in South Africa, SAPPI Forests and Mondi Forests. Additionally, the stated environmental policies of three large North American forestry companies will be examined; Boise, Weyerhaeuser and Canadian Forest Products (CANFOR). The discussion is based on the public Environmental Policies found on the websites of the companies (printed copies are presented in Appendix 1). The relevant

principles of the Forestry Stewardship Council (FSC) accreditation requirements will also be raised.

2.3.2.1 *Mondi Forests Environmental Management*

Mondi embarked on FSC certification of its plantations in 1996, “as it is strongly independent, actively supported by environmentalists and sets increasingly demanding standards”. Currently (2002) 52% of Mondi’s plantation area is FSC certified. The environmental performance of the company is audited regularly. The company policy statement highlights corporate awareness of the potential negative impacts of plantation forestry on biodiversity.

2.3.2.2 *SAPPI Forests Environmental Policy*

Similarly to Mondi, Sappi have implemented third party environmental management systems. ISO 14001 accreditation has been achieved on all plantations. Additionally, the forestry division is pursuing FSC accreditation (D. Everard *pers. comm.* 2001). The forest certification information pages acknowledge a number of issues specifically relevant to this dissertation.

- The mapping of wetlands and streams
- Planting restrictions in terms of distance from water, wetlands and other sensitive areas
- Soil protection using appropriate land preparation techniques
- Continuous monitoring of roads and their associated drainage structures

2.3.2.3 *Boise Environmental Policy*

Boise’s guiding principle is summarized in the first article of their policy document undertaking to promote sustainable forestry by employing an array of scientifically, environmentally, and economically sound practices in the growth, harvest and use of forests. Of interest to the subject of this dissertation, the third article commits the company to “protect water quality and conserve aquatic habitat”. To ensure the company’s performance is in accordance with its stated policies, a company appointed Forest Stewardship Advisory Council reviews the results of environmental audits and recommends changes to the corporate environmental

management principles if necessary. The company is compliant with the American Forest & Paper Association's Sustainable Forestry Initiative standards.

2.3.2.4 *Weyerhaeuser Environmental Policy*

Weyerhaeuser are committed to receiving ISO 14001 certification by 2005. The company undertakes to support and implement innovative environmental research, to promote the development of environmental laws that are balanced and to use incentive based schemes to improve environmental performance. Protection of water quality is explicitly listed as an issue. The company further undertakes to adopt internal standards where existing law or regulation is perceived as inadequate to achieve the objective of environmental protection.

2.3.2.5 *CANFOR Environmental Policy*

CANFOR have harvesting rights to 7 million hectares of forests in British Columbia and Alberta. All the forestlands are ISO 14001 certified, as well as complying to the requirements of the Canadian Standards Association Sustainable Forestry Management Standard. Additionally, CANFOR are preparing for FSC certification. The company policy undertakes to comply with, or surpass all these standards and requirements. It commits the company not only to audits of its environmental performance, but also to regular audits of its environmental management system.

2.3.2.6 *The Forestry Stewardship Council (FSC)*

A review of the Forestry Stewardship Council and its role in forestry is relevant since most of the forestry companies discussed above have, or are pursuing, FSC certification. The factors that define a well-managed forest, according to the FSC are contained in their Principles and Criteria Document (FSC 2000). These principles relate both to natural forests and plantation forests. The FSC requires written plans to be prepared and implemented to control erosion and minimize forests damage during all mechanical disturbances (e.g. harvesting and road construction) and to protect water sources. In addition to these general forestry principles, additional principles regarding plantation forestry can be highlighted as relevant to this dissertation.

“Measures shall be taken to maintain or improve soil structure, fertility, and biological activity. The techniques and rate of harvesting and trail construction and maintenance, and the choice of species shall not result in long term soil degradation or adverse impacts on water quality, quantity or substantial deviation from stream course drainage patterns.” (FSC 2000: 8)

Additionally, the FSC principles require the regular monitoring of off-site ecological and social impacts, including effects on water resources and soil fertility.

The specific requirements for South African conditions are contained in the Qualifor requirement document issued by SGS Forestry (2002). They contain specific requirements for buffer widths and soil conservation and erosion control.

Regarding buffers, the requirements state:

“buffer zones are maintained along watercourses and around waterbodies; these buffer zones are demarcated on maps and comply with specifications made in national and regional best practice guidelines” (Qualifor Programme Main Assessment Checklist, 2002: 28)

The relevant soil conservation requirements are:

“soil degradation due to forest operations is minimised (Forest practices are controlled according to slope restrictions and soil erodibility)” (Qualifor Programme Main Assessment Checklist, 2002: 29) and

“forest operations that might degrade water bodies are identified; degradation of water bodies is minimised (For example, through siltation, physical damage, pollution, excess water use, and/or increased water runoff)” (Qualifor Programme Main Assessment Checklist, 2002: 30)

2.4 MANAGING THE IMPACTS OF SOIL EROSION

The FSC standards for forest management, referred to above, are in essence an internationally accepted Best Management Practice (BMP), with specific regional instances. Throughout the world, forestry activities are guided by such practices. The

following section will examine a selection of forestry BMPs, as they relate to erosion and sediment control specifically.

2.4.1 Best Management Practices

The Tennessee Department of Agriculture's Division of Forestry defines BMPs as "practical guidelines that can be used to lessen the environmental impact of forest management activities" (Tennessee Department of Agriculture 1993: 3). This will be the working definition for this discussion. In contrast to legislation and certification adherence to published best management practices is generally voluntary. The effectiveness of BMP implementation was reviewed by Lynch and Corbett (1990). They concluded that the consistent implementation of BMPs could minimize the impact of forestry activities on water quality. It is the lack of environmental education and half-hearted implementation that negatively affects water quality rather than a lack of appropriate management tools (Lynch & Corbett 1990). The section below presents a review of a number of forestry BMPs, from United States of America, Australia and South Africa. These countries have been selected because they are actively engaged in the development and deployment of environmental policies for commercial forestry.

2.4.1.1 *Forestry Best Management Practices Manual (USA)*

The Division of Forest Resources of the Department of Environment, Health and Natural Resources (1989) of North Carolina produced these guidelines. The document highlights the need for an understanding of soil physical properties to enable responsible management of the soil resource. The following factors are identified:

- Minimizing soil disturbance that could reduce infiltration capacity
- Avoiding operations on wet soils
- Minimizing disturbance of the ephemeral stream system
- Maximizing distance between areas of bare soil
- Minimizing changes to the micro-topography
- Ensuring surface flow is directed through undisturbed vegetation (a buffer) before entering a watercourse.

All these factors are of particular relevance to harvesting and extraction practices. Buffer width recommendations are based on the periodicity of the streams and the slope of the adjacent land. The recommendations range from 16m to 42m.

2.4.1.2 *Tennessee Department of Agriculture Division of Forestry (USA)*

This document (Tennessee Department of Agriculture 1993) acknowledges the role of roads in the production of sediment and recommends avoiding wet areas and stream channels, steep slopes (greater than 12%), erodible soils and unnecessary streams crossings during road construction. The establishment of Streamside Management Zones (SMZ) is recommended for the control of erosion, amongst other benefits. The SMZ width is determined by the slope of the area and the erodibility of the soil, and may range from 8m on level ground to 40m on a slope of 60%. Stream crossings should be avoided if possible, although the guidelines recommend that crossings always occur where streams are straight, must intersect the stream at right angles, and should not interfere with normal streamflow. Depots should not occur on areas with a gradient greater than 5%.

2.4.1.3 *Forestry Best Management Practices for Nebraska (USA)*

This set of BMPs (Nebraska Forest Service 1998) emphasizes the importance of good planning. It requires that buffers be left around streams of widths ranging from 16m to 66m, based on stream widths of less than 6m to 13m. Roads are to be left unsurfaced, but should only be used when hard and dry. The gradient of roads should not exceed 10%, and drainage water should discharge into undisturbed vegetation away from stream channels. The use of vegetation in stabilizing disturbed areas and controlling erosion is emphasized. In this regard, preference should be given to indigenous species.

2.4.1.4 *The Code of Forest Practice for Timber Production (Australia)*

This Australian code of practice was produced by the Department of Natural Resources and Environment (2001: 6) in Victoria. It states:

“Measures must be take to control timber harvesting in the vicinity of streams, drainage lines, springs, soaks, swampy ground and bodies of standing water in

order to protect them and the associated riparian vegetation from disturbance and exposure that could reduce their water quality.”

It has specific recommendations regarding minimum buffer requirements and factors that require these minimum widths to adjusted. Buffer recommendations are provided for low slope, high infiltration areas and for high slope, low infiltration areas. Specific recommendations are also provided to manage the onsite erosion potential associated with roads, harvesting areas and timber depots.

2.4.1.5 Guidelines for environmental conservation management in commercial forests in South Africa

The South African Forestry Industry Environmental Committee produced a publication containing guidelines for environmental management in plantations (Forestry Industry Environmental Committee 1995). It contains a number of specific recommendations relating to the control of soil erosion and sediment delivery to streams.

- These include prescriptions relating to site preparation for soils of different erodibility across a range of gradients, ranging from full cultivation to pitting only. Recommendations for slash management as an erosion prevention tool are included.
- The road planning and routing guidelines specifically require that soil erosion prevention be considered. Roads may not run adjacent to watercourses, and if they do a buffer zone of 20m is required. Steep roads require special surface protection. Proper road drainage must be implemented and maintained, with at least 10m of vegetation between the drainage feature exit and a watercourse. Road crossings must be at right angle to the direction of flow.

There is consensus across all the practices reviewed that roads, general harvesting areas and depots are significant features requiring special attention to minimise soil erosion. Additionally, the role of undisturbed areas, or buffers, adjacent to erosion risk areas as sediment attenuation mechanisms is recognised.

2.4.2 Buffers as sediment traps

The disturbance of the landcover associated with forestry harvesting necessarily mobilizes sediment within landscape. Research has shown that buffer zones do ameliorate the impact of the sediment on the water quality in the local watercourses. The Institute of Foresters of Australia's Water Policy Document (Institute of Foresters of Australia 2001: 1) states "(t)he best means to protect water quality is to retain a zone of undisturbed vegetation alongside as many stream lines as possible". The basic mechanisms by which sediment reduction is achieved are the reduction of overland flow velocity and the reduction in overland flow volume. A number of studies showing the utility of buffers are discussed below.

While acknowledging the general consensus that riparian buffer strips are efficient in trapping sediment, Daniels and Gilliam (1996) undertook an experiment to determine the amount of sediment trapped in buffers, motivated by the fact that vegetated filter strips are promoted as erosion control mechanism by state and federal authorities in the USA, despite there being little quantitative data regarding their efficiency. They investigated the efficiency of natural buffer strips, of varying widths, for two soil types in North Carolina for both grassed and riparian buffer zones. Their results, derived from data gathered over two years, indicate that buffers decreased surface runoff by 50% to 80%. Sixty percent of sediment was removed in the first six meters, increasing to an 80% reduction, 18m into the buffer. They concluded that buffers were effective sediment traps provided they received sediment in sheet or rill flow. The efficiency of the buffers varied from 60% to 90%. High volume, or concentrated flows which inundate the buffer strips significantly reduce their efficiency. The greater the flow distance across the buffer, the greater the amount of sediment trapped. Concentrated flow, even in grassed waterways, reduced the efficiency of the buffer strips. Their results were consistent for both buffer types and both soil types.

The influence of gradient, rainfall and distance from the edge of the fallow strip in agricultural lands was the focus of a study by Robinson, Ghaffarzadeh and Cruse (1996). The experimental grassed buffers were established to minimize the likelihood of concentrated flow. Two slope gradients were investigated, 7% and 12%. Rainfall varied during the study, with very high intensity events (5 of 13 rainfall events) accounting for

67% of the total rainfall. Soil loss was greatest if the first rainfall event after disturbance had a very high intensity. Soil loss was greatest in the steeper slopes, but the behaviour of the buffers in terms of both infiltration and sediment reduction were similar for both gradients investigated. In both instances, the first three metres of the buffer was most effective in decreasing runoff and sediment concentration, with little effect on either occurring beyond 9.1m of the buffer. Runoff reduction for very high intensity events in the first three metres was from 40% to 20% of precipitation. Nine metres into the buffer, runoff had further decreased to less than 10% of precipitation. The first three metres accounted for 70% of the sediment removal on the 7% slope buffers, while on the 12% slope buffers the first three metres removed 80% of the sediment. Sediment removal reached 85% on both gradients by nine metres (Robinson, Ghaffarzadeh & Cruse 1996). This study did not observe any decrease in buffer efficiency over time.

Lacey (2000) investigated the effect of soil disturbance on buffer strip efficiency for runoff and sediment attenuation. The study focused on assessing the impact of disturbance that arises during logging operations. Four conditions were investigated:

- Undisturbed buffer strips
- Timber extraction tracks
- Timber extraction tracks and undisturbed buffer strips
- Timber extraction tracks and disturbed buffer strips

Buffers attenuate sediment delivery by reducing the flow velocity, which in turn, promotes infiltration and reduces the sediment transport capacity of the flow. Buffer effectiveness is determined by hydraulic conductivity, slope roughness, slope length, slope gradient and slope shape. The heavy machinery used for timber extraction results in severe localized ground disturbance that increases the likelihood of soil erosion and pollution of watercourses by sediment. It was found that undisturbed buffers frequently reduced runoff by over 90%. Sediment yield reduction in both disturbed and undisturbed buffers was usually over 98% and often over 99%. It was found that 10m buffers were adequate for sediment trapping for the range of conditions investigated. Disturbed buffers, though, were more likely to fail than the undisturbed buffers. During the course of the investigation, a 1 in 11 year rainfall event occurred – despite this extreme event, undisturbed buffers trapped

almost 100% of the sediment produced. These high trapping rates were achieved even though the gradient of the study area was high (21°).

2.4.3 Vegetative barriers as sediment traps

The three studies discussed above highlight the importance of concentrated flow as a negative factor in buffer efficiency. In addition to the traditional grassed or forested buffers, vegetative barriers can function as sediment traps. Figure 2.3 illustrates the difference between vegetated buffer strips and vegetative barriers. Vegetative barriers are relevant to the discussion of concentrated flow since they can be used effectively in concentrated flow conditions. Dabney, McGregor, Meyer, Grissinger and Foster (1993) reviewed the efficiency of vegetative barriers as runoff and sediment control mechanisms.

Vegetative barriers are thin strips of stiff, erect, perennial vegetation (e.g. *Vetiver zizanioides*). They are usually established along contour lines, or perpendicular to flow in areas of concentrated flow. These barriers rely on reducing flow velocity and causing sediment deposition to occur on the backwater upslope. This is the same principal as operates in grass buffer strips, but the stiffness of the vegetation reduces the likelihood of inundation, or the vegetation becoming prone.

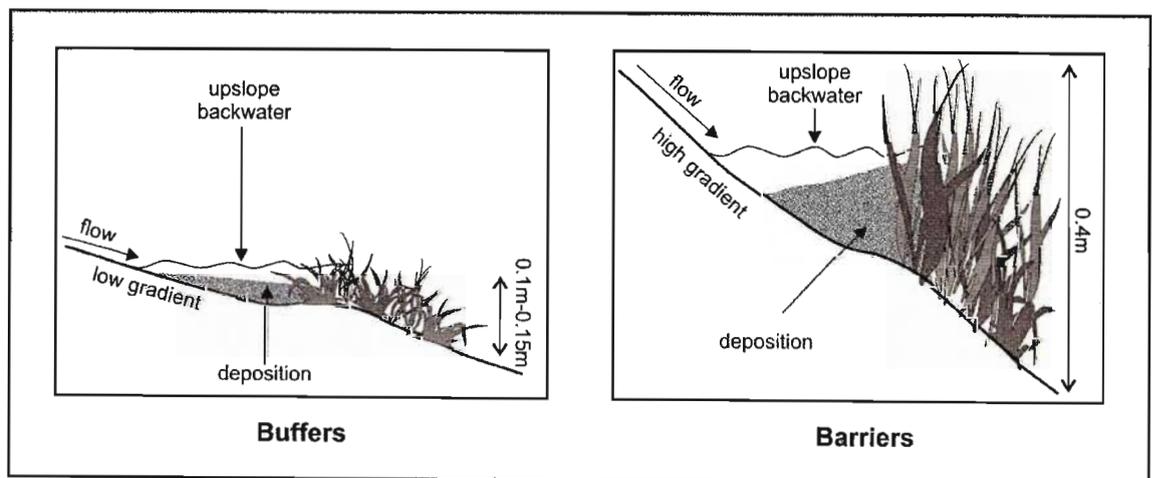


Figure 2.3: Schematic representation of barriers and buffers

Maximum backwater depth for grassed buffers is usually 0.1m while a three year old vetiver barrier can withstand backwater depths greater than 0.4m. Vegetative barriers have been used to reduce soil loss by up to 66% and water loss by 50% (Thomas 1988). In

concentrated flow areas vegetative barriers can be used to disperse the flow and to prevent the onset of gully erosion. It is vital that the established barrier extends far enough from the centre of the concentrated flow that no flow is likely to occur around the ends of the barrier (Thomas 1988). Unfortunately, the establishment of these barriers is most difficult in concentrated flow conditions, where the need is greatest. It must be noted though, that vegetative barriers require regular maintenance to ensure continued efficiency. They need to be mown regularly to manage the height (at about 0.4m to 0.5m) and to encourage thickening the barrier. The clippings can be deposited uphill of the barrier to improve the barrier's efficiency. Barriers should not be routinely burnt (Thomas 1988).

2.4.4 Review of sediment trapping efficiency

The use of buffers and barriers as sediment control mechanisms is well established. The tables below presents a summary of experimental evidence relating to the efficiency of buffers as sediment traps.

Table 2.4: Experimental evidence relating to buffer sediment trapping efficiency

Author	Trapping efficiency	Buffer type and special consideration
Neibling & Alberts (1979)	90%	• Grassed buffers
Young <i>et al.</i> (1980)	66 – 82%	• Grassed buffers
Magette <i>et al.</i> (1989)	52 – 75%	• Grassed buffers
Dillaha <i>et al.</i> (1989)	75 – 87%	• Grassed buffers
Cooper <i>et al.</i> (1987)	84 – 90%	• Natural forest buffer
Smith (1989)	87%	• Natural forest buffer
Cheschier <i>et al.</i> (1991)	90%	• Riparian forest
Ghaffarzadeh <i>et al.</i> (1992)	85%	• Vegetative filter strip • Slope effect (7% and 12%) insignificant in buffers wider than 9.1m
Castelle <i>et al.</i> (1994)	90 – 95%	• Natural forest buffer • Efficiency has non-linear relationship with buffer width
Gilliam (1994)	85 – 90%	• Natural forest buffer
Lowrance <i>et al.</i> (1995)	80 – 90%	• Natural forest buffer
Hairsine (1998)	90%	• Natural forest buffer

Author	Trapping efficiency	Buffer type and special consideration
Croke, Lane, Lacy & Fogarty (1999)	77 – 99%	<ul style="list-style-type: none"> • 6m wide buffer under variety of flow rates • Natural forest buffer • Antecedent moisture conditions do not impact efficiency • Surface roughness is critical

In addition to measuring the efficiency of buffers, researchers have investigated a number of factors that influence their efficiency. The key findings are presented in Table 2.5 below.

Table 2.5: General findings regarding buffers and sediment control

	Key findings	Authors
Deposition	<ul style="list-style-type: none"> • Most of the eroded sediment was deposited in the general harvesting area or stream buffer strips • In steep slopes with high sediment yield sediment was deposited up to 19m into the buffer • Fine sediment generated off roads is not trapped by buffers (95% transmission) and should be controlled at source 	Wallbrink <i>et al.</i> (1998) Dignan (1999) Loch <i>et al.</i> (1999)
Condition	<ul style="list-style-type: none"> • Runoff coefficients were between 5% and 25% on undisturbed buffers and as high as 97% on disturbed buffers • Up to 46% increase in sediment observed in disturbed buffers • Surface roughness is more important than antecedent moisture condition in determining buffer efficiency 	Croke <i>et al.</i> (1999)
Location	<ul style="list-style-type: none"> • All drainage lines and watercourses should have buffers between them and any sediment source • The effect of topographic convergence needs to be considered • Proximity to permanent sediment sources needs to be considered 	Hairsine (1998)

From the preceding discussion and tabular information the following conclusions can be drawn:

- Buffers are effective in trapping sediment
- Buffer widths of 10m are generally effective for sediment trapping (20m in steep areas)
- Buffer effectiveness is compromised when the buffer becomes inundated
- Buffer failure is most likely in areas of steep gradients and high runoff
- The condition of the buffer determines its efficiency
- Concentrated flow significantly compromises buffer efficiency
- Buffers are effective in relatively steep gradients (up to 21°)

- In very steep gradients vegetative barriers may be used
- Vegetative barriers can be used in concentrated flow conditions, or where available land for buffer creation is severely constrained

2.5 RIPARIAN BUFFER WIDTH DEFINITION

Recent South African legislation seems to have changed from having a prescriptive function into the provision of a framework of principles within which the industry has to self-regulate for legal compliance. Additionally, the adoption of forestry accreditation systems such as the Forestry Stewardship Council and ISO 14001 based systems require the industry to conduct itself in an environmentally responsible manner to ensure a market for its products. A requirement of both these systems is that the industry conduct its activities in compliance with the laws of the country in which the forestry activities occur.

The most fundamental question of riparian buffer design relates to the width of the buffer. In 1932, the Department of Forestry in South Africa adopted a policy prohibiting afforestation within 20m of a perennial stream. The policy applied only to state-owned forests, but was accepted to a limited degree by the industry in general. In 1969 the then Soil Conservation Act regulated a minimum buffer width of 20m, although this was not implemented uniformly in the country. A 1972 amendment to the Forest Act of 1968, Act No. 46 of 1972, again enforced a buffer width of 20 metres. The Conservation of Agricultural Resources Act (Act No. 43 of 1998) requires that plantation forestry not occur within 30m of the 1:50 year flood line of waterbodies. Despite there being clear legislative requirements in terms of buffer width, the utility of standard buffer width requirements is debatable. Specifically with regard to sediment control, buffer widths need to be established considering the sediment load on a particular stream reach. Given the wide range of environments in which commercial forestry occurs in South Africa, as well as the increasing environmental pressure on the industry, a scientifically defensible method for assessing erosion risk and developing buffer width recommendations is required.

Three specific methods for defining buffers, or establishing a buffer width will be discussed, The Bosch model (Bosch, Berliner & Le Maitre 1993) previously used by the South Africa forestry industry, the current procedure used by the forestry industry in South Africa

(Landuse and Wetland/Riparian Habitat Working Group 1999), and buffer definition methods that are based on hydrological principles as investigated by Bren (1998a, 1998b, 1999a, 1999b).

2.5.1 The Bosch Model

Until recently the width of buffers in commercial forestry areas in South Africa were determined using the Bosch model (Bosch, Berliner & Le Maitre 1993). This was a rule-based system for establishing the minimum buffer widths for any given stream. A number of conditions were identified that would increase the buffer width recommendation derived by applying the model. This method was designed to make buffer width recommendations for water quantity and quality. Conservation of riparian habitats and biodiversity were secondary considerations.

The Bosch model highlights three factors as important in determining minimum buffer widths.

- **Average stream channel slope**
Steep slopes are perceived as thoroughly and rapidly draining, meaning water will accumulate in lower slopes and valley bottoms
- **Stream order**
Indicates the upstream contributing area. The higher the stream order, the larger the upstream contributing area and the wider the saturated zone is likely to be.
- **Stream profile**
Concave stream banks will collect and store more water creating wider saturated zones

Everard, vanWyk and Viljoen (1994) present the model's three operational methods, the Quick method, the Manual procedure, and the Computer model. The first two of these will be discussed, since the third method is essentially an automated edition of the second. The selection procedure for the methods is presented below in Table 2.5.

Table 2.5: Bosch method selection criteria (Everard, van Wyk & Viljoen 1994)

Downstream water use*	High		Low	
Potentially contentious	Yes	No	Yes	No
Decision method to use:	Computer model	Manual procedure	Manual procedure	Quick method

Downstream water use is regarded as high if water is extracted directly from the stream or immediately downstream of the catchment

2.5.1.1 The Bosch-based Quick Method

The quick method provides a simple way of selecting between three minimum buffer widths based on a series of questions. It is presented in a tabular format (Everard, van Wyk & Viljoen 1994) below.

Table 2.6: The Bosch Quick Method

Minimum width	Criteria for excluding each minimum width
10m	<ul style="list-style-type: none"> The stream in question is a third order stream Water is extracted directly from the stream for use Slope of the stream bank is less than 20° and soils are deeper than 90cm There is high conservation status natural vegetation wider than 10m adjacent to the stream The area in question is a wetland
30m	<ul style="list-style-type: none"> Water is extracted directly from the stream for use Slope of the stream bank is less than 10° and soils are deeper than 150cm There is high conservation status natural vegetation wider than 30m adjacent to the stream
40m	<ul style="list-style-type: none"> A drainage density of more than 30m per ha

2.5.1.2 The Bosch-based Manual Procedure

The procedure is summarized in the tables below.

Table 2.7: Bosch Manual Procedure

Step	Guidelines
1 Classify all rivers according to their relative importance	<p>Class 1a There is perennial flow at the confluence with the next stream</p> <p>Class 1b Area is a depression with high water-holding capacity</p> <p>Class 1c Wetlands</p> <p>Class 2 Intermittent streams, baseflow occurs only a few times a year</p> <p>Class 3 Dry watercourses with no baseflow</p>

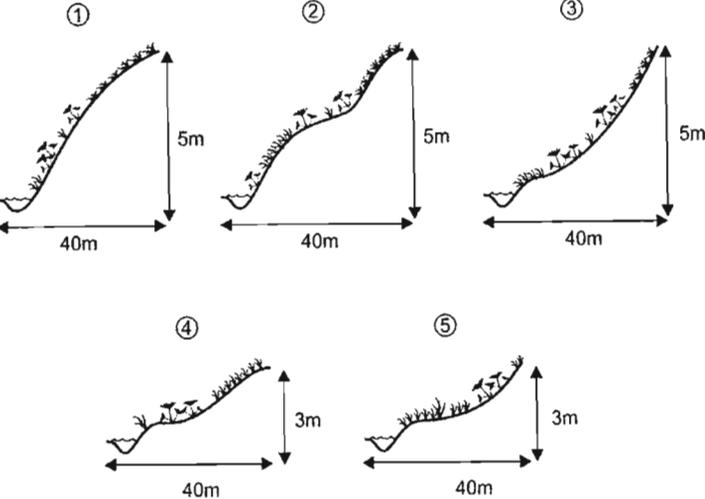
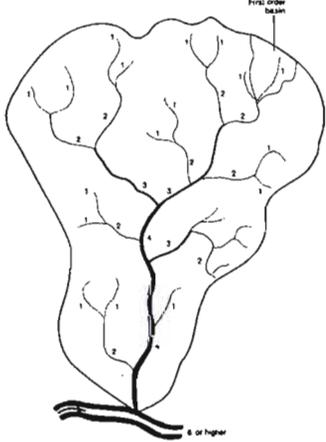
Step	Guidelines
<p>2 Divide streams into uniform sections based on slope, order and profile</p>	<p>Classification allows for 'give and take' in conservation prioritisation</p> <p>A. Select profile from figures below</p>  <p>B. Determine Hortonian stream order</p>  <p>C. Determine slope</p>
<p>3 Use table to determine minimum buffer width</p>	<p>Refer to Table 2.8 below</p>
<p>4 Evaluate if any overriding conditions exist</p>	<p>IF: Indigenous forest occurs in the catchment THEN: Forests, in their total extent, should not be disturbed</p> <p>IF: One or more exclusion zones can be used as a fire break THEN: Make zone(s) the width required for a fire break if this is greater than the minimum width obtained from Table 2.8 below</p> <p>IF: Streams form deeply-incised gorges inaccessible by roads THEN: Protect entire gorges by establishing trees in such a way that they will not fall into the gorge during thinning or clear felling.</p> <p>IF: Wetlands or vleis occur in the catchment THEN: Give careful consideration to afforestation programme in general and call in an hydrological expert.</p> <p>IF: Class I(b) areas have been identified THEN: All areas where mottling in soils occurs above 1,2 m should not be planted as they are seasonally water logged.</p> <p>IF: Species planted is <i>Eucalyptus</i> AND stream is class 1 THEN: Add 10 m to the minimum width calculated using Bosch matrix table</p>

Table 2.8: Bosch Matrix Table

Stream order	Profile	0 – 5°	6 – 10°	11 - 20°	21 - 30°	30° >
		Min. width (m)				
1st	1	0	0	0	0	0
	2	10	0	0	0	0
	3	15	10	0	0	0
	4	20	15	10	10	0
	5	25	20	15	15	0
2nd	1	25	15	10	0	0
	2	30	20	15	10	0
	3	40	25	20	15	10
	4	40	30	25	20	15
	5	50	40	30	25	20
3rd	1	40	40	25	10	-
	2	50	40	30	15	-
	3	50	50	40	25	-
	4	60	-	-	-	-
	5	60	-	-	-	-
4th	1	40	40	25	-	-
	2	40	40	25	-	-
	3	50	50	25	-	-
	4	60	-	-	-	-
	5	60	-	-	-	-

The Bosch model has been superseded by a new industry standard for identifying and delineating riparian and wetland habitats devised by the Landuse and Wetland/Riparian Habitat Working Group (1999). The reason for adopting a new procedure was to overcome the perceived subjectivity contained in aspects of the landscape assessment associated with the Bosch Model, as well as to introduce hydrologically sound riparian area identification procedures (L. Jarvel *pers. comm.* 2001, D. Everard *pers. comm.* 2001).

2.5.2 The procedure for identification and delineation of riparian and wetland habitat

Unlike the previous method, and most others reviewed, this method emphasizes the accurate delineation of the actual riparian or wetland¹ zone based on soil, vegetation and hydrological criteria (collectively called 'habitat' in the documentation), rather than the definition an appropriate buffer width from a watercourse, based on topographic or stream morphological characteristics. In addition to establishing the boundaries accurately, the

¹ 'Riparian' should be regarded as an inclusive term for all riparian and wetland habitats in subsequent discussion

method proposes a standard minimum buffer width of 20 metres, but issue a number of caveats in this regard.

- There will be specific instances in which buffers may be enlarged or reduced
- In timber areas, any deviations must be documented in an auditable format, compliant with the National Water Act (Act No. 36 of 1998), ISO 14001 or FSC
- This recommendation is 'hydrologically' driven, giving no consideration to biodiversity conservation or sediment delivery management

The method proposes classifying watercourses into three categories, the primary determinant of which is baseflow. The characteristics of the three classes are presented in Table 2.6 below.

Table 2.6: Characteristics of the three watercourse classes (Landuse and Wetland/Riparian Habitat Working Group 1999)

Characteristic	Class A	Class B	Class C
Baseflow	Never	Intermittent	Permanent inundation
Gradient of hillslope	Steep	Moderate	Gentle
Gradient of channel slope	Steep	Moderate	Gentle
Width of floodplain	None	None or very narrow	Narrow to broad
Nick point	None	Difficult to detect	Prominent
Depth to water table	Deep	Very shallow to zero	Zero
Slope of water table	Flat	Domed or flat	Sloping in
Ground / surface water interaction	Recharge surface to ground	Recharge or discharge	Discharge ground to surface
Flow regime	Ephemeral	Ephemeral wet season	Perennial flow
Degree of meander	None to very little	None to moderate	Moderate to senile
Residual channel pools	Never	Often	Permanent inundation
Erosion and deposition in the channel	Channel bed erosion	Deposition: coarse material	Deposition: fine material

Additional information, as presented in the Guidelines, relating to the three classes are listed below:

Class A watercourses

- Are 1st order streams
- Are steep and have steep lateral hillslopes
- Are likely to be eroding areas
- Do not have a riparian habitat (no distinctive vegetation or soils)
- Are the least hydrologically sensitive watercourses
- May have perched water tables, “mini wetlands” (Landuse and Wetland/Riparian Habitat Working Group 1999: 11), associated with them
- Need special protection (no planting, no tillage, no vehicles) along the drainage lines to prevent soil erosion (though no indication is given regarding the width over which the protection measures need to be implemented)

Class B watercourses

- Are situated in the fluctuating regional water table zone
- Are marked by the most headward extent of baseflow during wet periods
- May be associated with residual pools due to proximity to regional water table
- May be associated with the initial signs of floodplain development (deposition)

Class C watercourses

- Are perennial due to permanent contact with the regional water table
- Usually have low gradients and an associated floodplain

It is significant that the method specifically identifies Class A watercourses as being associated with erosion, Class B watercourses with deposition of coarse sediment and Class C watercourse with the deposition of fine material. In addition to classifying the watercourses, the method requires preferential recharge zones to be identified and managed appropriately. These are areas in the catchment that expedite the movement of surface

water to the water table via direct paths, for example fractured rocks, riparian or fault zones. No specific buffer width recommendations are made for the three watercourse classes. The three classes of watercourse are presented graphically in Figure 2.4.

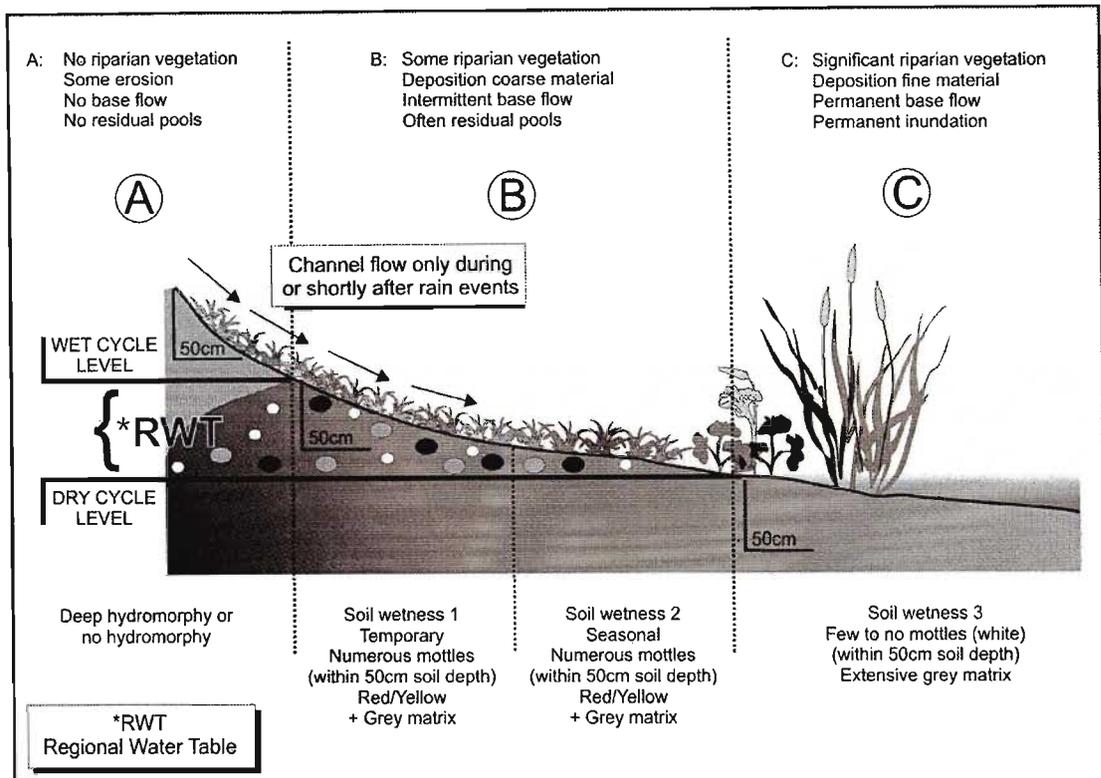


Figure 2.4: Combined stream classification procedure (Landuse and Wetland/Riparian Habitat Working Group 1999)

Kotze, Klug, Hughes and Breen (1996) identified three zones associated with riparian habitats based on the frequency of inundation; temporary, seasonal and permanent. These are presented graphically in Figure 2.5. Critical to the implementation of this new procedure within the forestry industry, is the effective delineation of the outer boundary of the riparian zone, the edge of the area of temporary inundation. There are four specific indicators associated with riparian areas – terrain morphological unit, vegetation, soil form and soil wetness factor.

Terrain morphological unit

- Riparian zones are usually associated with valley bottom units (Terrain Unit 5, McVicar *et al.* 1977)

- Typically occurs in depression areas, which may occur in any other terrain morphological unit
- This is an important factor because it eliminates areas where hydromorphic soil dominate that are not riparian areas (e.g. Zululand Coastal Plain)

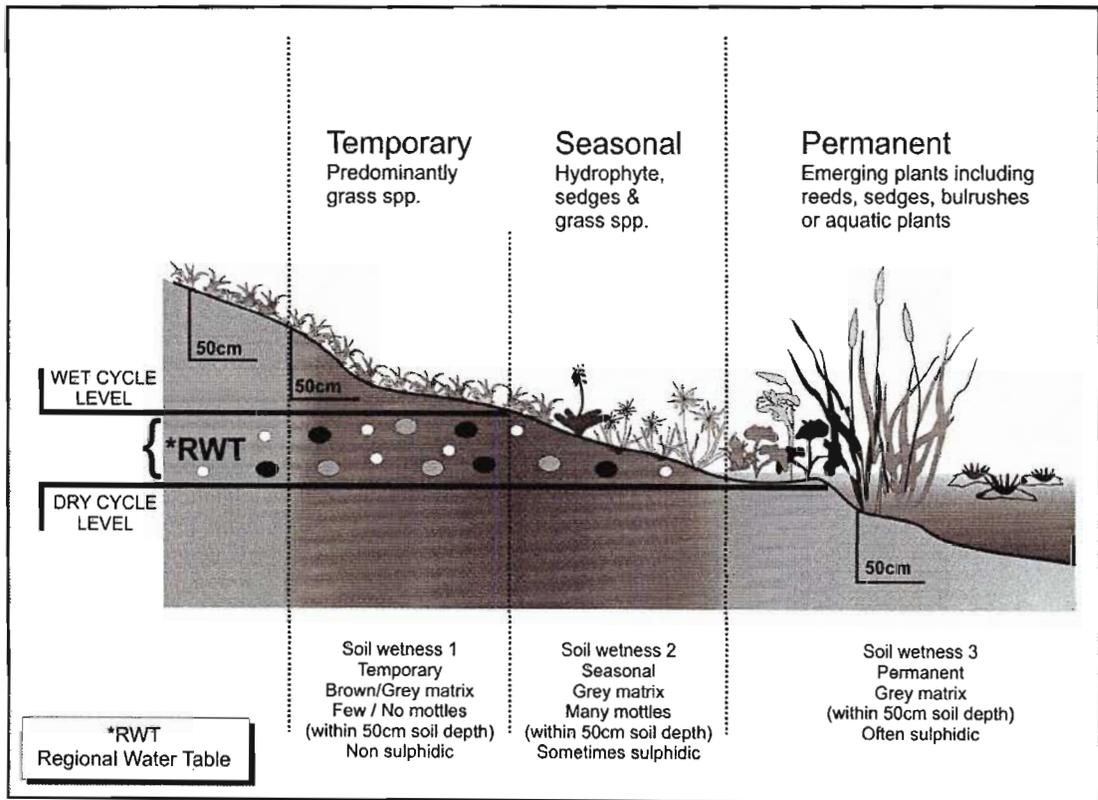


Figure 2.5: Combined riparian area identification procedure (Landuse and Wetland/Riparian Habitat Working Group 1999)

Vegetation

There are four categories based on their probability of occurring within wetlands (Reed 1988).

- Obligated wetland species – 99% of occurrences associated with wetlands
- Faculative wetland species – 67% to 99% of occurrences associated with wetlands
- Faculative species – 34% to 66% of occurrences associated with wetlands
- Faculative dryland species – usually grow in non-wetland areas, between 1% and 34% of occurrences associated with wetlands

Appendices to the Guidelines help to identify the obligated and facultative wetland species. If these species cover more than 50% of the area, it is a riparian area. If the cover is less than 50%, it may still be a riparian area. If these plants are not present it is not a riparian area. It is critical to consider that if the degree of wetness has been changed for a period of time, the vegetation may not reflect the hydric nature of the area.

Soil form

- The permanently inundated areas will have one or more of the following soil forms (Soil Classification Working Group, 1991) present: Champagne, Katspruit, Willowbrook or Rensburg
- Seasonal and temporary inundation areas will have one or more of the following present: Kroonstad, Longlands, Wasbank, Lamotte, Estcourt, Klapmuts, Vilafontes, Kinkelbos, Cartref, Fernwood, Westleigh, Dresden, Avalon, Glencoe, Pinedene, Bainsvlei, Bloemdal, Witfontein, Sepane, Tukululu, Montagu, Inhoek, Tsitsikamma, Houwhoek, Molopo, Kimberley, Jonkersberg, Groenkop, Etosha, Addo, Brandvlei, Glenrosa or Dundee.

Soil wetness factor

- There must be signs of wetness within 50 centimetres of the soil surface
- Assessed by examining the chroma, mottles and the grey matrix level

2.5.3 Hydrological models for buffer width determination

The methods described above are meant to be functional and relatively easy to implement. Essentially both are constant width methods, the difference between the two being the derivation of the edge of the feature to be buffered. However, Bren (1995, 1998a, 1999a) questioned the validity of constant buffer width approaches regardless of how the edge of the feature is defined. Bren's concerns arise from both the questionable hydrological validity of such approaches, as well as a consideration of the potential loss of utilizable area to stream buffers, an important consideration in South Africa where the potential for forestry expansion is severely constrained by available water resources. These concerns are echoed by Fried, Zweifler, Gold and Brown (1999).

Bren (1998b) established that the geometric complexity of buffer features was highest in buffers defined with small buffer widths (10m), decreasing with an increase in buffer width. This complexity, it is argued, would make the management of such buffers “difficult to administer” (Bren 1998b: 8). However, the accessibility of areas external to the buffer decreased while the complexity of the buffer / non-buffer mosaic increased as buffer width increased. With wide buffers, the potential for maintaining areas absolutely undisturbed is substantially reduced, since passage through buffers will have to be established to reach the ‘islands’ of harvestable timber.

Bren (1998b, 1999b) argues that an advantage of hydrological approaches are that subjective judgments regarding buffer width can be avoided by implementing computerized models of hydrological loading. Hydrological loading can be defined either by constant loading or by absolute convergence.

The method of constant hydrological loading was presented by Bren (1998b). Buffer width is defined by a ratio between buffer area and upslope contributing area. This ensures that each stream segment is equally protected. In the approach using absolute convergence, buffer width (Bren 1999b) is determined by defining an acceptable threshold ratio between upslope contributing area per unit length of contour line. The threshold needs to be determined by field observations of the onset of gully erosion. An advantage of this method is that upslope areas of high convergence, without a distinct watercourse, are adequately protected. This result is controversial in Australia, as it would no doubt be in South Africa where first order streams are described as “the least sensitive watercourses in terms of hydrological processes” (Landuse and Wetland/Riparian Habitat Working Group 1999: 10). The research undertaken by Daniels and Gilliam (1996: 251) produced similar findings, “(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.

Bren (1998b, 1999b) described the spatial application of these methods as computationally intensive. Unfortunately, in applying these methods, Bren concludes that the results of the analysis are counter-intuitive in many instances, and given the variation in buffer width along a watercourse, extremely difficult to implement. The information requirements are

higher than traditional buffer delineation methods. It is further concluded (Bren 1998b, 1999b) that traditional methods best meet forest manager's needs, since they isolate conflict to the issue of where streams start. The recommendation arising from this research (Bren 1999a,b) is that managers should consider a widening of the buffer in convergent areas, and a reduction in divergent areas.

2.6 SYNTHESIS

Two key issues can be identified from the discussion in this chapter. Firstly, soil erosion and sediment delivery to streams are regarded as the most significant pollution problems associated with commercial forestry. The most important sediment source areas are roads, extraction tracks, depots and harvesting areas. Sediment delivery to streams is strongly influenced by the degree of road-stream connectivity. Secondly, riparian buffer zones (including wetlands) are effective in reducing the sediment load in surface runoff. The use of these landscape features is an integral part of the erosion management strategies throughout the world. A number of approaches to defining buffer widths have been described, but none of these are designed to address the specific role of reducing sediment delivery to streams.

The critical factor in designing any erosion control strategy is ensuring that the benefits of any intervention are optimised. In order to achieve this one needs to establish the areas likely to be producing sediment, the paths along which it will be delivered to streams, as well as any natural features that can be incorporated into a landscape-scale erosion control plan.

Many factors have been identified that contribute to the occurrence and severity of erosion. It is not possible to change the physical factors such as terrain morphology, soil structure and climatic conditions. Therefore, it is necessary to concentrate management interventions on the contributing effect of factors that are manageable, and to establish priorities between the specific occurrences of these manageable factors. Figure 2.6 presents the problem, the impacts and the opportunities for managing soil erosion within the context of commercial forestry.

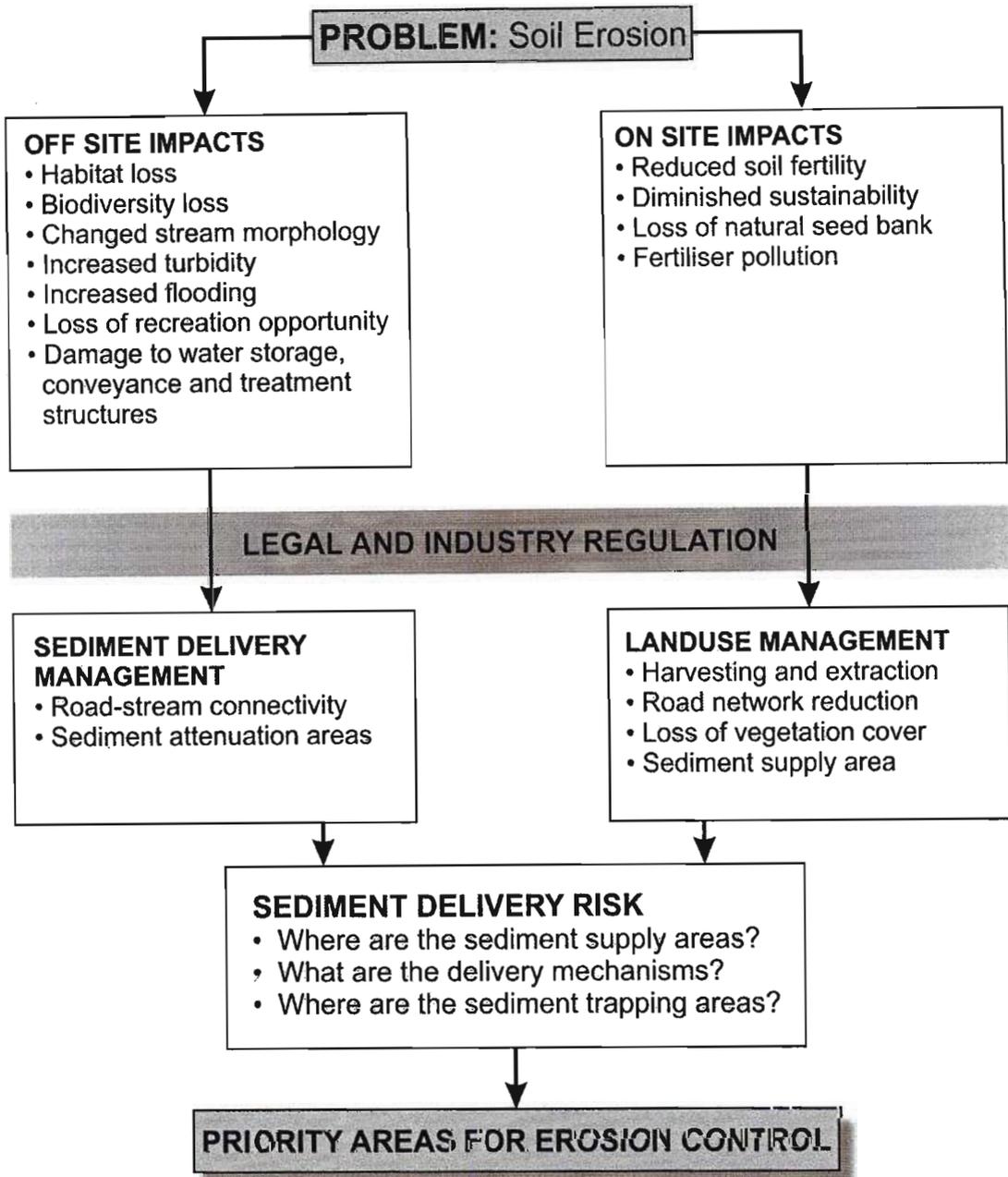


Figure 2.6: Factors contributing to the identification of priority areas for erosion control

2.7 METHODOLOGY

This dissertation will endeavour to provide answers to the three questions in Figure 2.6 through the application of spatial models. Specifically, the models will attempt to do the following:

- Identify areas of sediment supply within the landscape, using established erosion models
- Identify the sediment delivery mechanisms
- Identify potential landscape elements that can act as sediment traps

Methods to address these issues will be presented in the following two chapters. Chapter 3 will present the method for identifying sediment supply areas. Chapter 4 will present the methods for identifying the sediment delivery risk and potential attenuation features. In each chapter the explanation and rationale for the adopted approaches will be presented. The methods will be illustrated using two scales; a small representative land-unit within the larger study area as well as the entire study area. Where appropriate, finer scale maps depicting a representative land-unit will be presented.

2.8 THE CASE STUDY AREA

The Water Research Commission has undertaken a project that is focused on the development of tools for riparian zone management and river rehabilitation. The catchment selected by the research project team for prototyping and developing the methods was the Mhlatuze catchment. The uppermost quaternary catchment (W12A) has extensive commercial forestry areas.

Three blocks of the Mooiplaas plantation owned by Sappi Forests, were selected as the case study area since these cover a variety of terrains, from steep, hilly areas adjacent to the Mhlatuze river to areas of low slope in the higher lying areas. The remaining two blocks of the plantation fall outside the Mhlatuze catchment. The accessibility of data was another consideration that made this plantation a suitable case study area. Figure 2.7 shows the location of Mooiplaas study area in the Mhlatuze catchment. Table 2.7 presents the data used in the case study, and the data sources.

Table 2.7: Data used in the case study

Data	Source	Usage
Elevation	Sappi Forests	5m contours were used to develop the digital elevation model (using ArcInfo TopoGrid)
Streams	Sappi Forests	Observed streams used as input into TopoGrid Used in sediment risk modelling
Roads	Sappi Forests	Used in sediment risk modelling
Digital Terrain Model	Derived (10m resolution)	Used in sediment supply modelling Used in all aspects of terrain analysis Used in derivation of hydrological networks Used in catchment delineation
Soils	Sappi Forests	FSD standard soil database assessed for input into sediment supply modelling
Landtypes	Agricultural Research Council	Derived soil erodibility information used in sediment supply modelling

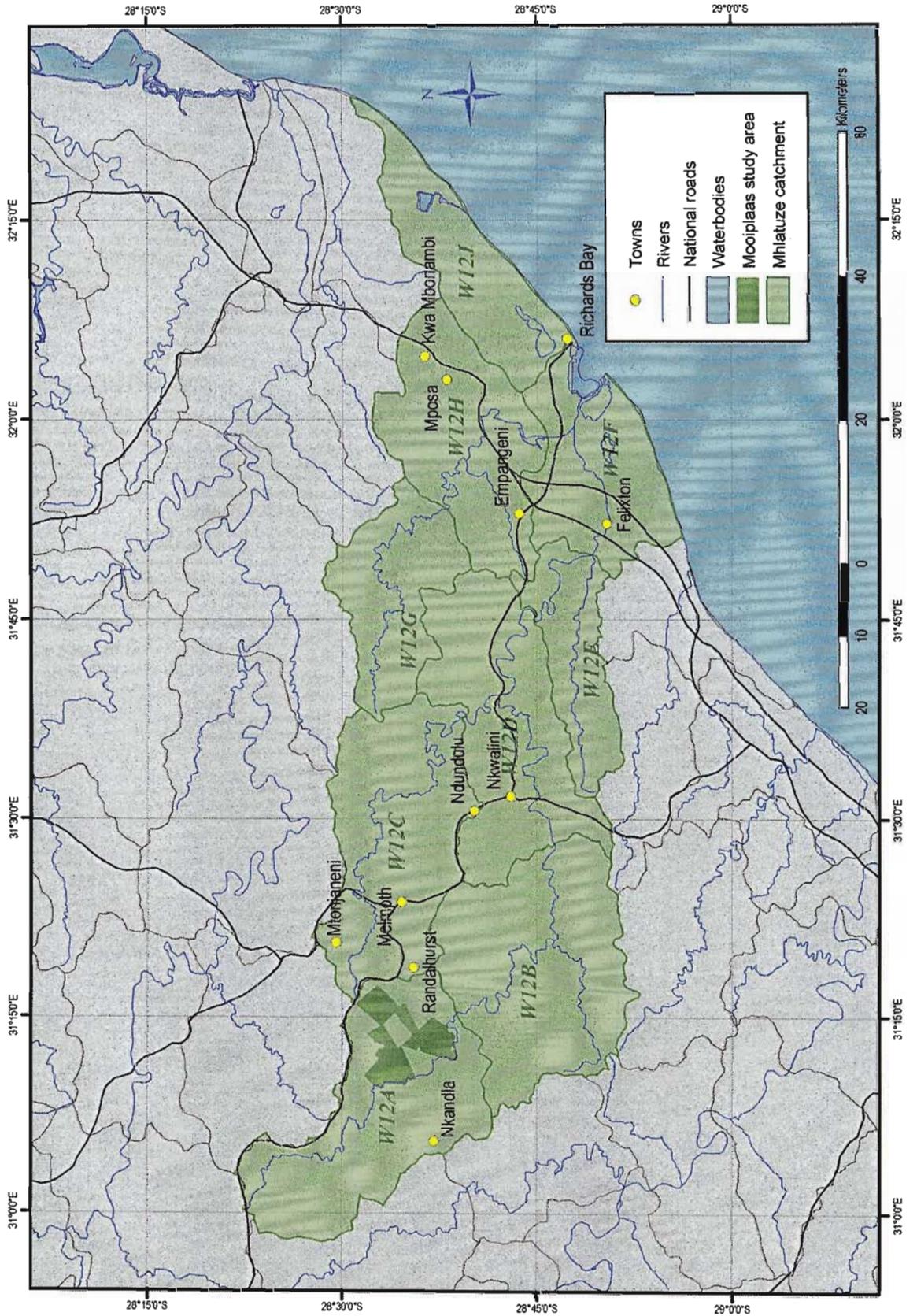


Figure 2.7: Location of the study area within the Mhlataze catchment

Figure 2.8 presents the location of the representative landunit within Mooiplaas plantation. It is a small micro-catchment, 66 hectares in size, selected for its utility in demonstrating the modelling procedures.

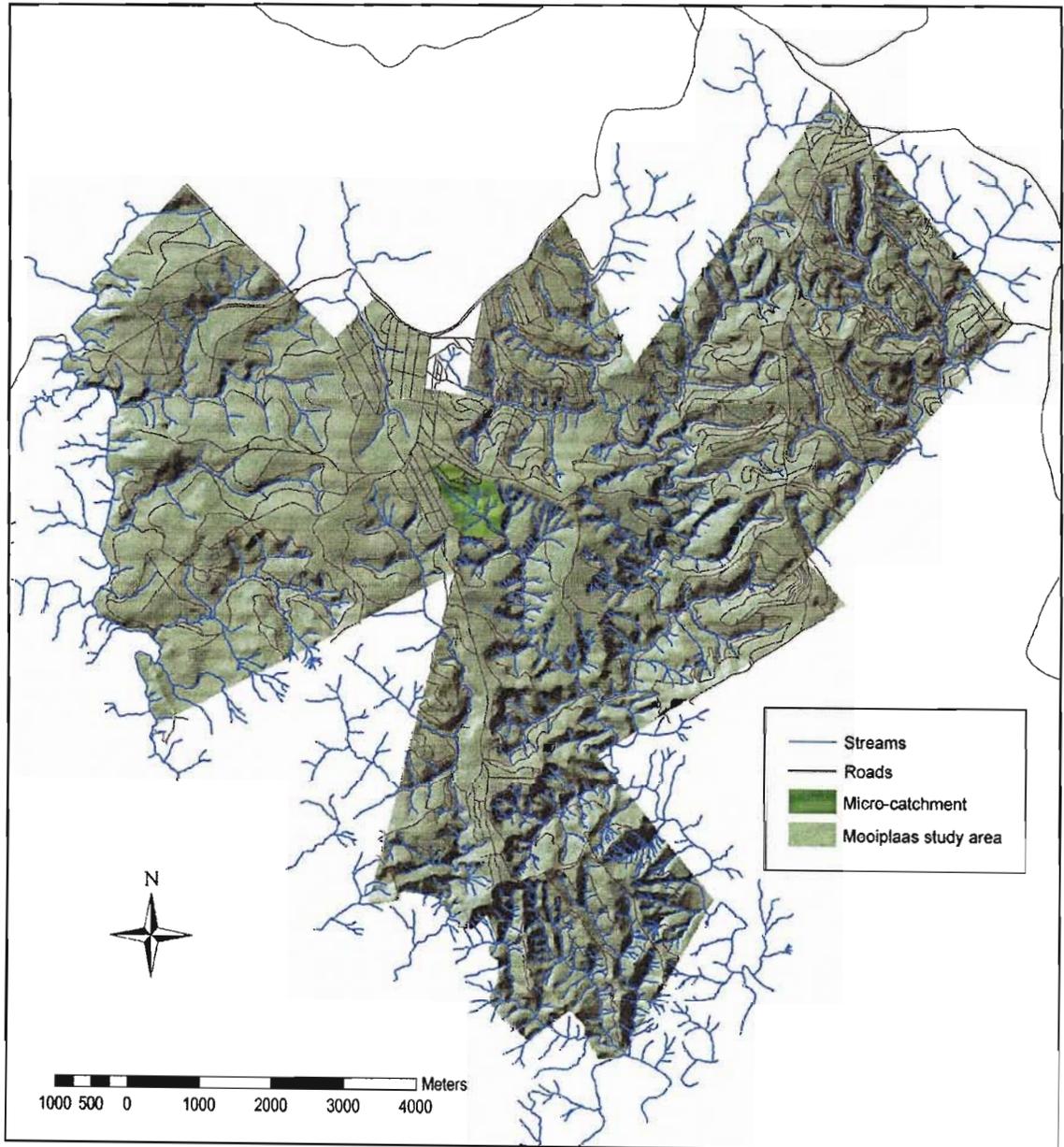


Figure 2.8: The position of the illustrative micro-catchment within Mooiplaas plantation

CHAPTER 3: IDENTIFYING AREAS OF SEDIMENT SUPPLY

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 erosion².

While more complex models that attempt to 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. These include ANSWERS (Beasley, Huggins & Monke 1980), CREAMS (Knisel 1980; Foster, Lane, Nowlin, Laflen & Young 1981), KINEROS (Woolhiser, Smith & Goodrich 1990) AGNPS (Young, Onstad, Bosch & Anderson 1987) and WEPP (Lane & Nearing 1989). The data requirements of these models are more extensive than those of the empirical models.

The level of detail that can be derived from the application of process models exceed the requirements of this research, which is to identify the relative erosion potential across the landscape. The USLE-based models will be implemented in this research due to data limitations and the fact that they satisfy the requirements of the research, principally to determine a relative assessment of erosion potential across the landscape.

3.1 THE UNIVERSAL SOIL LOSS EQUATION

There seems some confusion about the exact date of the publication of the USLE in the literature, but Renard, Lane, Foster and Laflen (1996) set the date as 1965, the publication date of the USLE in Agriculture Handbook 282 by the U.S. Department of Agriculture. The USLE is an empirically derived model, developed for application in sediment supply areas within agricultural lands.

The USLE equation is given as:

$$A = R \cdot K \cdot LS \cdot C \cdot P \quad (1)$$

² Unless referring to specific revisions of the basic USLE, the modelling procedures undertaken for this dissertation will use the term USLE to describe all models based on the A=RKLSCP formula.

where

- A = the computed long term average soil loss per unit area ($\text{t.ha}^{-1}.\text{annum}^{-1}$)
- R = an index of rainfall erosivity ($\text{MJ.mm.ha}^{-1}.\text{h}^{-1}.\text{annum}^{-1}$)
- K = soil erodibility factor ($\text{t.h.MJ}^{-1}.\text{mm}^{-1}$)
- LS = combined flow length and gradient factor (dimensionless)
- C = cover and management factor (dimensionless)
- P = support practice factor (dimensionless)

It is important to note that the USLE is not suitable for application in areas that are not sediment supply areas. Since its publication, the USLE has undergone regular revisions, notably the sub-factor method for estimating cover management factor introduced in 1970, and the inclusion of data from rainfall simulations in 1978.

The most major revision of the USLE started in 1985 and was completed in 1991. It resulted in what is known as the Revised Universal Soil Loss Equation (RUSLE). RUSLE retains the basic form of the USLE equation but the derivation of the factors was significantly modified, to include aspects of the process methods (ratio of rill and interrill erosion) developed as part of the Water Erosion Prediction Project (Lane & Nearing 1989). Importantly, the model was computerised and extensive databases developed to accompany the model, which improve its utility in non-prototype conditions (Renard, Lane, Foster & Laflen 1996).

The third adaptation of the USLE presents a modification for event-based estimation of sediment yield, rather than long-term yield predictions. The MUSLE (Williams & Berndt 1977; Williams 1982) replaces the rainfall erosivity factor with a runoff term derived from the event-based runoff volumes and peak-flow rates. This development enabled event-based predictive capability of sediment yield, which is implemented in the ACRU model (Schulze 1995).

3.2 DERIVING THE SUB-FACTORS

Most of the factors required in the USLE equation can be readily determined for a particular site. The rainfall erosivity index can be determined in southern Africa by information presented by Smithen and Schulze (1982).

Smithers *et al.* (1995) present various methods for establishing the soil erodibility (K) factor. It can be estimated from the soil form and series of the Binomial Soil Classification (McVicar *et al.* 1977), or the form, family and textural class of the Taxonomic Soil Classification (Soil Classification Working Group 1991). It is possible to derive a value for this factor from the soil erodibility class, which was established for southern Africa by the erstwhile Department of Agricultural Technical Services in 1976. Where detailed soils information is available, the nomograph developed by Wischmeier, Johnson and Cross (1971) can be used. This method requires detailed soil particle distribution and percentage organic matter information.

The C factor related to landcover is identified as being the most important because it represents conditions that can be easily managed to reduce erosion (Renard, Foster, Weesies & McCool 1991). The support practice (P) factor represents how surface conditions affect flow paths and flow hydraulics, and represents the broad general effects of practices such as contouring. Both can be established for South African conditions by referring to Smithers *et al.* (1995) in Smithers and Schulze (1995).

Unlike the factors already discussed, the LS factor has been the subject of much debate regarding the USLE (Moore & Burch 1986; Moore & Wilson 1992; Foster 1994; Moore & Wilson 1994). The reason for the debate is the perceived degree of subjectivity required to determine the flow length (L) sub-factor of the slope length (LS) factor.

The flow length factor is defined as the distance from a point of origin of overland flow to the point where either the slope gradient decreases sufficiently for deposition to take place, or the runoff enters a well-defined natural or artificial watercourse (Wischmeier & Smith 1978). Assessing where channels form, or deposition begins to occur is difficult. It is scale dependent and particularly difficult to accomplish at a catchment scale.

Moore and Burch (1986) interpret the LS factor as a measure of the sediment transport capacity of overland flow. According to Moore and Burch (1986) the empirically derived LS factor for USLE is responsible for inconsistencies and underestimations of erosion that have appeared due to its failure to account for all sediment transport mechanisms. In particular, the inability of the USLE to distinguish between or consider the implication of rill and sheet erosion is seen as problematic. In response to this problem, Moore and Burch (1986) propose a method for deriving the LS factor based on unit stream power theory.

Three spatial applications of the USLE-based erosion models will be examined in the following section. Each of these presents a different method of developing the LS factor in the equation.

3.3 SPATIAL APPLICATION OF USLE-BASED APPROACHES

Various attempts have been made to apply the USLE spatially using Geographic Information Systems (GIS). Three have been selected, each illustrating a different approach to the spatial application of USLE-based models (Mander, Quinn & Mander 1993; Kienzle & Lorentz 1993; Engel 1999). All spatial applications of the USLE reviewed acknowledged the contentious nature of estimating an accurate LS (Slope Length) factor. Mander, Quinn and Mander (1993) used a method developed by Schulze (1979), based on the slope of the landscape. Kienzle and Lorentz apply the approach reported in Renard *et al.* (1991). Engel (1999) uses the equation developed by Moore and Burch (1986) that is based on flow accumulation and slope. Each of these spatial applications will be examined in more detail.

3.3.1 Mander, Quinn and Mander (1993)

The Umhlali / Umvoti Environment Committee approached the Institute of Natural Resources to assist in the development of a rehabilitation plan and management guidelines for riparian areas in the Umhlali catchment in 1993. Mander, Quinn and Mander (1993) advocate a two-pronged approach to developing erosion management interventions; firstly identifying areas of greatest erosion potential and high priority for rehabilitation, and secondly implementing a system to assist landowners identifying conservation or rehabilitation measures appropriate to the site, by implementing a decision support system.

Mander, Quinn and Mander (1993) selected the USLE to identify areas of high erosion potential since it is the most widely used estimator of long term average annual soil loss according to Wischmeier and Smith (1978). In addition, components of the equation have been extensively researched for South African conditions (Schulze 1989). The landcover and management factor and the support practice factor, however, were not included in this analysis. The decision to base the erosion prediction entirely on topography was driven by the need to eliminate any implicit criticism of the farmer's land management practices, which, it was hoped, would improve the acceptability of the decision support system to the farmers. Factors included in the model were soil erodibility, slope-length and gradient. Homogeneous rainfall erosivity across the 10 km² catchment was assumed.

The soil erodibility factor was derived from landtype information supplied by the then Soil and Irrigation Research Institute. Soil information is presented within landtypes that can be further subdivided based on terrain unit. Mander, Quinn and Mander (1993) obtained landtype boundaries from the Institute for Soil, Climate and Water Research. Terrain units occurring within each landtype were manually delineated. An erosion hazard rating was assigned to each unique by area weighting the erosion hazard rating (Smithers *et al.* 1995) of each soil form, for each soil form occurring within every landtype/terrain unit combination.

The flow length subfactor (L) was derived by applying Schulze's (1979) method for estimating slope length based on gradient, a method Schulze (1979) himself describes as 'tenuous'. Schulze's (1979) approach is give in Equations 2 and 3 below.

$$L = -3.0S_{\%} + 100 \text{ for } S_{\%} < 25 \quad (2)$$

and

$$L = 25 \text{ for } S_{\%} \geq 25 \quad (3)$$

where

$$\begin{aligned} L &= \text{flow length (m)} \\ S_{\%} &= \text{gradient in percent} \end{aligned}$$

Gradient was determined using SPANS GIS. The primary data was 5m contours digitized from 1:10 000 orthophoto maps, from which a digital elevation model (DEM) was derived.

The combined flow length and gradient factor (LS) was determined using the original USLE sub-factor derivation formula (Wischmeier & Smith 1978).

$$LS = \frac{[L \div 22.1]^m \cdot (430S^2 + 30S + 0.43)}{6.613} \quad (4)$$

where

L	=	slope length (m)
S	=	slope of land expressed as a fraction (S _% /100)
M	=	0.3 for slope < 0.03
	=	0.4 for slope < 0.05 and ≥ 0.03
	=	0.5 for slope ≥ 0.05

Applying the USLE to spatial datasets of slope, slope-length and soil erodibility derived a surface the authors described as ‘topographic erosion potential’. This dataset was used to identify riparian zones adjacent to areas of high erosion potential, and prioritise these for rehabilitation. Areas identified as having high erosion potential correlated well with observed erosion during field visits although this was not assessed quantitatively, and the modelling technique “was found to be a sufficiently good predictor of erosion” (Quinn, Breen & Hearne 1993: 8).

3.3.2 Kienzle and Lorentz (1993)

The identification of nutrient and sediment transport through a catchment is regarded as among the most important tasks associated with integrated catchment management by these authors. The research applied the RUSLE, using the raster module of ArcInfo GIS (GRID), to develop a spatial distribution of sediment yield in the Henley Dam catchment in KwaZulu-Natal.

The RUSLE was selected over USLE due to “many significant erosion and deposition mechanisms [that] have been incorporated into the revised factors” (Kienzle & Lorentz

1993: 566). Soil erodibility was derived in the same manner as Mander, Quinn and Mander (1993), from landtype data supplied by the Institute for Soil, Climate and Water. However, the definition of terrain units was accomplished by using GIS models based on the ISCW definitions of terrain units (combining slope and surface curvature information).

The approach of Kienzle and Lorentz (1993) for determining the LS factor is described in the supporting documentation of the RUSLE (Renard, Foster, Weesies & McCool 1991). This method requires the input of the effective flow length. This can be derived from the output of the flow direction algorithm (ESRI 1996), using the ArcInfo FlowLength request. This request is an additive calculation of the number of cells flowing into a given cell that incorporates consideration of the cell size as well as the effect of flow occurring diagonally across cells. The RUSLE LS-factor (Renard, Foster, Weesies & McCool 1991) is derived using the following set of equations.

$$LS = L_s \cdot S_{sf} \quad (5)$$

where

L_s = slope length factor

S_{sf} = slope steepness factor

$$L_s = \left(\frac{\lambda}{22.1} \right)^{m_{st}} \quad (6)$$

where

λ = flowlength

and

$$m_{st} = \frac{\beta_r}{1 + \beta_r} \quad (7)$$

where

$$\beta_r = \frac{\sin(S)}{0.0896[3.0(\sin(S))^{0.8} + 0.56]} \quad (8)$$

where

S = gradient in degrees

and

$$S_{sf} = 10.8 \cdot \sin(S) + 0.03 \quad \text{for } S_{\%} < 9\% \quad (9)$$

$$S_{sf} = 16.8 \cdot \sin(S) - 0.5 \quad \text{for } S_{\%} \geq 9\% \quad (10)$$

$$S_{sf} = 3.0 \cdot (\sin(S)^{0.8}) + 0.56 \quad \text{for } \lambda < 5\text{m} \quad (11)$$

where

S = gradient in degrees

S_% = gradient in percent

The spatial resolution of the modelling was 250m. They note that the resolution of the digital elevation model is a critical factor in running erosion models spatially, since significant smoothing occurs at coarser resolutions. A comparison of the derivation of slope, at 250m and 100m resolutions, yielded maximum values of 33% and over 400% respectively. The predicted sediment yield was 50% higher using the 100m resolution dataset, with all other factors remaining constant, than that using the 250m resolution dataset. This generalisation arises from the use of extremely coarse data.

3.3.3 Engel (1999)

Moore and Burch (1986) proposed a method of LS factor derivation that is based on unit stream power. Engel (1999) applied this method and derived the LS factor by combining the output of the flow accumulation model of ArcView Spatial Analyst with the gradient.

In order to derive the flow accumulation, the flow direction has to be established. The flow direction algorithm used in ArcInfo and ArcView is the D8 method, developed by Jenson and Domingue (1988), where flow is directed to from one pixel into one of its eight nearest neighbours. Flow accumulation is a count of the number of upslope cells that flow into the processing pixel (ESRI 1996). Moore and Wilson (1992) argued that the physically based LS-Factor developed by Moore and Burch (1986) can account for complex slope geometries and describe soil transport by both sheet and rill flow, reducing observed inconsistencies in the result of USLE-based models. As a consequence, it is likely that the application of this method of sub-factor derivation will result in a slightly higher prediction of erosion.

The Moore & Burch (1986) LS factor is derived as follows:

$$LS = \left(\frac{al}{22.13} \right)^{0.4} \cdot \left(\frac{\sin S}{0.0896} \right)^{1.3} \quad (12)$$

where

$$\begin{aligned} al &= \text{upstream contributing area} \\ S &= \text{gradient in radians} \end{aligned}$$

Translated for application in GIS using raster data structures, the equation can be written as:

$$LS = \left(\frac{fa \cdot ca}{22.13} \right)^{0.4} \cdot \left(\frac{\sin S}{0.0896} \right)^{1.3} \quad (13)$$

where

$$\begin{aligned} fa &= \text{results of Flow Accumulation algorithm} \\ ca &= \text{area of raster cell} \\ S &= \text{gradient in radians} \end{aligned}$$

The data for the other factors in the USLE equation (Eqn. 1) were established from observed data. Engel (1999) concludes that the application of the equation is easily accomplished in ArcView.

3.4 IDENTIFYING AREAS OF LOW SEDIMENT MOBILITY

Importantly, none of the spatial applications discussed appear to eliminate areas of where erosion is unlikely to occur, which is essential to the accurate quantitative assessment of erosion using the USLE family of models (Wischmeier & Smith, 1978; Renard, Foster, Weesies & McCool 1991). Although the purpose of this research is not to assess the erosion potential quantitatively, it does use the predicted values for developing relative estimates that inform the prioritisation process. The identification of sediment supply areas where it is inappropriate to apply the USLE, therefore, will improve the identification of priority areas for intervention. This is achieved by eliminating areas where the gradient and terrain morphology are likely to reduce sediment mobility.

It is possible to define a gradient threshold, below which deposition is assumed to occur. Smithers and Schulze (1995) set the gradient threshold for deposition occurrence at 5%. Areas below this threshold are excluded from the area of USLE application, because they are assumed not to be sediment supply areas.

GIS technologies permit the modelling of the terrain morphology from digital elevation models. In the ESRI suite of GIS applications, this modelling function is known as curvature. The curvature function (ESRI 1996) allows for the derivation of information about the topography of the landscape. An index is assigned on a cell-by-cell basis indicating the convexity or concavity at that cell, relative to its eight nearest neighbours. In addition, the function produces two other curvature output datasets.

The profile curvature is the curvature of the terrain in the direction of the slope. It is therefore an indicator of acceleration and deceleration of flow. The planform curvature is the curvature perpendicular to the direction of flow. It indicates the convergence and divergence of flow across the landscape. In all derived datasets, a negative value represents concavity and a positive value represents convexity. The magnitude of the index ranges according to the ruggedness of the terrain.

By developing a matrix of the landform curvature components that occur in a landscape based on the data derived from curvature analysis, it may be possible to identify areas likely to exhibit low sediment mobility. It is assumed that convergent and accelerating slopes increase the mobility of sediment in the landscape. Conversely, divergent and decelerating slopes reduce sediment mobility. There are four possible combinations of the results of the two curvature datasets. In assigning sediment mobility potential to these combinations, a conservative approach was adopted. If either of the factors were regarded as increasing sediment mobility, the combination was assumed to indicate high sediment mobility potential. This means that only the combination of decelerating and divergent slopes is assumed to be indicative of low sediment mobility potential. The proposed matrix is presented in Table 3.1.

Table 3.1: Proposed sediment mobility matrix based on the results of the curvature model

		Profile curvature	
		+ve accelerating	-ve decelerating
Platform curvature	+ve divergent	High mobility potential	Low mobility potential
	-ve convergent	High mobility potential	High mobility potential

By combining the results of the gradient threshold limitation with the results of the curvature analysis it is possible to identify areas of low sediment mobility, which can be excluded from the study area during USLE modelling. The algorithm for identifying deposition areas is as follows:

$$D = 0 \text{ if } (P_{rcurv} < 0) \text{ and } (P_{lcurv} < 0) \text{ and } (S < 5) \quad (14)$$

$$\text{Else } D = 1$$

where

- D = deposition areas
- P_{rcurv} = profile curvature
- P_{lcurv} = profile curvature
- S = slope in degrees

The results can be used to eliminate areas potentially inappropriate for the application of USLE-based erosion models from the study area.

3.5 IDENTIFYING SEDIMENT SUPPLY AREAS

In order to identify the sediment supply areas using the methods investigated, spatial modelling was undertaken using the Spatial Analyst extension of ArcView GIS (Version 3.2). The topographic analysis and application of both erosion models (Renard, Foster, Weesies & McCool 1991; Moore & Burch 1986) were automated using Avenue, the proprietary scripting language of ArcView Version 3.

In addition, stream delineation and ordering routines as well as catchment delineation for derived streams were included in the modelling interface. The Avenue coding for the interface is presented in Appendix 2 along with a screen capture of the initial user interface.

Figure 3.1 presents the process flow for deriving a Sediment Supply Index (SSI) using the USLE-based equations discussed in Section 3.2.

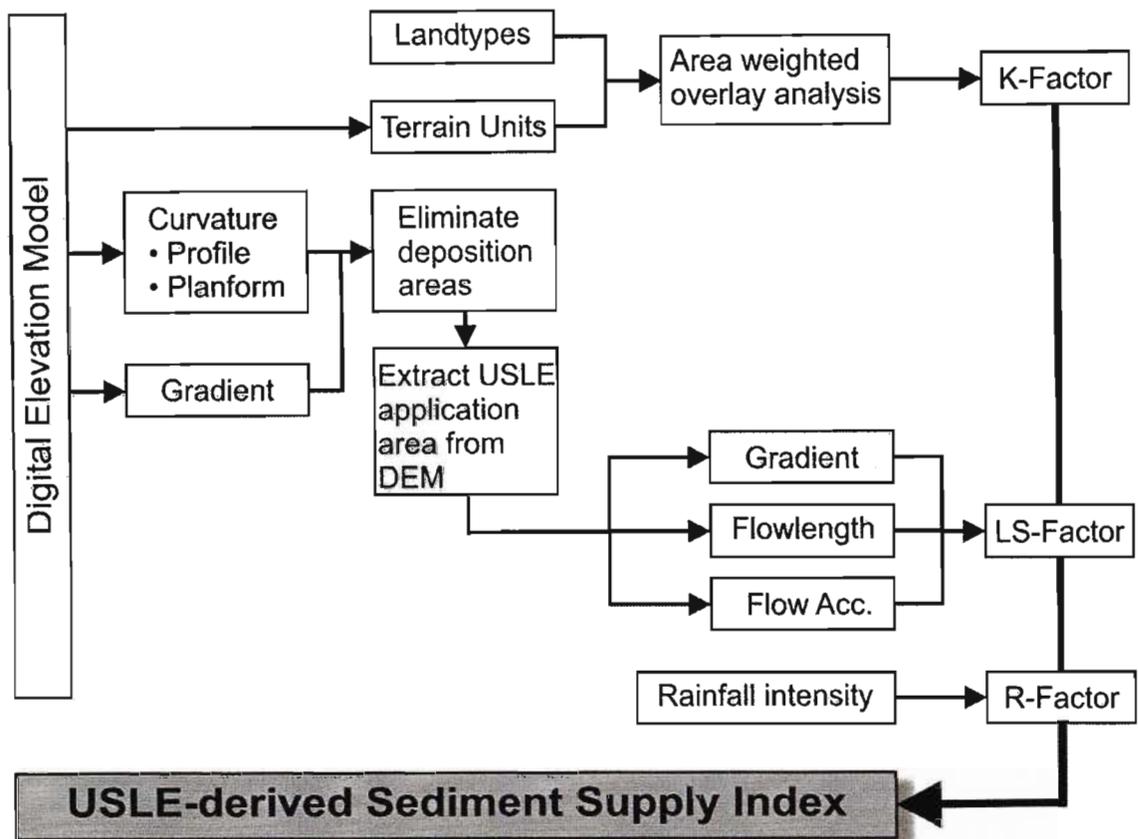


Figure 3.1: Process for derivation of the Sediment Supply Index

3.6 SEDIMENT SUPPLY INDEX

The Sediment Supply Index (SSI) is derived from the application of the USLE-based erosion prediction models (Equation 1), 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. The remaining factors are the rainfall erosivity, the soil erodibility and the topographic (slope-length) factor.

The rainfall erosivity factor was determined using information presented by Smithen and Schulze (1982). It is uniform across the study area ($380 \text{ MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}\cdot\text{annum}^{-1}$).

The derivation of the soil erodibility factor required extensive spatial modelling. It was originally anticipated that the soil data from soil surveys of the Mooiplaas plantation. This data is presented in an industry standard format, the FSD Data Standard (Forest Industry Soils Database Cooperative 1995). The FSD data format does not include the soil parameters necessary for the detailed determination of the K-factor, making the data unusable for the purposes of this research. Additionally, soil surveys are conducted for the planted areas of plantations only, undermining the utility of the data in developing integrated management strategies. Consequently, the landtypes developed by the Agricultural Research Council (ARC) were used as a substitute for soil survey data.

The ARC landtype dataset depicts areas of uniform terrain form, soil pattern and macroclimate. The associated memos, describe the distribution of soil forms within each terrain unit in the landtype. Estimates of the erodibility of each soil form have been derived and are available in the ACRU manual (Smithers *et al.* 1995). By modelling the spatial distribution of terrain units from a DEM, it is possible to assign soil erodibility values to each unique combination of terrain unit and landtype using an area-weighted analysis. Figure 3.2 depicts the results for the micro-catchment that was described in Section 2.8.

Before applying the RUSLE it is necessary to identify areas of low sediment mobility, and to exclude from the area of application. These areas have to be eliminated before the derivation of the topographic (LS) sub-factor. The results of this process, explained in Section 3.3, are presented in Figure 3.3 for the micro-catchment.

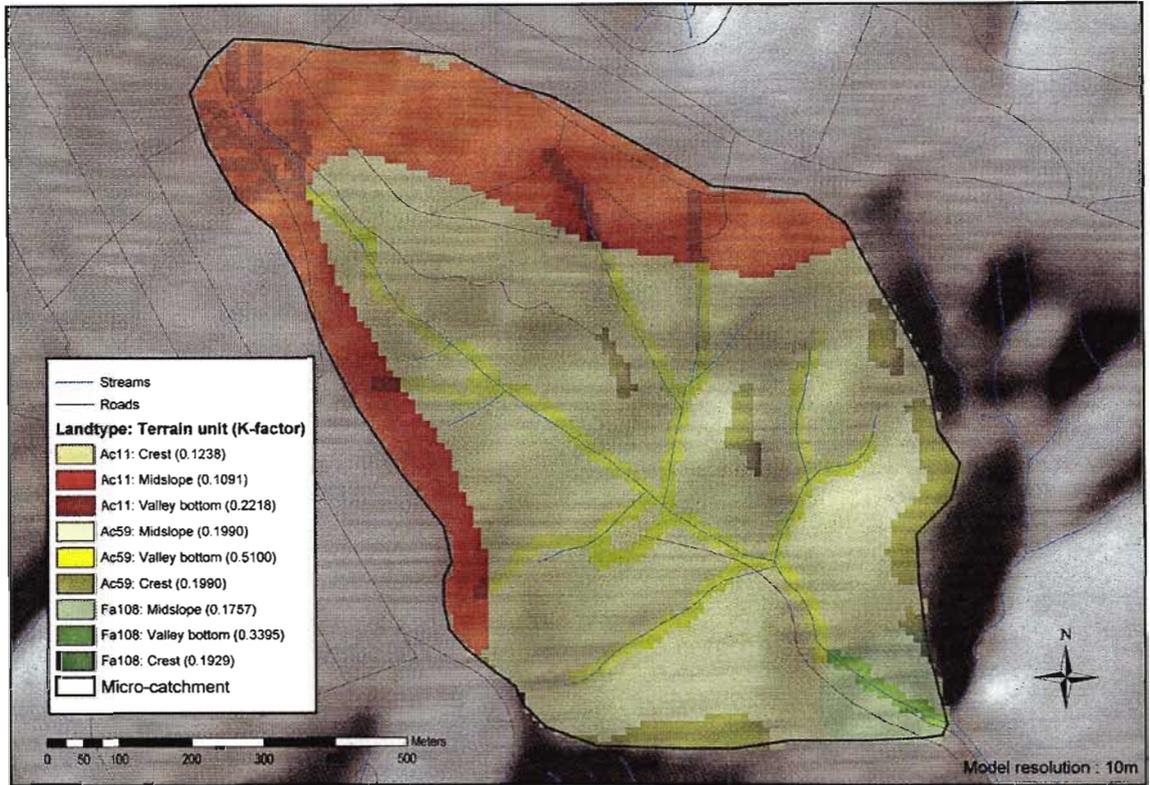


Figure 3.2: Landtype-terrain unit combinations and associated K-values for the micro-catchment

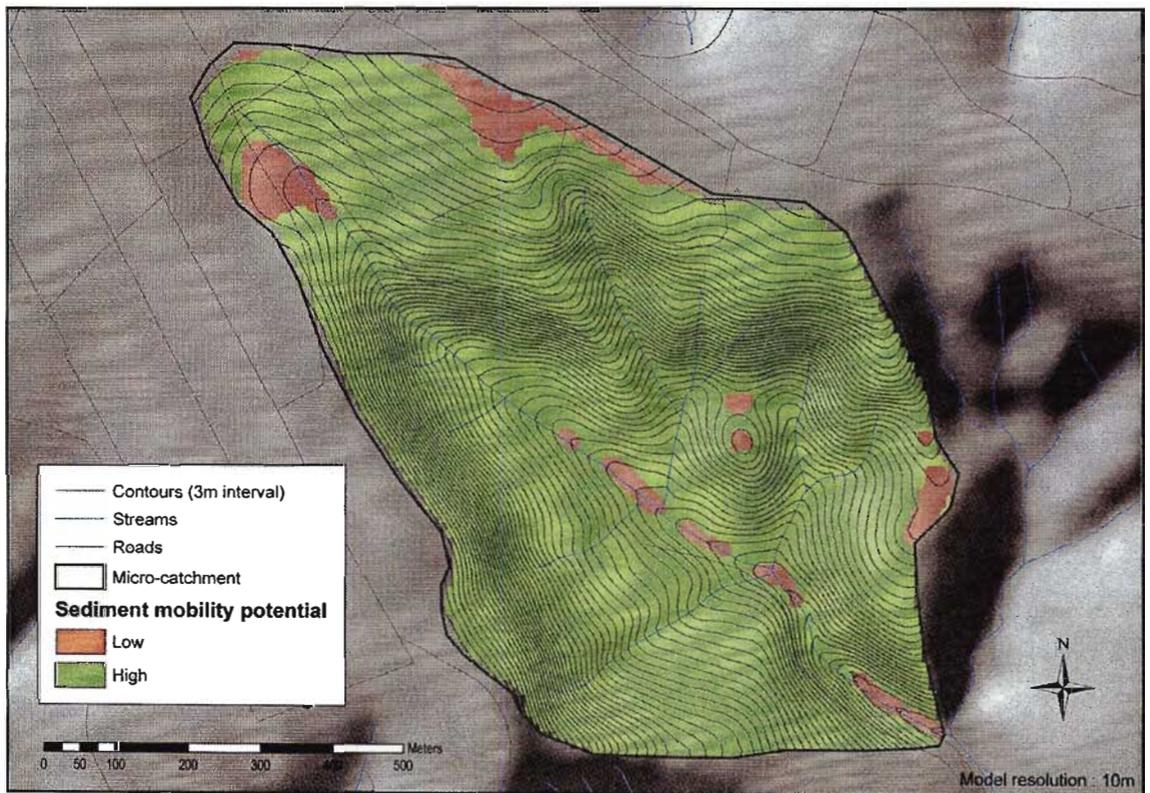


Figure 3.3: Areas of low sediment mobility for eliminating from the USLE application area derived using Equation 14

Figure 3.4a and Figure 3.4b present the LS-factor derived using the RUSLE (Renard, Foster, Weesies & McCool 1991) and Flow Accumulation (Moore & Burch 1986) methods for the micro-catchment.

It is apparent from the illustrations that the area of application is extended in the Flow Accumulation based model for LS determination. This is because the flow-accumulation implementation does not require deposition areas to be eliminated, since the model identifies the deposition and sediment supply areas based on the flow characteristics resulting from the terrain morphology (Moore & Burch 1986). Additionally, there are higher values within the flow-accumulation method dataset. The larger area of analysis and the higher LS values result in a higher predicted sediment yield across the landscape, which Moore & Burch (1986) claim is a better representation of the actual sediment yield than can be derived using the RUSLE.

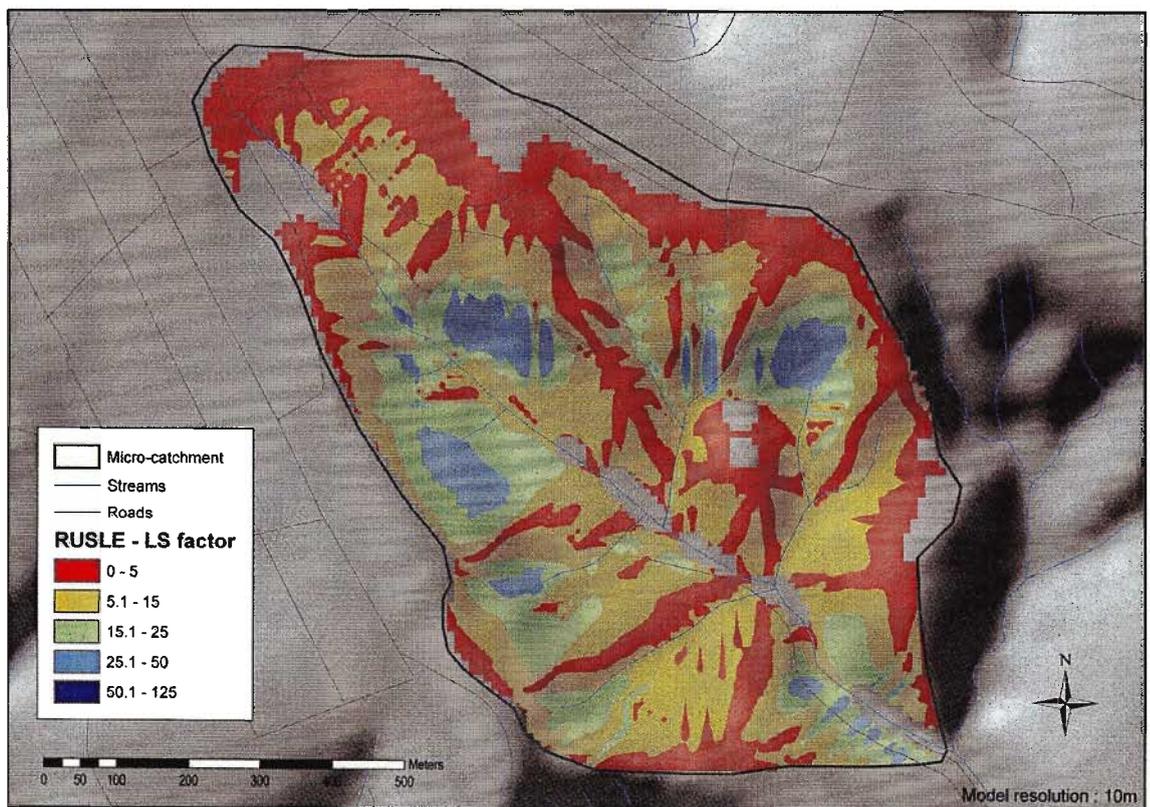


Figure 3.4a: The LS factor derived using the RUSLE method (Renard, Foster, Weesies & McCool 1991)

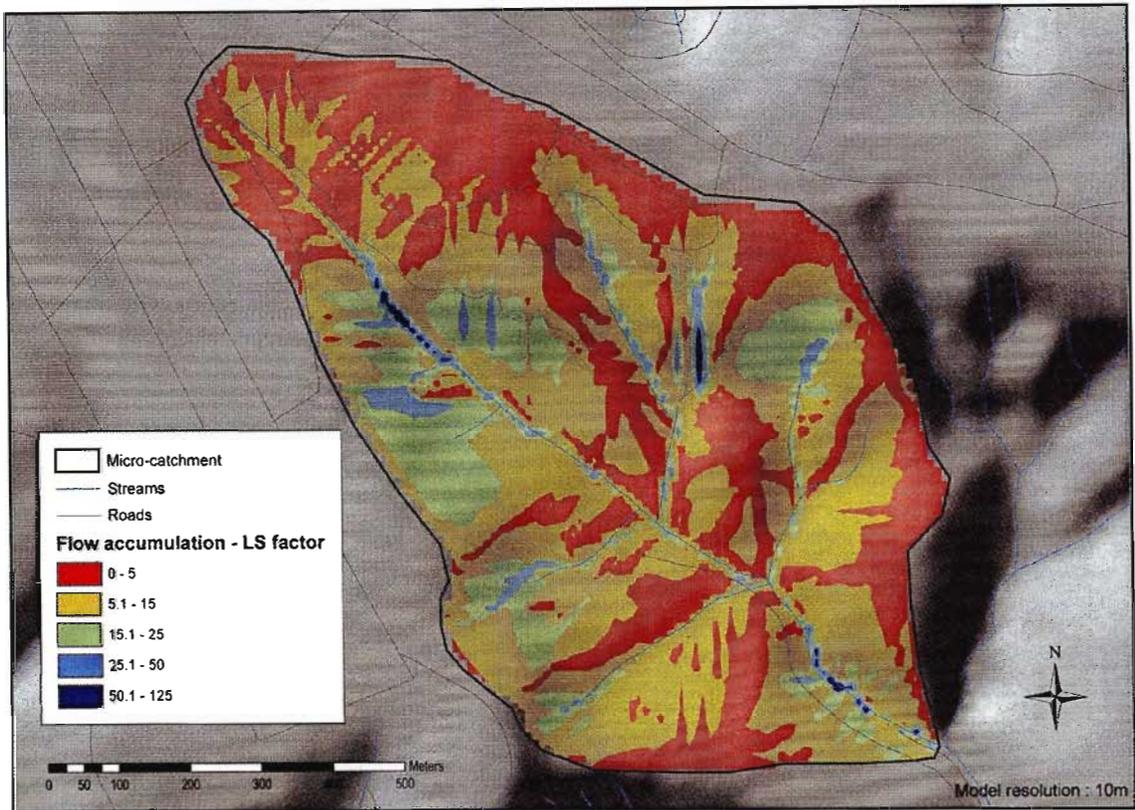


Figure 3.4b: The LS factor derived using the flow accumulation method (Moore & Burch 1986)

Figure 3.5 presents the results of the Flow Accumulation (Moore & Burch 1986) method for determining sediment supply for the micro-catchment. Photographs taken on a field visit are presented as part of the ground-truthing of the model results. Observations of the soils are presented, not as factors influencing the derivation of the SSI, but to assess whether the incidence of high SSI scores can be related to evidence of erosion in field. The observations are made in the same compartment, suggesting that the landuse history of the sample points is the same. Differences in the observations can thus be attributed to topographic erodibility, presented in the SSI, rather than landuse. The numbers on the map refer to the positions at which photographs presented in Figures 3.6 to Figure 3.10 were taken.

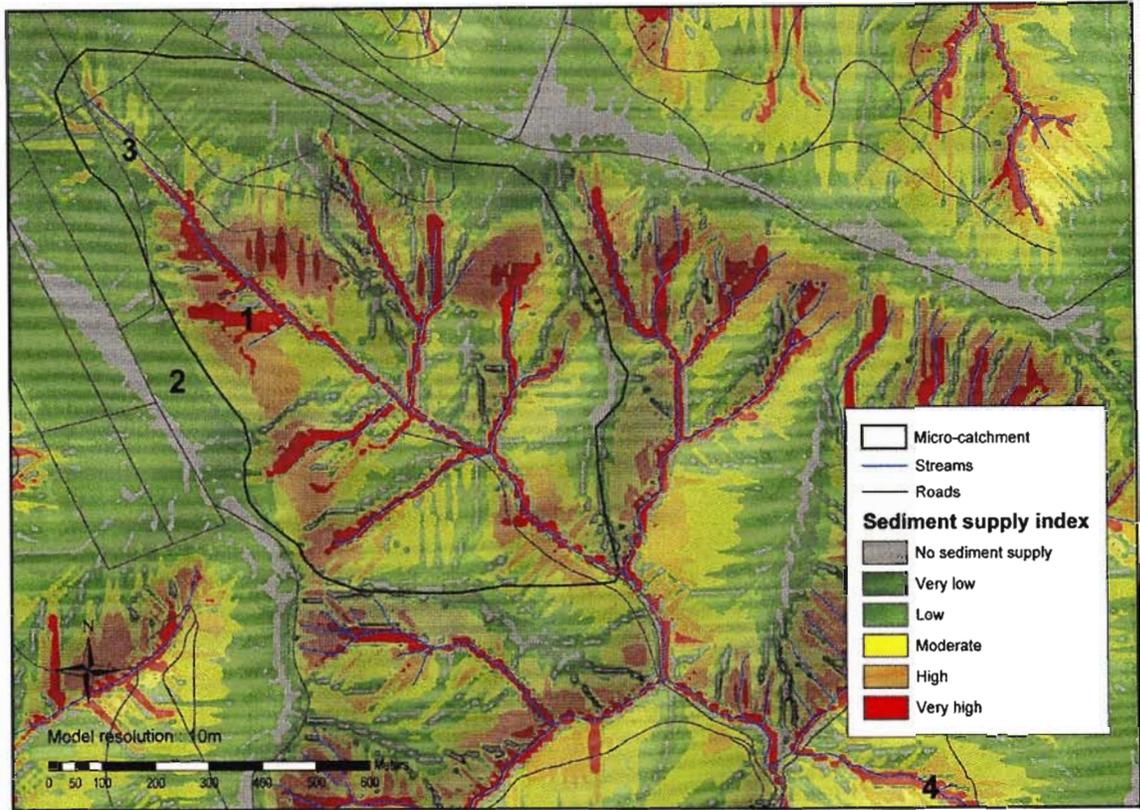


Figure 3.5: The SSI derived using the Flow Accumulation method (Moore & Burch 1986) showing photo points

In all SSI maps the modelling results have been classified into five categories, with each successive class representing a doubling of the magnitude of the sediment supply index. The classes have been assigned a descriptive category based on the relative erosion potential across the study area.

Figure 3.6, taken at photo point 1, shows the steep terrain of the planted area, characterised by high SSI values. A thick layer of vegetative matter covers the ground. Figure 3.7 reveals that there is no topsoil beneath this layer suggesting that erosion has occurred, as the high SSI value associated with the location would suggest.

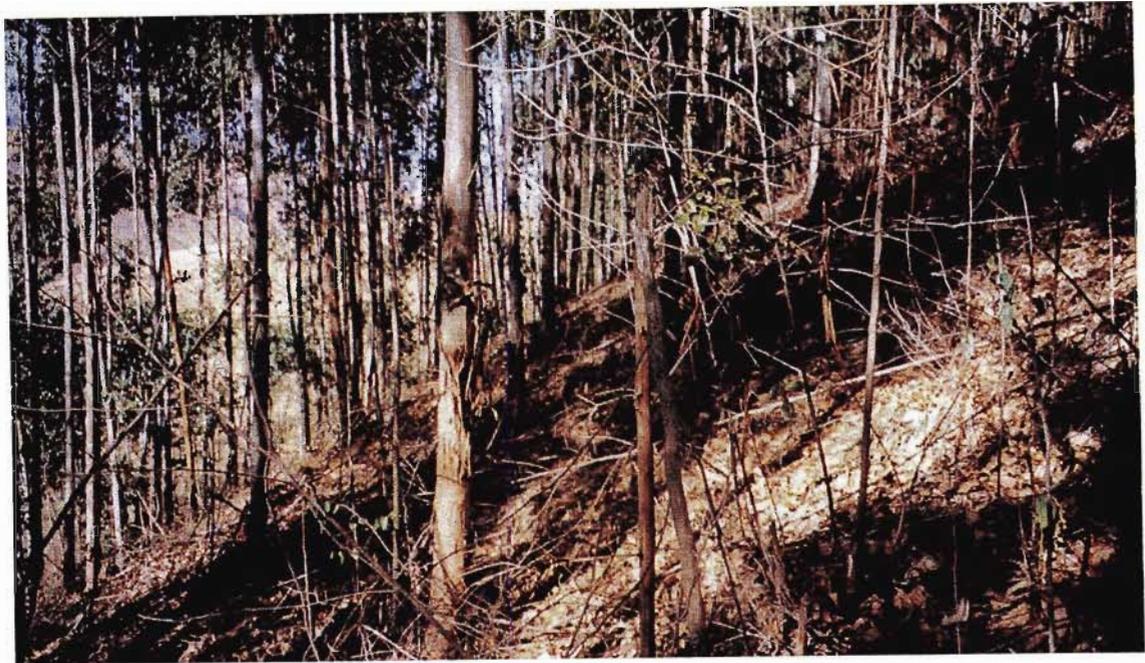


Figure 3.6: Compartment characterised by high gradients at photo point 1



Figure 3.7: Photograph showing exposed subsoil at photo point 1

Compartment characteristics further up the slope, at photo point 2, where the slope is lower and the area has a low SSI value, are presented in Figure 3.8. There is a layer of humic soils under the vegetative litter, as illustrated in Figure 3.9. The presence of topsoil, suggesting that erosion has not occurred, corresponds with the low SSI value at the location.



Figure 3.8: Compartment characterised by level terrain at photo point 2



Figure 3.9: Humic topsoil characteristics of the site at photo point 2

Figure 3.10 and 3.11 were taken at photo point 3. They show gully erosion occurring along a line of high SSI value. This area shows convergent topography and moderate slope. There is a road approximately 150m upstream of the onset of the gully.



Figure 3.10: Onset of gully erosion at photo point 3



Figure 3.11: Lower reaches of the gully originating at photo point 3

Figure 3.12 shows the view from photo point 4. The gully on the neighbouring farm is identified using the SSI as a high-risk area. Figure 3.13 depicts a 3-d visualisation of the landscape presented in Figure 3.12. It shows the area of high SSI value on which the gully

occurs. It is significant to note that surrounding areas of high SSI value do not show the same severity of erosion. This suggests that the road, clearly visible in Figure 3.12, running directly upslope of the onset of the gully is implicated in its formation. It is likely to be acting as a conduit of overland flow increasing the peak flows down the valley, which has become eroded as a result.



Figure 3.12: Gully on neighbouring farm visible from photo point 4



Figure 3.13: 3-d visualisation of the area presented in Figure 3.12 with a vertical exaggeration=1.5 (Note the road upslope of the gully)

Figure 3.14 presents the results of the flow accumulation model (Moore & Burch 1986) for the Mooiplaas plantation. Figure 3.15 depicts the results of the RUSLE (Renard, Foster, Weesies & McCool 1991) approach. The low-gradient plateaus in the northwestern parts of the study area are identified as having a low SSI. Areas of topographic convergence are identified as higher risk than the areas immediately adjacent to them. Generally, the western section of the study area is at greater risk and this is due to the erodibility of the soils in that area. The high SSI values in the southern and south-eastern areas of the study area can be attributed to the rugged terrain.

In order to verify the results on a wider scale, an overlay between the developed Sediment Supply Index and a set of aerial photographs, from which gully erosion can be identified visually, was undertaken. Figure 3.16 presents the overlay for an area in the south-western area of the plantation. The slight offset between the spatial information and the aerial photography is due to the photography not being ortho-rectified. The predicted SSI and the observed erosion show a high degree of spatial coincidence. It is apparent from the modelling results that the areas associated with first order streams are particularly sensitive, and show a high sediment production potential across the entire study area. This is due to convergent landscape in these areas, which in the case of Mooiplaas, is also associated with relatively steep gradients. This observation corresponds to the results of Bren (1999b), which identified convergent areas and first order streams as significant erosion risks. As presented in Section 2.5.2, the South African Landuse and Wetland/Riparian Habitat Working Group (1999) also identifies these Class A watercourses as likely to erode. However, according to the current guidelines, they do not have to be excluded from the planted area. This suggests that the potential of these areas to erode is likely to be realised when the compartments in which they occur are harvested.

Both methods of SSI derivation reveal a similar distribution of high-risk areas. It is claimed, though, that the flow accumulation can account for complex slope geometries and describe soil transport by both sheet and rill flow (Moore & Burch 1986). Additionally, this method is not dependent on the elimination of deposition areas prior to application. Consequently, the results of this method are used as the basis for further analysis, as well as SSI presentation in maps, unless otherwise indicated.

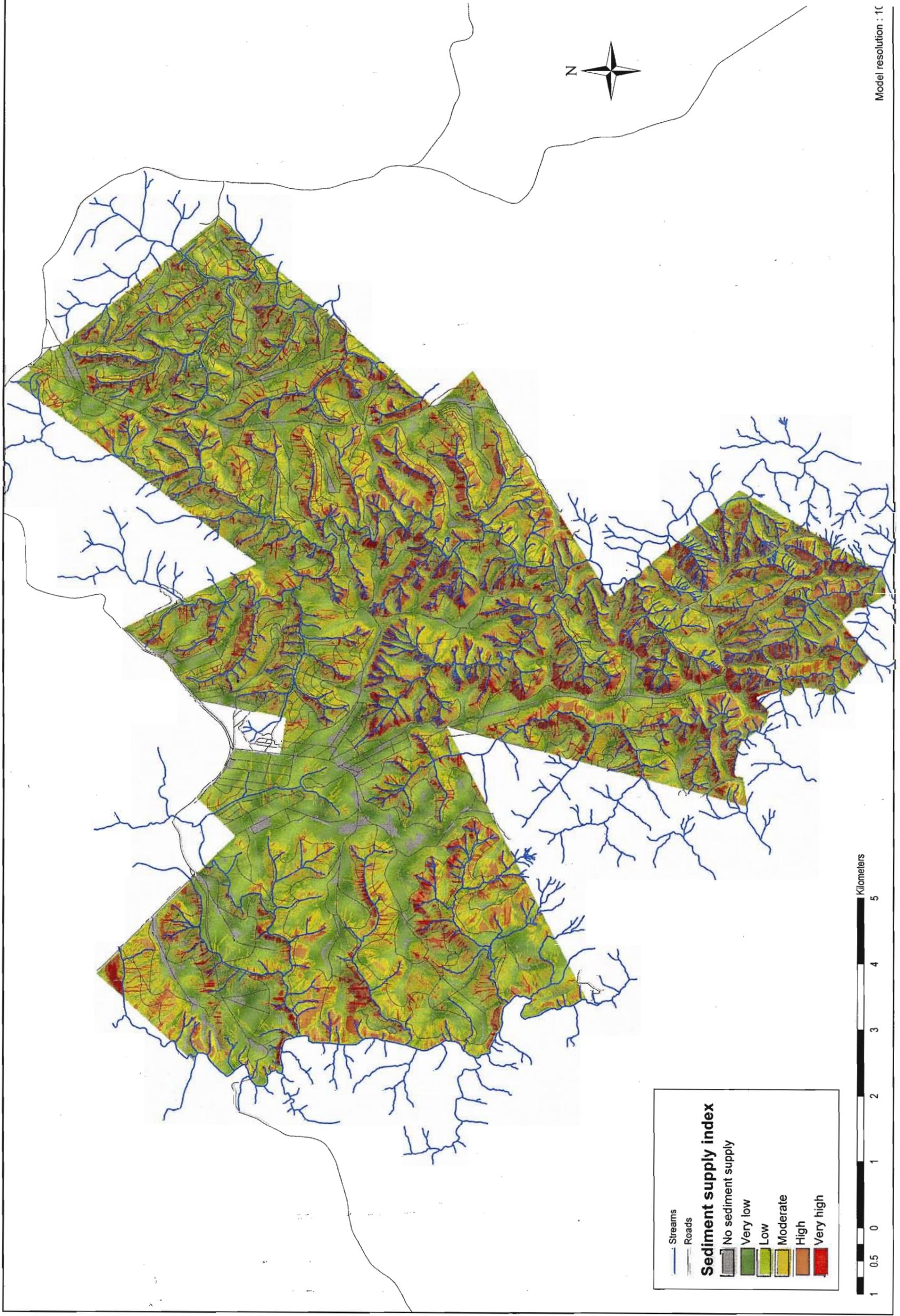


Figure 3.14: Results of the flow accumulation method of sediment supply derivation for the Mooiplaas study area

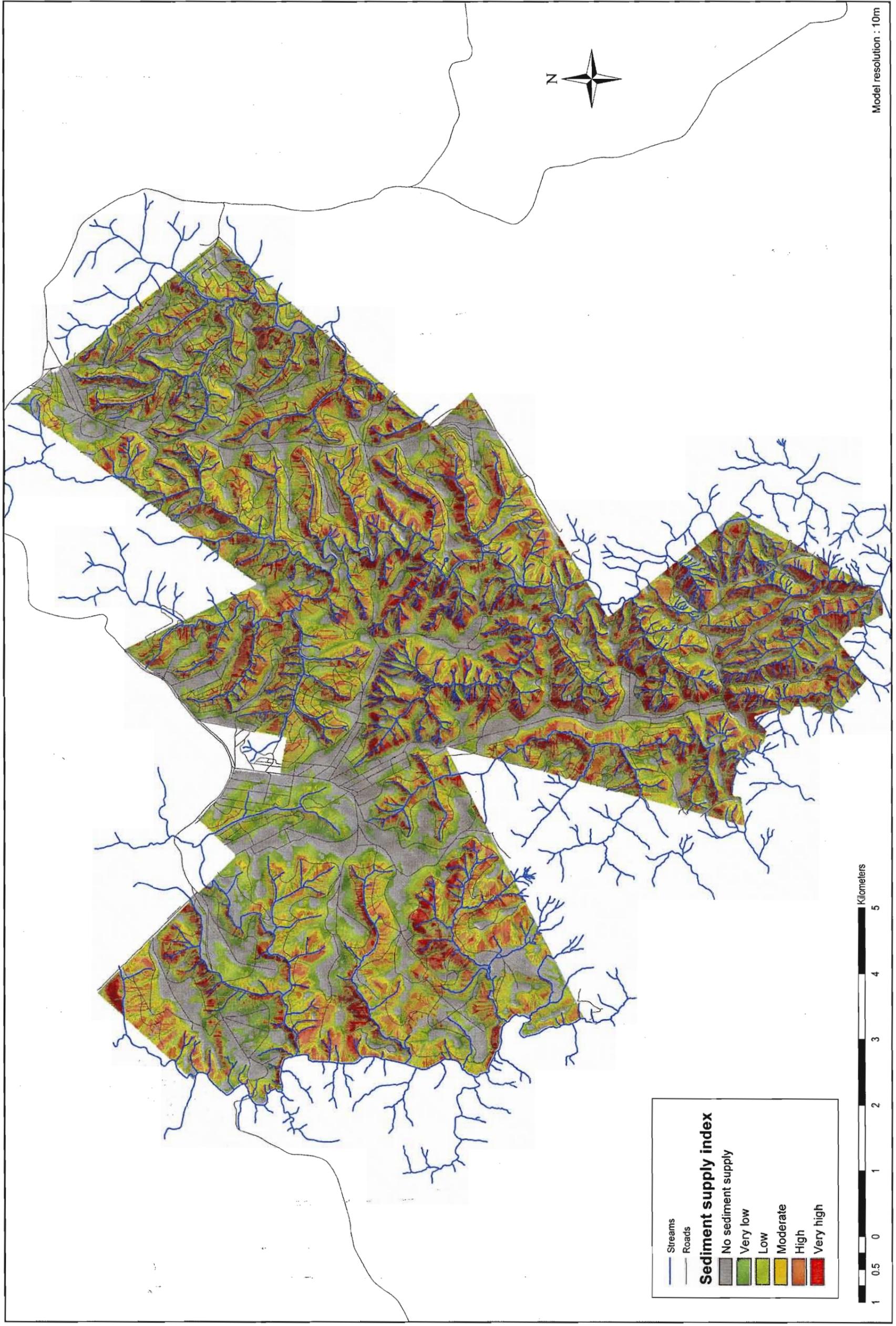


Figure 3.15: Results of the RUSLE method of sediment supply derivation for the Mooiplaas study area

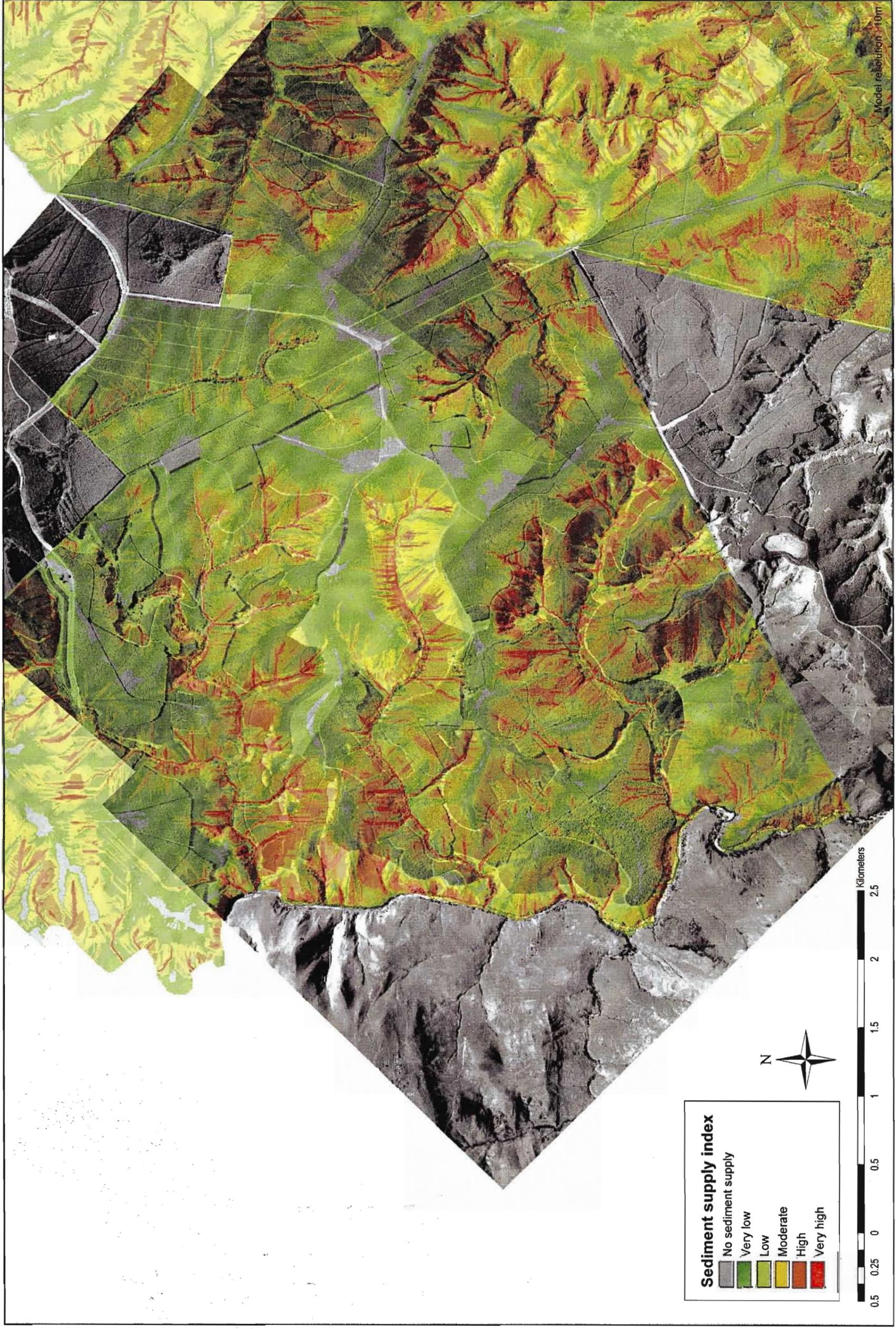


Figure 3.16: Overlay of the flow accumulation derived SSI and aerial photographs covering the western section of the study area

The results of this exercise can be used for developing site-specific recommendations for managing the risk of erosion. However, although a useful indicator of where the problem of erosion may be anticipated, it does not address the issues of sediment delivery or the opportunities for trapping eroded sediment. Chapter 4 will attempt to address these needs.

CHAPTER 4: SEDIMENT DELIVERY AND ATTENUATION

The mobilisation of sediment from areas of high risk of erosion is the first part of a process that can result in sediment delivery to streams, and the associated decrease in water quality. Understanding the mechanisms that determine the paths over which the sediment is likely to travel across the landscape, provides an opportunity to intercept the sediment before reaching a watercourse. This chapter presents methods for assessing the contribution of landscape factors to sediment delivery, as well as identifying features within the landscape that may have the potential to act as sediment traps.

4.1 SEDIMENT DELIVERY

Managing the impacts of erosion requires a two-pronged approach. The first requirement is to manage sediment production at source. This requirement is often constrained by the landuse associated with the erosion source, for example high tillage agricultural practices, road construction or plantation forestry. The second requirement is to intercept the sediment during the transport phase from source to watercourse. Intercepting the sediment before delivery to a watercourse requires that cognisance is taken of a number of issues. Firstly, the delivery feature (e.g. the road, waterway or general overland flow), secondly the erodibility of the delivery feature itself, thirdly the degree of connectivity between the stream and the delivery feature, and finally the condition of the area immediately adjacent to the watercourse, the riparian buffer. The effective functioning of this area as a sediment control mechanism is the final opportunity for sediment control within a landscape.

As discussed in Section 2.2.1 the road infrastructure associated with commercial forests is a significant factor in sediment delivery. Road-stream connectivity effectively extends the drainage network within a catchment by establishing new paths for surface flow to enter existing watercourses. Road-stream connectivity influences the efficiency of sediment delivery to streams considerably. Additional impacts relate to alterations in peak flows and the increased likelihood of road-associated pollution spills 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 & Croke 1999; LaMarche & Lettenmaier 2001). Not only do the gullies increase the efficiency of sediment delivery to streams, they are also sources of sediment, and there is an increase in the likelihood of mass failure in the vicinity of gullies. The probability of gully formation is largely determined by the degree to which the flow of culvert output is concentrated by the topography, the convexity or concavity, of the landscape. Delivery of sediment into vegetated buffer strips in the form of concentrated flow (as is associated with gullies) considerably reduces their efficiency as sediment traps.

Additionally, the position of the road in the landscape is a contributing factor, with cut-and-fill roads more likely to contribute to sediment production than ridge-top roads (Croke *et al.* 1999). This is partly due to the increase in surface flow as sub-surface flow is transformed into surface flow at the cut-slope of the road, and increased likelihood of mass-failure in both the cut-slope and the fill-slope. Studies have established empirical relationships between the onset of gullies and terrain (Mockler & Croke 1999; Luce & Wemple 2001), but these are site specific and cannot be generalized across landscapes. These studies rely on intensive data regarding the road drainage structures within the study area, and the observation of sediment delivery over a period of time. Unfortunately, this level of data is generally not available. One of the objectives of this dissertation is to provide a means of assessing erosion risk using available data.

Based on the above discussion, and evidence collected in the literature review, five factors which 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:

- Actual stream crossings; points where streams and roads intersect
- The level of adjacency between streams and roads; areas where roads and streams run parallel, or in close proximity to one another
- The topographic connectivity between streams and roads; areas where topographic convergence creates links between roads and streams
- The erosion potential of the road surface itself

- The state of the road surface; which combines consideration of the type of surface and the condition of the surface

Figure 4.1 presents the proposed procedure for developing a Delivery Risk Index 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.

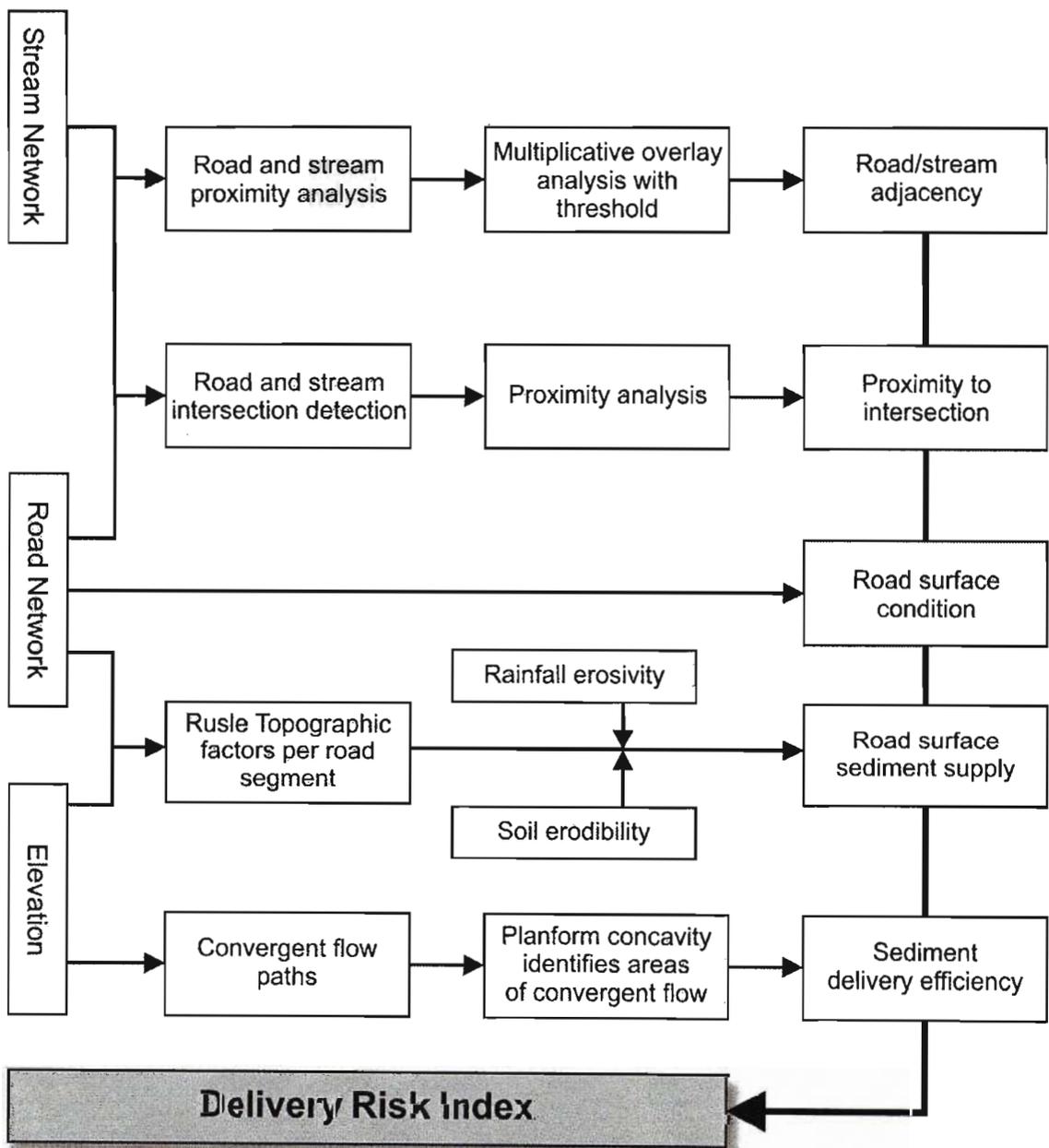


Figure 4.1: Process for the derivation of the delivery risk index

4.2 DELIVERY RISK INDEX

This section presents the procedures followed to develop the Delivery Risk Index (DRI) according to Figure 4.1. It will present the processes for the derivation of the five sub-factors that contribute to the index.

4.2.1 Road-stream adjacency

The original approach for the derivation of this sub-factor was to identify the intersecting areas of Euclidean buffers generated around the roads and streams. However, the resultant dataset was an underestimation of the adjacency areas, because this procedure extracts only areas common to both sets of Euclidean buffers, excluding the features associated with an adjacency area but that are external to the intersected area itself. Due to this shortcoming in the modelling procedure an alternative solution was sought.

Using the proximity function in ArcView Spatial Analyst it is possible to determine the Euclidean distance between features in a spatial dataset. The result of this analysis is a surface that is best described as a continuous buffer between features. The features themselves are assigned a value of one (1) in this analysis. The function was applied to the roads dataset and to the streams dataset, thus producing two continuous surfaces presenting the distance between the features within each dataset. By multiplying these surfaces together, and extracting values beneath a certain threshold it is possible to develop a better index of road stream adjacency than using the original approach described previously. Based on the findings presented in Section 2.4.2 a 10m to 20m buffer width should be adequate for sediment attenuation. The upper estimate is used for establishing a threshold for extracting road-stream adjacency areas. The reason for doubling the width was the need for a conservative assessment, given the generally mountainous terrain of the study area. This means that road-stream adjacency is defined by areas where the product of the two proximity datasets is less than or equal to 400 (20 multiplied by 20).

However, since the identification of the area is driven by the product of the sub-factors, any combination of values that results in a value lower than the threshold are accepted as valid areas of adjacency. This results in a dataset in which the entire road and stream

features themselves, which are assigned a value of one, are included (1 multiplied by 1 < 400).

To overcome this problem, the areas where the product of the two Euclidean distance datasets was equal to one were eliminated. This however, resulted in areas that were not contiguous, divided by linear features the width of the analysis resolution, which arose from the removal of the road and stream features. These were eliminated by performing a focal statistical analysis, which assigned the maximum value within a 3 by 3 matrix to all cells within the matrix, across the study area. A comparison of the results attained with the original road and stream datasets suggests that this process produces an acceptable indicator of areas of road-stream adjacency (Figure 4.2). The areas identified as adjacent were assigned a value of ten and all other areas were assigned a value of one³.

The algorithm for identifying areas of adjacency between roads and streams is:

$$RS_a = 10 \text{ if } (R_a \cdot S_a) \leq 400 \quad (15)$$

$$RS_a = 1 \text{ if } (R_a \cdot S_a) > 400$$

where

RS_a = Road stream adjacency index

R_a = Road adjacency

S_a = Stream adjacency

The results of the modelling are depicted for the micro-catchment in Figure 4.2. It should be noted that the actual risk is associated with areas where the stream is downslope of the road. The modelling results depicted above do not address this issue. However, the results are adequate for identifying general areas of risk in the landscape.

³ Zero cannot be assigned since it would result in the exclusion of most of the study area, when combining the sub-factors to produce the index.



Figure 4.2: Identified road-stream adjacency sub-factor within the micro-catchment

4.2.2 Proximity to road-stream crossings

The literature review identifies road-stream crossings (Hairsine 1998; Tennessee Department of Agriculture 1993) as areas of particularly high risk for sediment delivery to streams. These crossings can be identified using an intersect-overlay analysis routine in ArcView. This creates a point dataset depicting every road-stream crossing. The same proximity analysis as was performed in deriving the road-stream adjacency analysis, producing a surface of Euclidean distance between stream crossings. This dataset can be classified to produce a value for the proximity to road-stream crossings sub-factor. The values for the sub-factor were assigned as presented in Table 4.1.

Table 4.1: Road-stream intersection proximity sub-factor

Proximity to intersection (m)	Intersection proximity value
0 – 10	10
10.1 – 20	7
20.1 – 100	2
> 100	1

The values are based on the assumption that the impact of the interaction between the roads and streams is driven by the proximity to the intersections between them. This relationship is assumed to be non-linear; features within the immediate surroundings of the crossings assumed to have greater potential to impact on the associated watercourse. The impact is assumed to be negligible beyond 100m from the crossing. As with the adjacency sub-factor, it is the upslope area from each crossing that is critical, although the utility of the results in identifying areas of concern is not undermined. Figure 4.3 presents the results of applying this process for the illustrative sub-catchment.

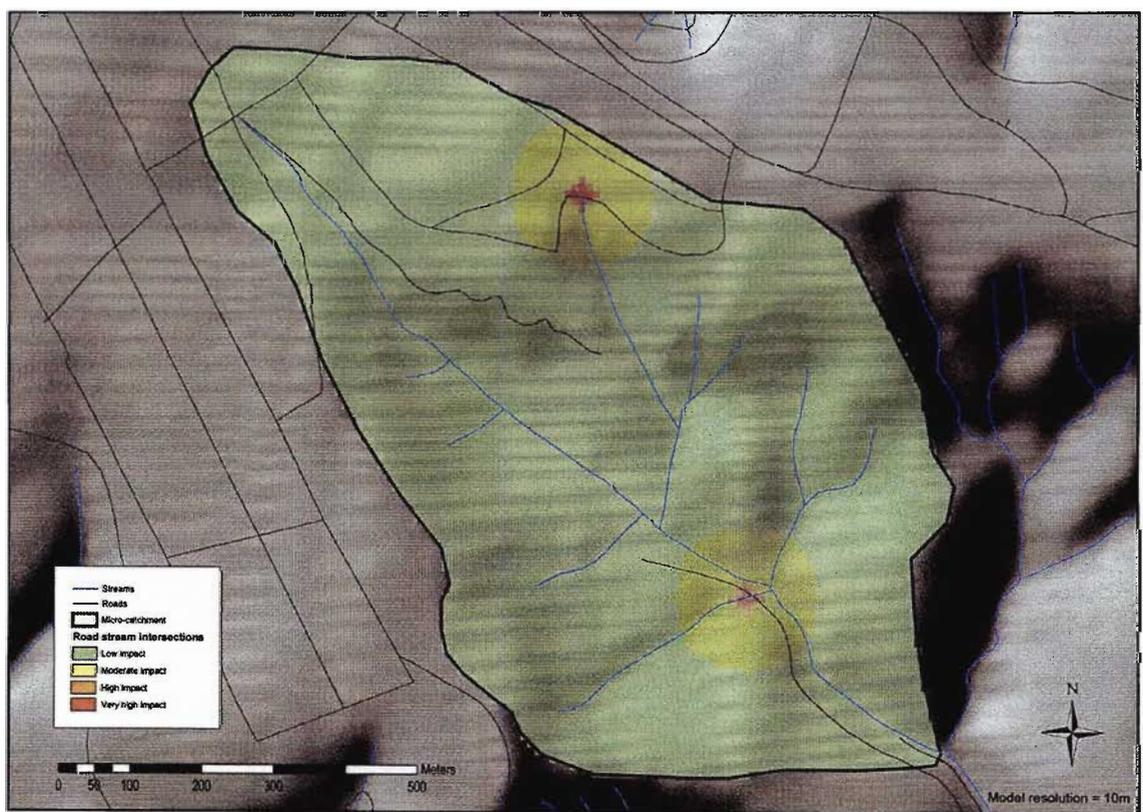


Figure 4.3: Identified road-stream intersection sub-factor within the micro-catchment

4.2.3 Road-surface condition

The road surface condition is a factor that cannot be modelled. Ideally, an in-field assessment of every road is required. This is extremely labour intensive given the high road density associated with South African plantations (there are more than 700 km of road in the road dataset for Mooiplaas plantation). There are, however, classification systems for roads that are used within the forestry industry, but these systems, although similar, are not standard across the industry. The road dataset used in the case study had the standard

Sappi Forests classification applied. The class of the road had to be used as a proxy for surface condition. The road classification and associated risk value assigned to each class of road are presented in Table 4.2. The assumed risk values are based on the factors identified in the discussion in Section 4.1.

Table 4.2: Road surface condition sub-factor

Road class	Description	Risk	Value
A	Tarred road with proper drainage	Very low	1
B	Gravelled or unsealed road > 5m wide	Moderate	6
C	Unsealed road, 3-5m wide	Very high	10
D	Grassed track < 3m wide	Low	4

Areas not occupied by road surface were assigned a value of one. Figure 4.4 presents the rasterised plantation road network within and adjacent to the micro-catchment shaded according to this classification.

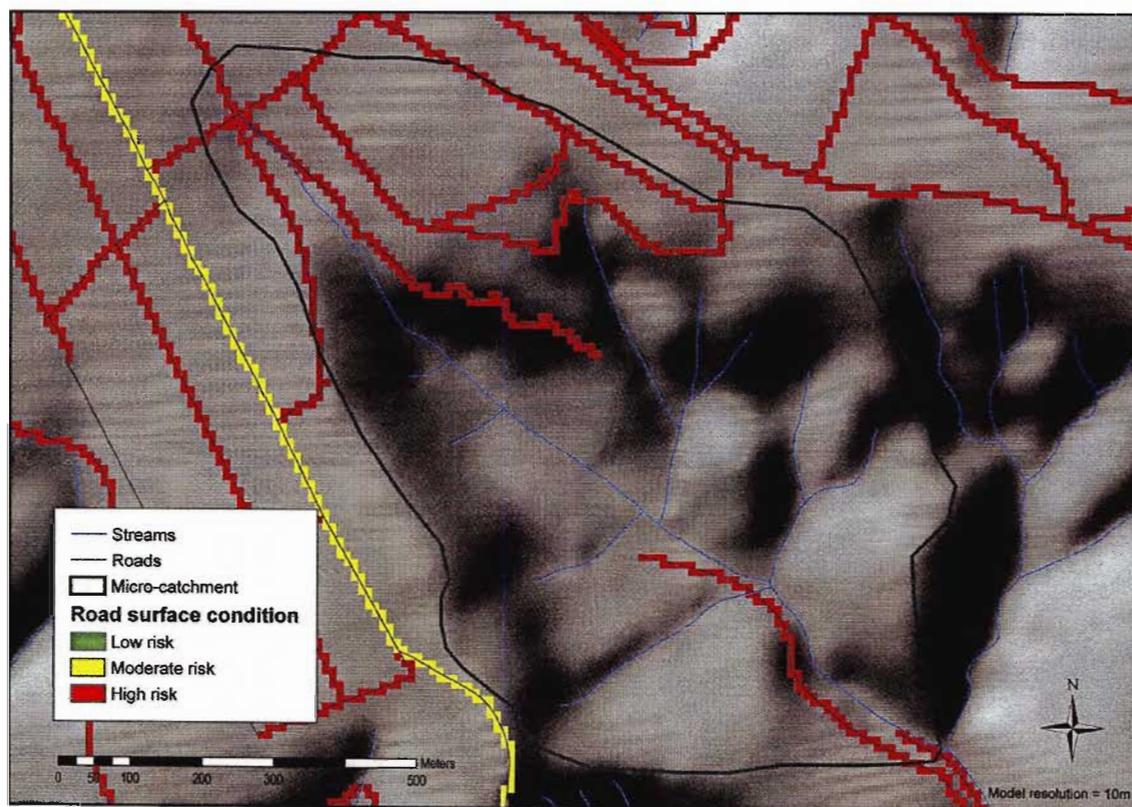


Figure 4.4: Road surface condition sub-factor for roads within and adjacent to the micro-catchment

4.2.4 Road surface erodibility

The road surface erodibility is the most difficult sub-factor to model, although the actual model used is the same as for the Sediment Supply Index (Section 4.1). One confounding aspect is that roads do not follow the morphology of the terrain they run through. This complicates the modelling of the slope and flow-length along the roads enormously. One cannot rely on standard terrain modelling to derive any of the sub-factors.

The first requirement is to develop a linear dataset that reflects the morphology of the road network. By intersecting the road network with a set of contours with a three-meter interval derived from the DEM, an elevation point dataset, sampled along the roads, can be developed. Attempts to produce a raster dataset, from this point dataset, where the interpolation was constrained by the known road width, proved unsuccessful. Processing times exceeding 96 hours, combined with unpredictable results, made this method unusable.

To overcome this nodes were created in the road dataset wherever the roads and 3m contours intersected. This produced a dataset of roads where there is a three-meter change in elevation along each road segment. Deriving the length for each segment was accomplished using the ArcView "shape.returnlength" request. This enabled the slope of each road segment to be calculated, since the run and the rise had been established. Additionally, the roads were intersected with the landtype/terrain unit polygons, effectively transferring the K-value from the landtype data to each road segment. This procedure does not account for the possibility that the road surface may be gravelled. To adequately address this issue would require a detailed set of attributes for each road length, which are not available in the standard road attributes maintained by the forestry industry.

The resultant tabular dataset associated with the spatial road dataset was transferred to a spreadsheet (Microsoft Excel). In Excel the slope (%) was calculated. From this, slope in degrees was derived for each road segment. This angle was translated into radians for the application of the USLE (Eqn. 2). The LS subfactor derivation used was the Moore and Burch (1986) method based on unit stream power (Eqn. 13). The Excel spreadsheet was transferred back into ArcView and linked back to the spatial road dataset using the

internal unique ID in the attribute table. The road network was converted into a raster dataset using the calculated topographic erosion potential as the value item. The values in the resultant grid were normalized to a score out of 10 and areas not occupied by the road surface were assigned a value of one.

Figure 4.5 presents the results of the modelling for the micro-catchment. For illustrative purposes areas with a value of one have been excluded to highlight the sub-factor value along the road network.

As with the SSI for the landscape, road-surface erodibility results have been classified into five categories, with each successive class representing a doubling of the magnitude of the sediment supply index. The classes have been assigned a descriptive category based on the relative erosion potential of the road surfaces within the study area.

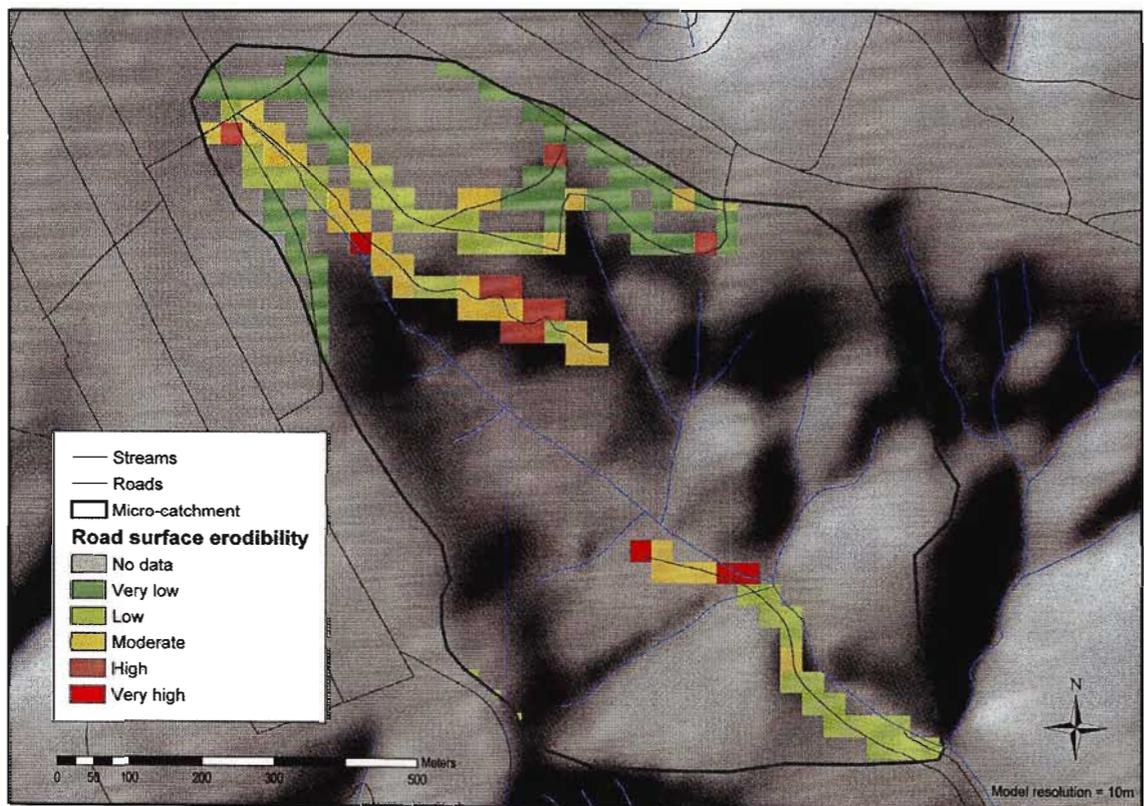


Figure 4.5: Road surface erodibility sub-factor within the micro-catchment

This procedure assumes all road surfaces in the dataset to be sediment-producing surfaces. This assumption would not be necessary if detailed road information was available.

4.2.5 Topographic delivery efficiency

This final sub-factor refers to the topographic characteristics of the terrain that may expedite sediment delivery to streams. Essentially, this identifies areas of convergent flow across the landscape. It is derived by extracting the negative values from the results of the planform curvature, derived using the curvature request in ArcView Spatial Analyst. This function has been discussed in Section 3.4. All areas of convergent flow were assumed to provide topographic linkages between roads and streams, and were assigned a value of 10. All other areas were assigned a value of one. The areas identified are presented for the illustrative sub-catchment in Figure 4.6.



Figure 4.6: Topographic delivery efficiency within the micro-catchment

4.2.6 Combining the sub-factors

The five sub-factors need to be combined in order to establish the overall delivery risk index. The index was derived by calculating the average value of all five sub-factors across the landscape. A sensitivity analysis was undertaken because, although each factor is an acknowledged contributor to the index, the impact of the interaction of the sub-factors is uncertain. The sensitivity analysis provided a way of assessing whether the priorities

identified by the proposed method changed significantly with each scenario definition. Significant differences would be the identification of different hotspots that would result in a different management approach being adopted to manage erosion in the landscape. Three varying weighted overlay scenarios were undertaken which are defined in Table 4.3.

Table 4.3: Factor weightings (%) for Delivery Risk Index scenario definitions

	Intersection proximity	Road/stream adjacency	Delivery efficiency	Road surface condition	Road surface erodibility
Scenario 1	20	20	20	20	20
Scenario 2	20	30	30	10	10
Scenario 3	30	30	30	5	5

Scenario 1 is a baseline equal weighting overlay. In Scenario 2, road-stream adjacency and delivery efficiency have been weighted to account for 50% of the index. The remaining sub-factors, road surface condition and road surface erodibility, are assigned equal weighting. It is assumed, in this scenario, that convergent flows between roads and rivers, separated by a narrow corridor are significant factors in the delivery risk index. This is based on the observation in Australia of how watercourses become linked to streams by gully formation at the outlets of drainage structures (Furniss, Flanagan & McFadin 1999; Mockler & Croke 1999; Lamarche & Lettenmaier 2000). The actual sediment contribution of the gullies themselves have been excluded, since their existence is hypothetical.

Scenario 3 was defined to minimize the impact of the datasets in which confidence is lowest, or have higher level of assumptions, on the final delivery risk index. Given the computational problems encountered in the development of the road surface erodibility sub-factor, and the assumptions regarding road class and the surface condition sub-factor, the weighting of each of these has been reduced to 12.5%. The remaining factors have been weighted equally (25%). The results of these scenarios, for the illustrative sub-catchment are presented in Figure 4.7, Figure 4.8, and Figure 4.9.

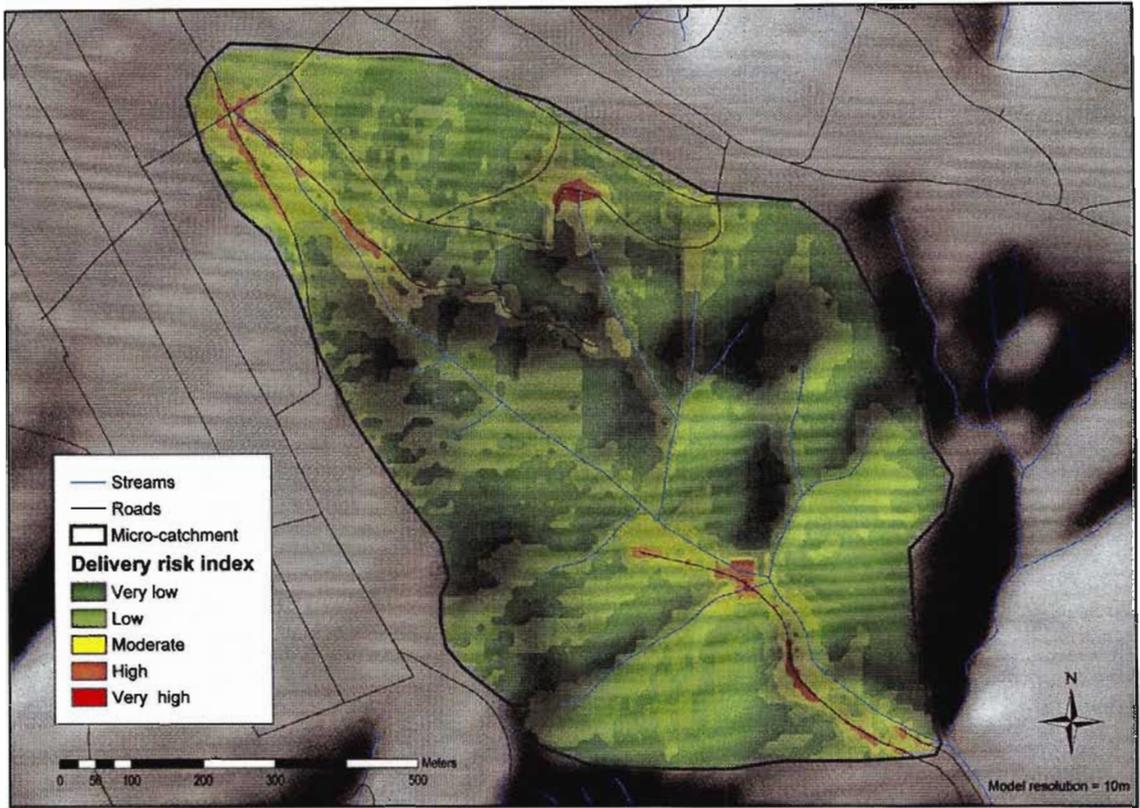


Figure 4.7: Delivery Risk Index results for the micro-catchment as defined by scenario 1

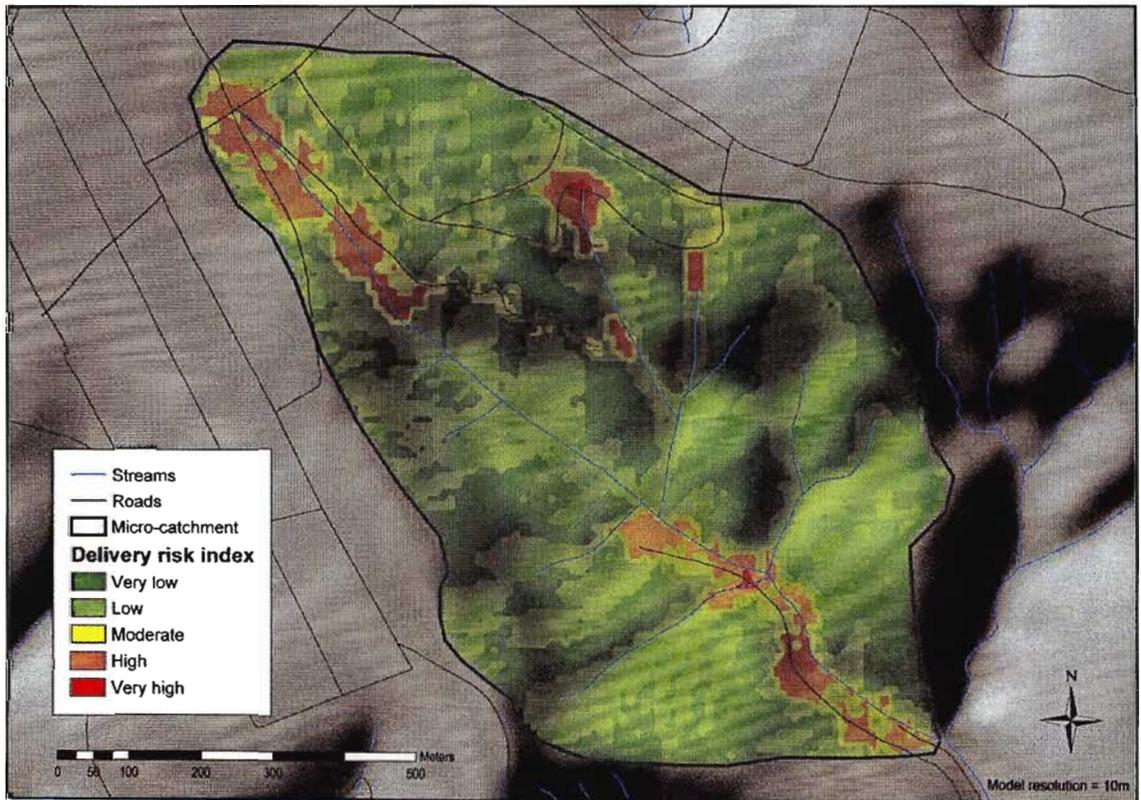


Figure 4.8: Delivery Risk Index results for the micro-catchment as defined by scenario 2

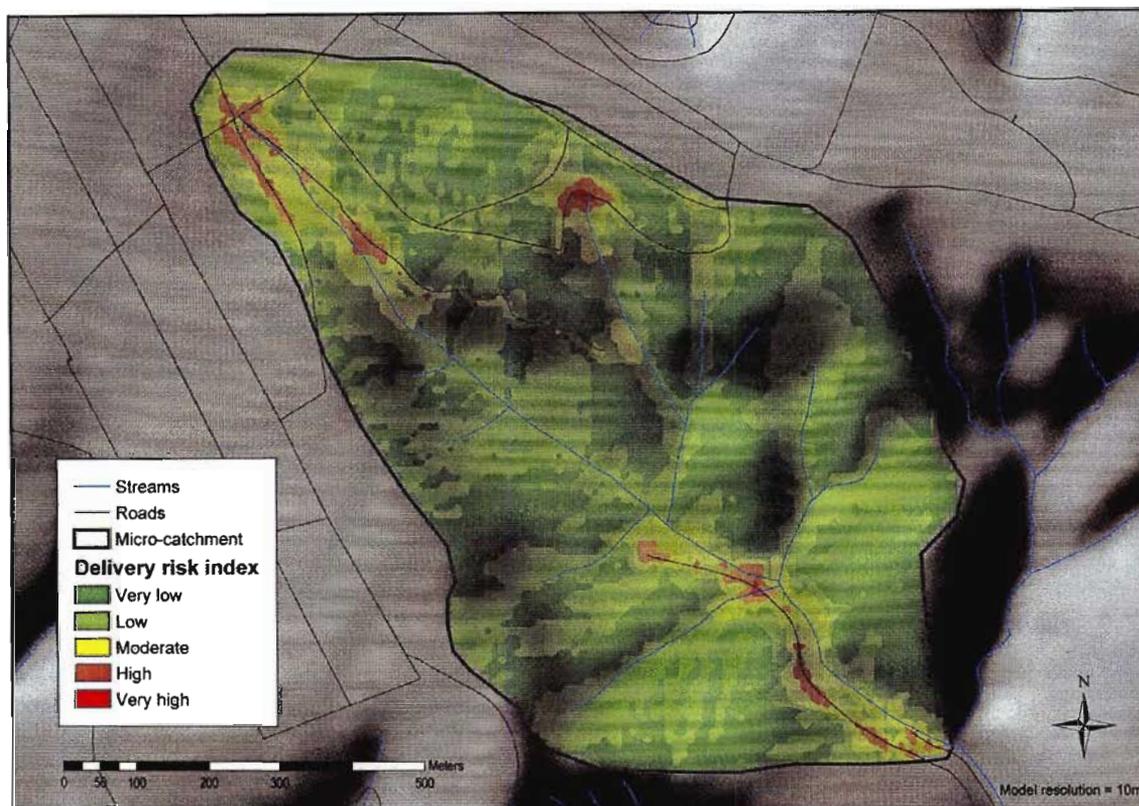


Figure 4.9: Delivery Risk Index results for the micro-catchment as defined by scenario 3

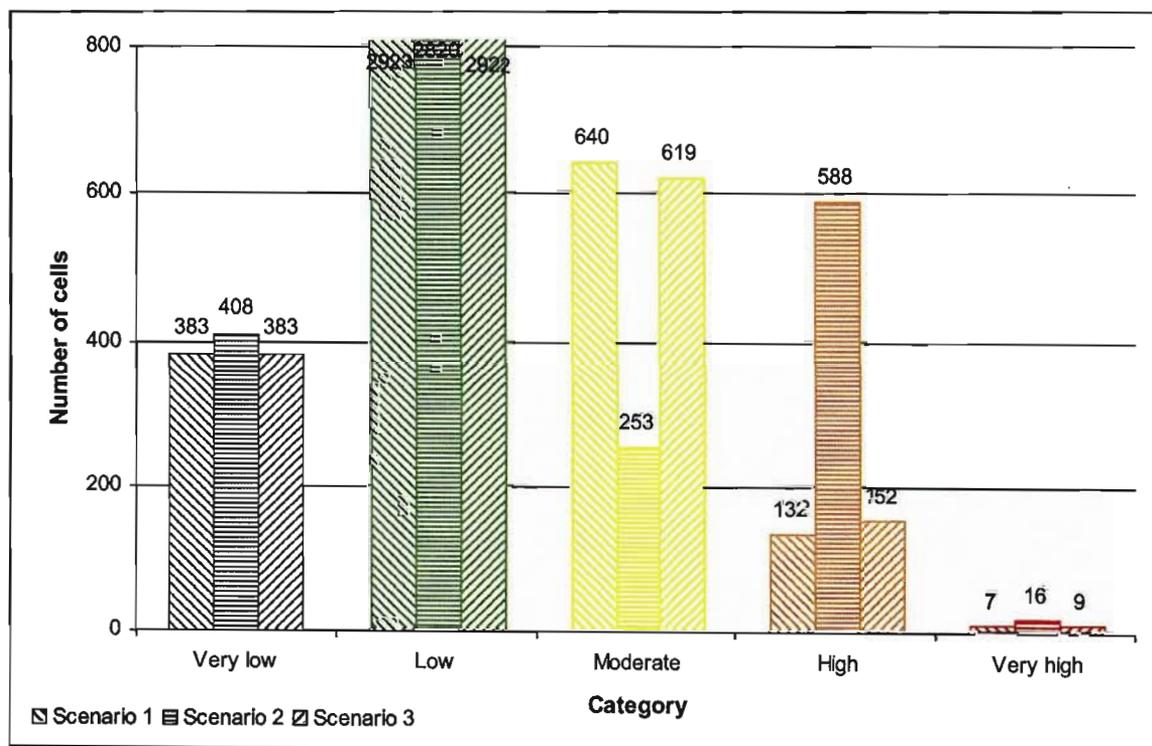


Figure 4.10: Graph depicting distribution of scores for the three Delivery Risk Index scenarios

The results of the three scenarios differ in the distribution of the moderate to high categories. However, the spatial distribution of the higher risk categories is similar in all three scenarios, suggesting that all three would identify the same specific areas as hotspots in the landscape. The distribution of the categories across the micro-catchment is present as a bar graph in Figure 4.10. This reveals the difference between the three scenarios more clearly. The Y-value represents the number of cells within each category. The X-axis has been scaled to reveal the distribution of scores across the landscape. Consequently, the upper limits of 'Low' category are not visible.

Based on the sensitivity analysis, the method using an equal weighting of the sub-factors was applied to the entire study area. Figure 4.11 presents the results for the study area.



Figure 4.11: The delivery risk index for the Mooiplaas study area

The distribution of DRI values shows the densely roaded eastern sections of the study area having a greater incidence of high and very high delivery risk than the less roaded western section. The influence of valley bottom roads, constructed in close proximity to watercourses is particularly apparent. Across the landscape the road features themselves, fall into categories higher than the surrounding areas. The results of the method devised for assessing delivery risk are consistent with the experimental evidence that informed the development of the method, discussed in Section 2.2 and Section 4.1. The significance of this consistency should not be over-emphasised since the applied method is simply a spatial assessment of the contributing factors.

4.3 SEDIMENT ATTENUATION INDEX

Topographic sediment traps are areas within the landscape where the terrain morphology, gradient, 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 4.12 presents the proposed method for identifying topographic sediment attenuation features. 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.

4.3.1 Identifying topographically suitable areas

As discussed in Section 3.4, 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.

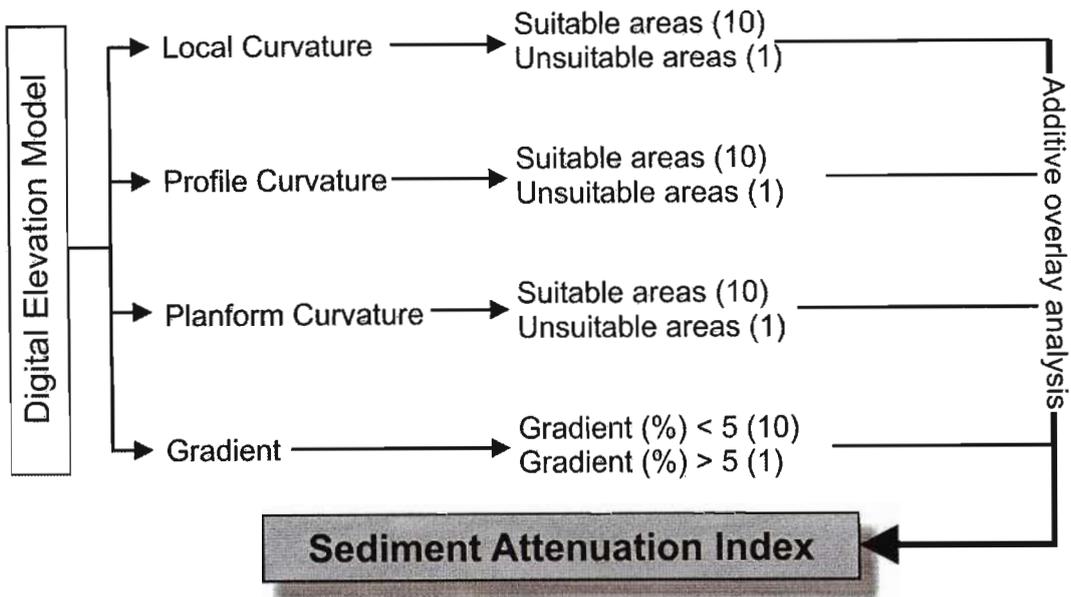


Figure 4.12: Process for identifying the probability of sediment attenuation features occurring in the landscape showing the sub-factors and their scores

4.3.2 Identifying low gradient areas

The gradient of the terrain is another contributing factor in identifying areas that may act as sediment sinks in the landscape. In the discussion of the SSI derivation, it was noted that gradients of less than 5%, are assumed to be deposition areas (Smithers & Schulze 1995). This same threshold is applied here as an indication of sediment attenuation potential.

4.3.3 Applying the method

Combining the results of curvature function in ArcView Spatial Analyst with gradient information derived from the slope function, and areas of undefined flow according to the process described above produces a surface identifying areas within the landscape where the topography facilitates sediment deposition.

Reclassifying the results of a slope analysis easily identifies areas where the gradient is suitable for sediment attenuation. Figure 4.13 depicts the gradient sub-factor values for the micro-catchment. The micro-catchment is characterised by steep terrain, which is why the entire area appears to be entirely unsuitable. There are, however, four isolated cells within the catchment that are identified as having a slope lower than 5%.

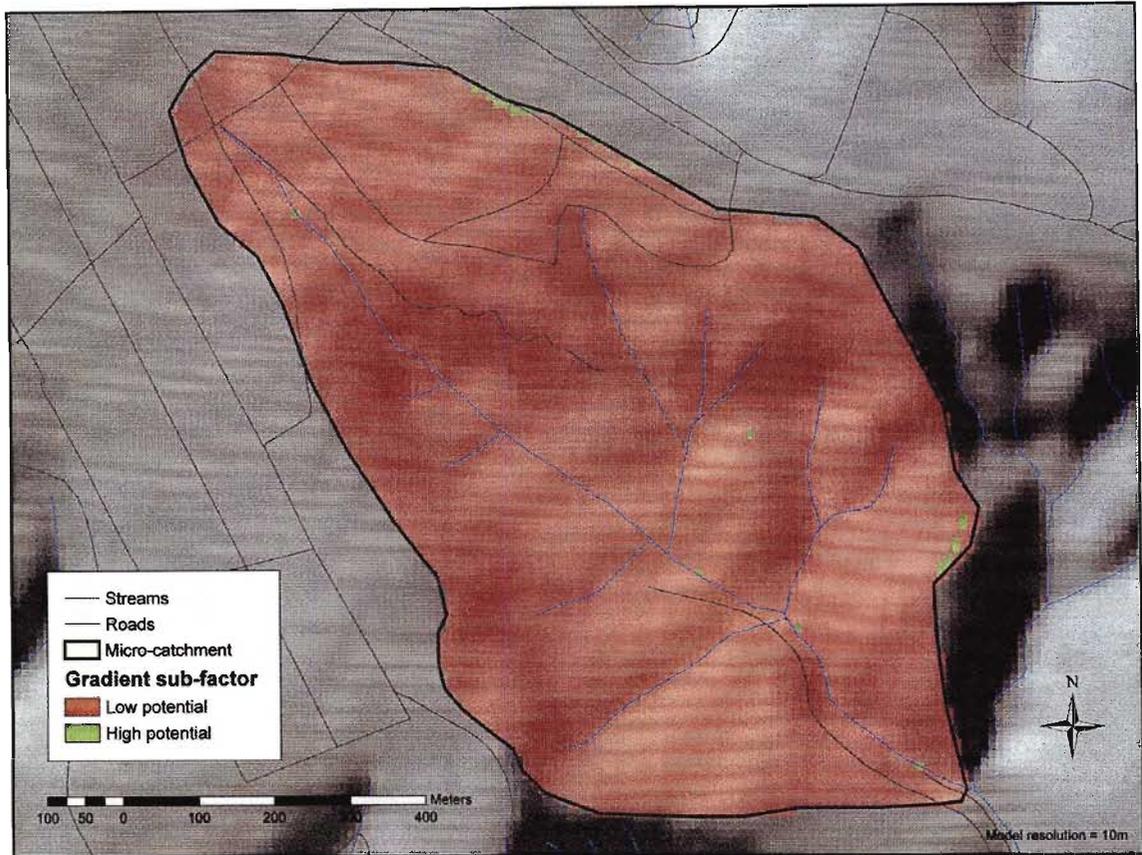


Figure 4.13: Gradient sub-factor within the micro-catchment

Wetlands are more likely to form on areas of less extreme topography. The three datasets produced by the curvature analysis were reclassified to eliminate extreme terrain. A manual inspection of the datasets, and examination of the ranges of values informed the development of a classification scheme. Areas were classified as topographically suitable if the values representing convexity and concavity were less than 10% of the maximum values for these indices. Thus the limits of concavity and convexity, the negative and positive values in the results of the curvature analysis, were set to eliminate the areas where the value exceeded 10% of the maximum score. Figure 4.14 depicts the areas identified as topographically suitable within the micro-catchment based on the results of the curvature analysis. The extremes of divergent and convergent areas within the catchment are identified in this process.



Figure 4.14: Topographic suitability sub-factor for the micro-catchment

Figure 4.15 shows the results of a simple additive overlay of the gradient and topographic suitability sub-factors. For the micro-catchment most of the area was classified as topographically suitable and the gradient of the area was the limiting sub-factor. A focal maximum process, with a 3 by 3 matrix, was run on the dataset to improve the visibility of identified area. This process effectively enlarges the areas identified.

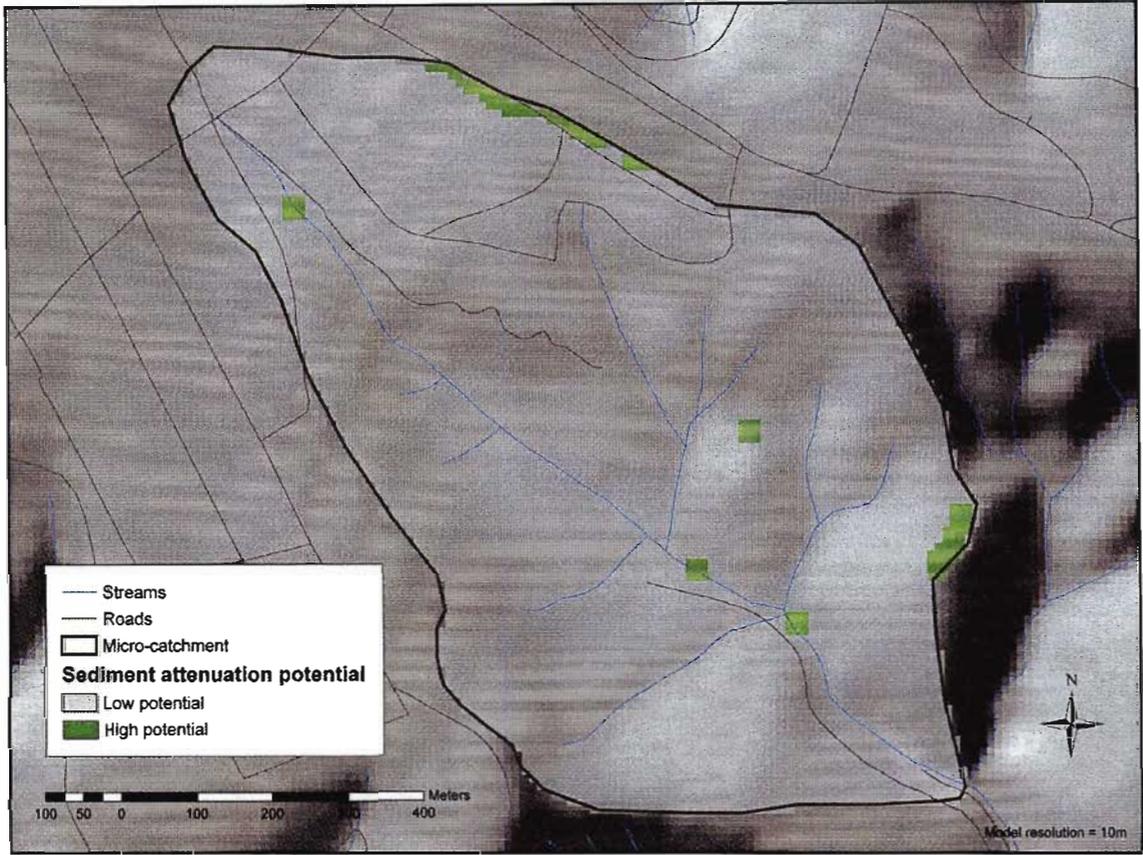


Figure 4.15: Areas with sediment attenuation potential derived by additive overlay

In order to assess whether the proposed method presented a realistic way of identifying areas of sediment attenuation potential in the landscape, the results were overlaid with the aerial photographs of the study area. Although, the canopy of the plantation obscures some of the detail in the landscape, there are three instances within the micro catchment that could verify the validity of the method. Two of these areas appear to be riparian wetlands, while the third appears to be a wetland seep area on an adjacent hillside. These are highlighted in Figure 4.16.

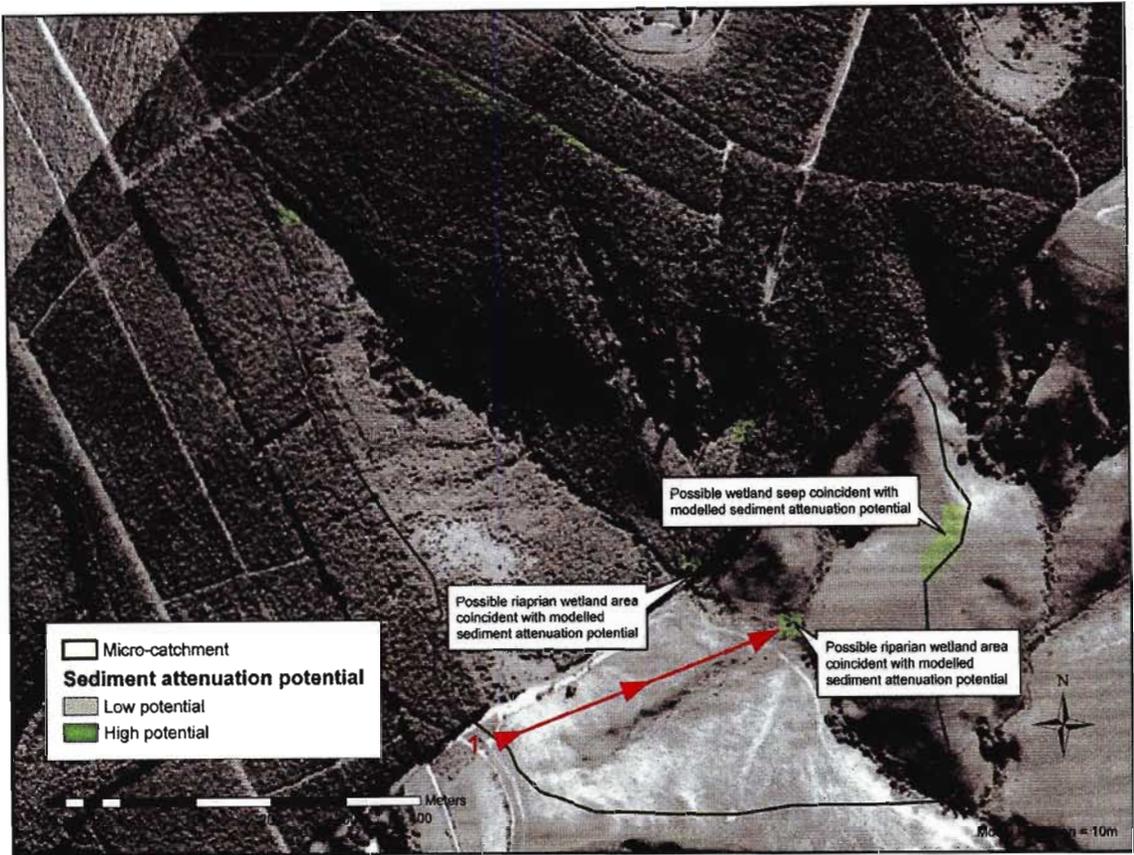


Figure 4.16: Modelled sediment attenuation potential within the micro-catchment in relation to observed features in the aerial photograph

Figure 4.17 shows the view looking from photo point 1 into the valley (the arrow indicates the direction of the view). A wetland (sediment trap) is clearly visible in the position predicted by the Sediment Attenuation Index (SAI). The seep area identified did show a clear vegetation change from the surrounding area. The extent of the area is not accurately depicted in the modelling results. It is likely that by refining the thresholds for the SAI derivation routine, that a better spatial representation of these area may be achieved. The functionality of the index, as it stands though, appears adequate for identifying the areas with sediment attenuation potential. It is apparent from the photograph that the area within the Mooiplaas plantation is severely disturbed, with the wetland area choked with weeds. Downstream of the boundary however, the wetlands are easily identifiable. The photo also indicates that the area identified as possibly being a wetland seep, is in fact the flat ridge of one of the spurs defining the micro-catchment.

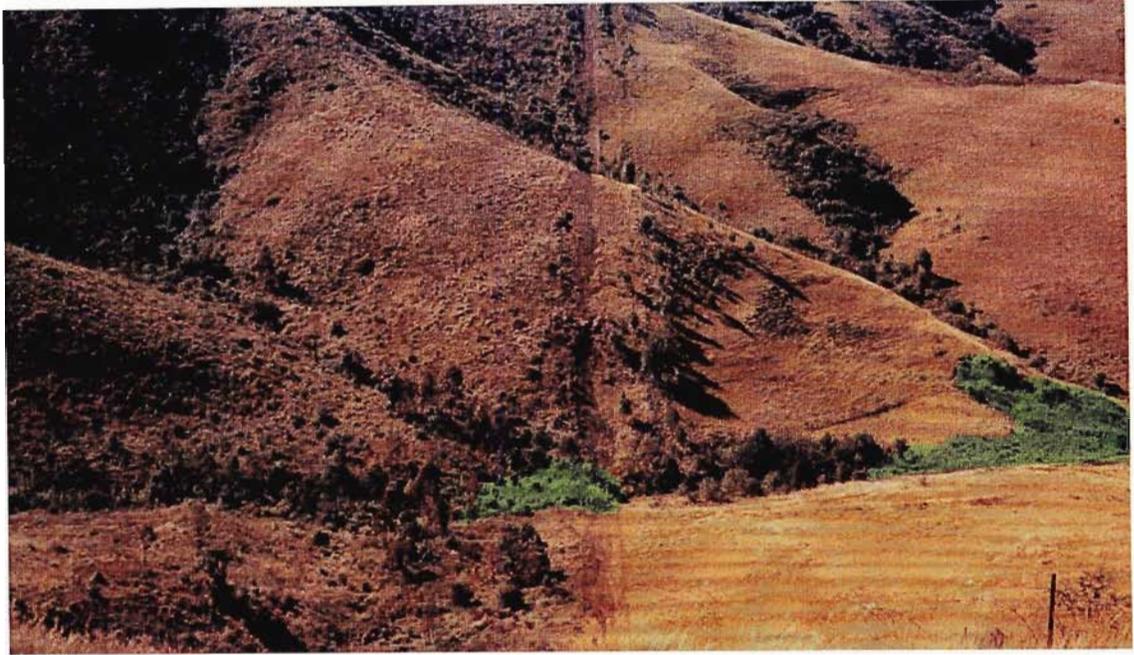


Figure 4.17: Photograph highlighting wetlands identified in the micro-catchment using the SAI

While a number of areas were identified across the study area, many are not necessarily valid sediment attenuation areas due to their position in the landscape. As with mistakenly identified 'wetland seep', flat areas along the spurs in the landscape can fulfil the criteria defined in the SAI modelling procedure. In order to identify these areas, the ridges were extracted using the modelled terrain units used in the Sediment Supply Index derivation. These have been overlaid on the sediment attenuation potential map. Given the ruggedness of the terrain, there are not many opportunities for using landscape services to reduce the delivery of sediment to streams. The application of the method in less extreme terrain would verify its potential to accurately identify sediment attenuation features within a landscape.

Figure 4.18 shows the results of the Sediment Attenuation Index modelling for the study area indicating the ridge features in the landscape. The distribution of sediment attenuation potential is constrained by the generally rugged terrain of the study area. The larger features identified are in the low-slope areas in the western and south-western parts of the study area, with a few small features being scattered in the rugged terrain, which is well represented by the micro-catchment in the central parts. The shape of larger features

appears to be more accurately modelled than the small features, though this is probably governed by the modelling resolution.

The indices developed in Chapter 4 are useful in the same way that the SSI is useful. They are efficient indicators of specific areas of potential, positive or negative, within the landscape. However, the application of all three indices in an integrated manner is likely to have greater benefit, in terms of developing erosion management strategies, than using the indices in isolation. It is necessary, in the application to be aware of the limitations and potential for improvement of the indices. Chapter 5 will discuss methods for improving the derivation of the indices, and present an example of their integrated application.

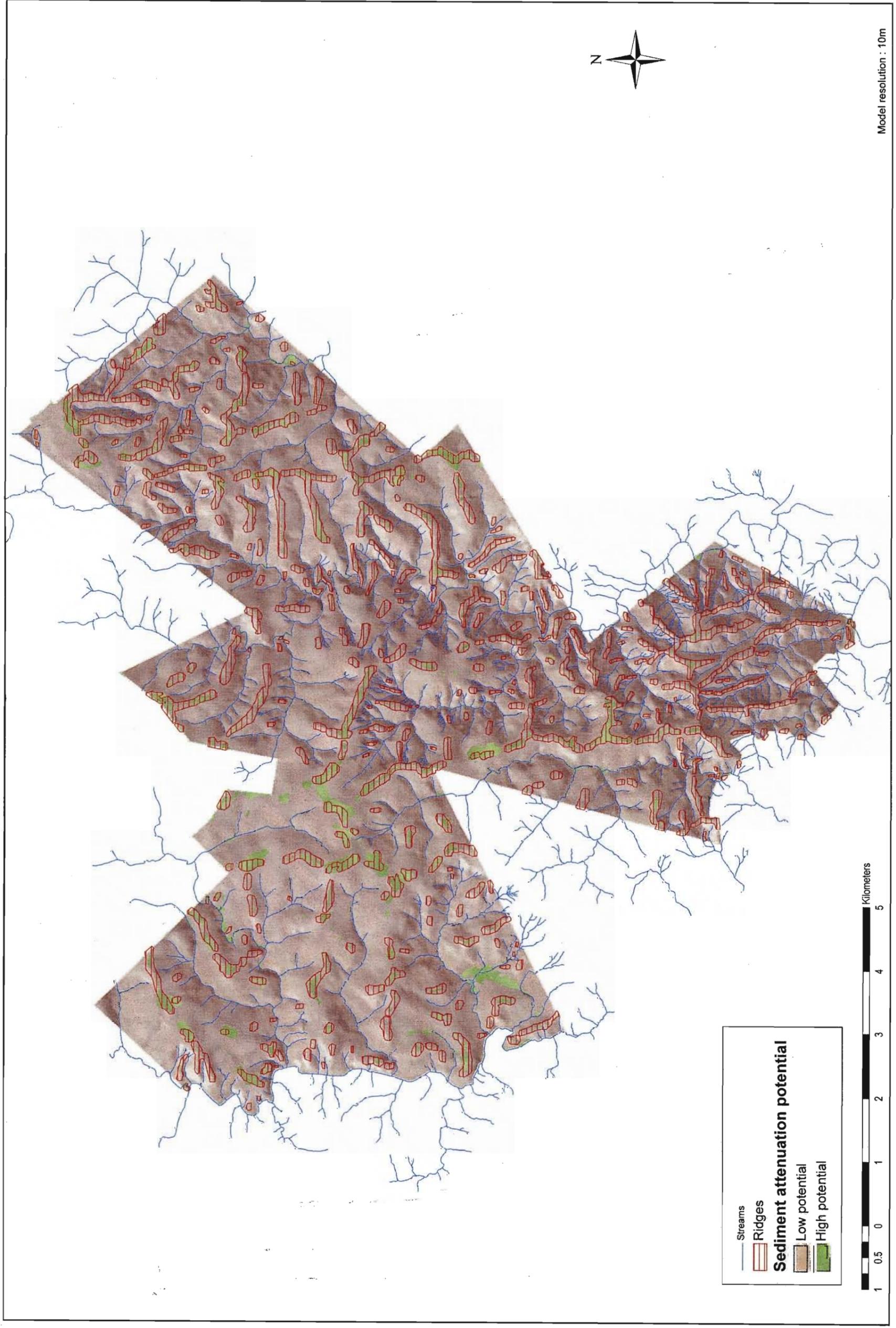


Figure 4.18: Results of the sediment attenuation potential modelling procedure for the Mooiplaas study area

CHAPTER 5: INTEGRATION AND DISCUSSION

This chapter will examine the developed procedures and outputs, identify both their strengths and weakness and suggest ways of improving them. Methods for integrating the three derived indices will be investigated with the objective of improving any management decisions that could be based on them individually.

5.1 IMPROVING THE DERIVATION OF THE INDICES

This section will concentrate on the technical aspects of the derivation of the indices. It will highlight the problems encountered in their development and the assumptions on which they are based. It will highlight ways of improving the three indices. Improvements relating to the quality of the input data will impact on the quality of the modelling results for all the sub-factors. One of the objectives of the research is to assess the utility of readily available industry and national datasets, so the discussion in the following sections will be limited to improvements to the modelling processes, or the derivation of the sub-factors. Where the impacts of improved data maybe particularly significant, these will be highlighted.

5.1.1 Improving the derivation of the sediment supply index

The Sediment Supply Index was derived by applying USLE-based erosion models. The landcover and management practice sub-factors were excluded, to avoid any implicit criticism of existing land management practices and to present the actual risk associated with freshly harvested areas. The USLE factors that are used in the SSI modelling are the rainfall erosivity (R), the soil erodibility (K) and the topographic factor (LS).

While the resolution of the R factor data is extremely low, it is the best available for implementing the procedure. If the process was adopted by the forestry industry as a best management practice, the collection of the required variables at an improved resolution should be considered. Smithen and Schulze (1982) specify an approach that could be used to derive better local scale estimates should it be necessary.

The soil erodibility sub-factor (K) was derived from coarse national landtype data. Although soil survey data is available in commercial forestry areas, the coverage is not complete across all plantations. Of particular significance, is that the surveys only cover the commercial areas, leaving, on average 30%, of the plantation area unsurveyed, and consequently excluded from the analysis area. Surveys conducted prior to the development of the Forestry Soils Database standard (Forest Industry Soils Database Cooperative 1995) are presented in different formats, which makes the integration and subsequent utilisation of these data difficult.

Since adequate resolution data is available at a national scale to implement the proposed methods, the application of improved algorithms for terrain analysis presents the greatest immediate opportunity for improving the modelling results. Early attempts to implement the USLE-based soil erosion models fell short due to problems in estimating the slope-length (LS) factor. There are no difficulties in establishing, or opportunities to improve, the gradient (S) sub-factor.

The Moore and Burch (1986) method of establishing the LS, based on flow accumulation can be effectively implemented spatially, as can the RUSLE method, requiring the effective flow length. Since both flow accumulation and flow length are derived from the flow direction, the application of improved flow direction algorithms will improve modelling results. The method used in ESRI GIS software is known as the D8-method developed by Jenson and Domingue (1988). The flow from a given cell is directed to the lowest of its nearest eight neighbouring cells. There is an implicit grid bias in the approach that limits the flow direction options to one of eight cardinal directions. It is also assumed that all the water available is directed into a single neighbouring cell. This method results in problems in areas of low slope, where parallel drainage lines are often the result of the analysis. Improved methods for modelling flow across a landscape have been developed, such as DEMON (Digital Elevation Model Networks) (Costa-Cabral & Burges 1994) and the D_{∞} method (Tarboton 1997). The D_{∞} model is available as a spatial application, in TARDEM (Tarboton 2000). It assigns flow direction by selecting the steepest downhill slope of eight triangular facets centred at each grid point. This method eliminates the grid-bias of the D8 method, as well as the unrealistic dispersion caused by other methods (Tarboton 2000). By

using the D_{∞} model to derive the flow direction and derivative flow accumulation and flow length, the result of all spatial applications of USLE based erosion models should improve. Table 5.1 presents the assumptions on which the Sediment Supply Index is based, as well as an indication of the confidence in the assumption.

Table 5.1: Confidence in the assumptions relating to the sediment supply index

Assumption	Confidence	Comment
USLE-based models are suitable for predicting soil erosion	High	
The ARC Landtype data is adequate resolution for forestry applications	Moderate	In the absence of better resolution datasets of the required extents this data has to be used
The flow accumulation method for LS-factor determination is preferable to RUSLE	Moderate	Literature suggests this model accounts for different types of erosion better than the RUSLE sub-factor derivation routines
Areas not suitable for USLE model application can be identified using GIS modelling techniques	Moderate	Assumptions that need testing <ul style="list-style-type: none"> • Slope threshold • Curvature analysis validity

5.1.2 Improving the derivation of the delivery risk index

The development of the delivery risk index, unlike the sediment supply index, did not have the benefit of a tried, tested and accepted method ready for application. In contrast, it relies greatly on inferences from the findings of research reviewed in Chapter 2. This index is primarily data driven. Consequently improvements to the index are achieved primarily by the improvement and extension of the input datasets. An exception to this is the road surface erodibility sub-factor, which will be discussed at length in Section 5.1.2.2. The following discussion highlights some of the data considerations and identifies ways of improving the development of the index.

5.1.2.1 *Data currency, resolution and derivation considerations*

This index is dependent on the analyses of existing data. Unfortunately, the resolution of the available datasets is not consistent. As a result there is a combination of datasets that may seem inappropriate due to the differing resolutions. This problem is acknowledged, however, the validity of the approach to assessing delivery risk is adequately illustrated using the available data. It should be noted in this regard that a stated objective of the research was to evaluate the utility of industry standard datasets in the application of the methods developed.

Many of the sub-factors of this index are derived by identifying the intersections, or determining the proximity of features in one dataset with the features in another dataset. The absolute efficiency of the method is determined by the accuracy with which the features were identified during the initial development of the input datasets. This is particularly relevant to the discussion of the rivers dataset. Development of the rivers dataset based on a manual photogrammetric interpolation (as was used by commercial forestry companies in South Africa) contains an element of subjectivity, particularly in areas where the canopy of the riparian vegetation is closed. The validity of the roads dataset is dependent on corporate data maintenance strategies. These data quality considerations fall beyond the scope of the research, which is focussed on the application of industry standard datasets, but should be considered before the methods proposed are applied.

The index can be improved by including specific drainage features along road segments, when considering road-stream interactions. The placement and condition of culverts and cut-off drains is critical in determining the impacts of the interaction between overland flow (before it reaches a stream), roads and riparian areas and their associated streams. These points of hydrological interaction should be included in the analyses for assessing sediment delivery risk. Unfortunately these data did not exist for the study area. However, the requirements of the certification and accreditation authorities may require that these data be collected. This would greatly improve the quality of the index, although the derivation of the index would require modification.

A further issue that needs to be considered relates to lengths of the road surface that act as direct conduits of overland flow. As mentioned in Section 4.2.4, roads do not follow the natural topography of the landscape because their construction often requires the modification of localised topography. It is impossible to determine road topography effectively using medium resolution elevation datasets, since the width of the road is generally less than the data resolution, which essentially smoothes out the micro-topography of the roads themselves. However, the

extremely high-resolution elevation data that can be derived from LIDAR (Light Detection and Ranging) surveys can overcome these problems. Due to the extremely high resolution of the data (10 - 25 cm sampling, with a relative vertical accuracy of 2cm) road features, and even drainage features along them, become distinct in the DEM derived using LIDAR survey techniques. Additionally, since the data is a direct measure of the ground surface the behaviour of overland flow can be modelled with greater accuracy.

Sample LIDAR data, supplied by Sappi Forests, from a plantation in Mpumalanga has been used to identify overland flow patterns successfully. The process involves the development of a flow accumulation surface, which depicts the number of upstream cells contributing flow to a given cell. The hydrological network is derived by setting a threshold for flow accumulation above which the flow is assumed to be a first order stream. Roads acting as conduits for overland flow are easily detected in the results. Where these length of roads that function as watercourses are identified, the risk factors associated with the points of interaction between the road and streams and culverts would need to be weighted to account for the increased flow contributed by the road surface. Figure 5.1 shows the LIDAR-derived DEM for the Mpumalanga sample data. The resolution of the dataset is 0.5m. The derived watercourses, depicted in blue, clearly identify reaches of road likely to act as conduits of overland flow.

It must be noted that the resolution of LIDAR data is too high for application in the development of the standard topographic factors, such as slope or curvature that are associated with the sediment supply index. This is due to the fact that the unit of analysis is too small for the landscape trends to be detected. The potential of this data to improve results is high, but LIDAR surveys are not currently part of any standard corporate data acquisition strategies in the South African forestry sector.

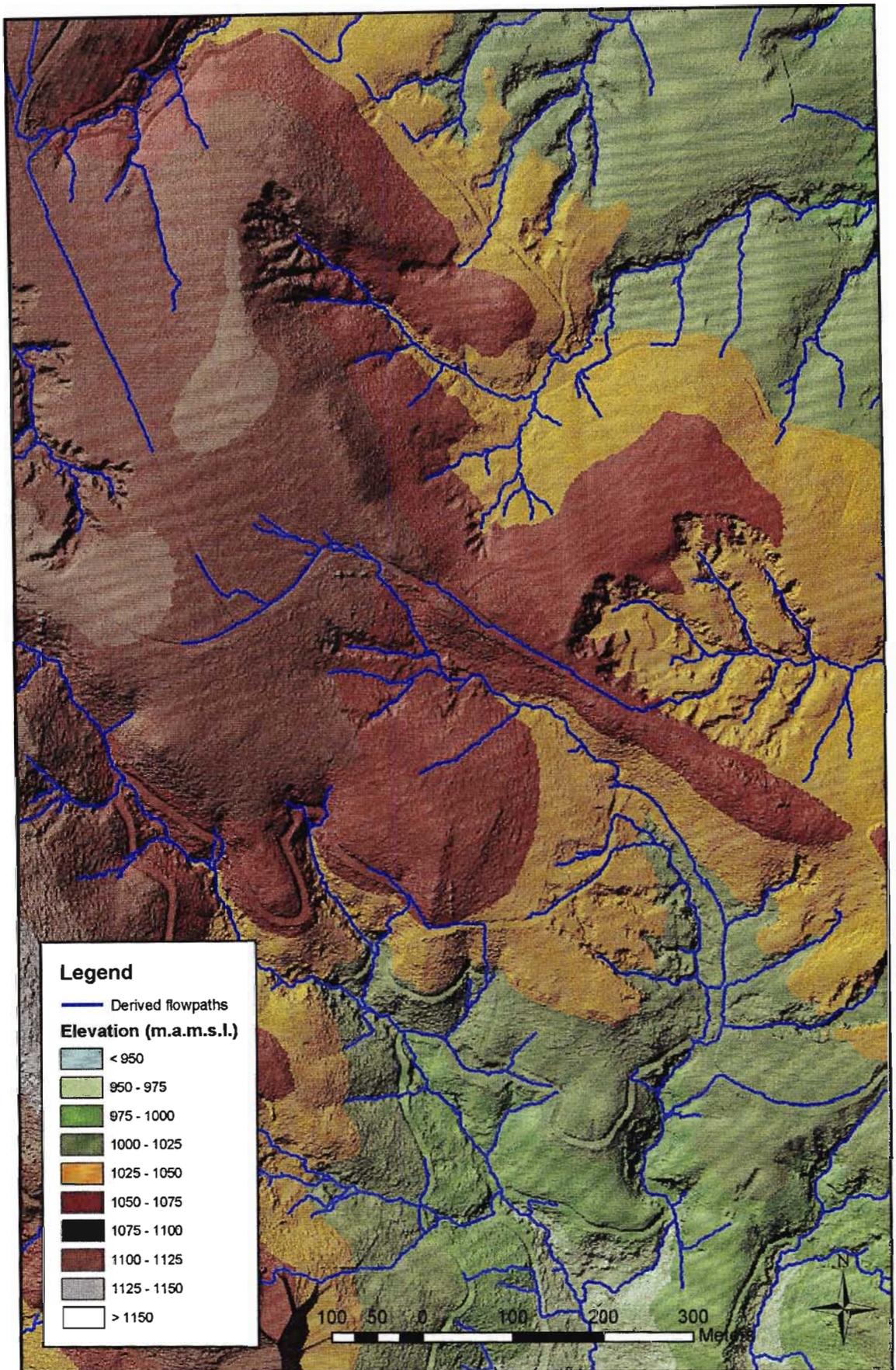


Figure 5.1: LIDAR-derived DEM with derived watercourses

5.1.2.2 Road surface erodibility

The discussion in Section 4.2.4 highlights some of the problems experienced in the derivation of this sub-factor. The most problematic shortcoming in the proposed method is that breaking the roads into segments according to a known change in elevation, and assessing the erosion potential of each segment individually, eliminates the effect of cumulative flows since the analysis does not account for topographically continuous reaches of road. Although modelling procedures were attempted which would resolve this, the complexity of limited interpolation extents seems to exceed the computing power available in the desktop GIS environment.

As with the process for assessing road stream interaction described above, the main issue is the development of a dataset that accurately represents the topography of the road network, as opposed to the terrain morphology. Advanced survey techniques, such as LIDAR discussed in Section 5.1.2.1 above, can solve the problem since the direct and high-resolution observations can enable the development of a topographically correct road model. The utility of this method is limited, unless these surveys are incorporated into the standard data acquisition strategies of the forestry industry. The underlying assumptions of the Delivery Risk Index are presented in Table 5.2.

Table 5.2: Confidence in the assumptions relating to the delivery risk index

Assumption	Confidence	Comment
The relative importance of the various sub-factors is equal	High	Sensitivity analysis showed no significant change in the distribution of identified hot spots
Distance / interaction thresholds	Low	Assumptions based on the findings in the literature review
Road class is an adequate proxy for road condition	Low	Assumption driven by availability of data. Actual road condition data will improve the derivation of this sub-factor. Field visits confirmed that road class is inadequate
Modelling of sediment supply of road surfaces is adequate	Low	Fails to account for topographically continuous road lengths. More advanced modelling is required to combine road reaches into topographic units. Incorporating the results of aspect analysis may assist in solving this problem
Influence of convergent flow paths	Moderate	Can be improved by relating the value of the convergence index to the actual risk thus refining the impact of topography
Road – stream interactions	Moderate	Sub-factor would be improved by data regarding the condition of each crossing to permit weighting of risk associated with particular crossings
Subjectivity of qualitative assessment of sub-factors	Low	Improvements in the completeness of input data would substantially reduce reliance on subjective assessments of sub-factors

5.1.3 Improving the derivation of the sediment attenuation index

Of the three factors identified as relevant in developing a management strategy to minimise sediment delivery to streams, this is the simplest. The modelling routines are all directly available through the ArcView Spatial Analyst, with no customisation required.

However, there is a modelling routine that may be used to enhance the calculation of this index. It is appropriate for application in areas where the topography is less extreme than in the study area for this research. As described in Sections 3.3.3 and Section 5.1.1, the flow direction algorithm used in Spatial Analyst (D8-method) has a grid bias and all flow is directed into a single neighbouring cell. This makes the performance of stream delineation in low gradient areas problematic since there is no clear flow path to be defined. This can be exploited in defining sediment traps since this is exactly the flow characteristic that would promote diffusion of overland flow, causing a reduction in velocity and deposition. However, it may be that these undefined areas are already accounted for in the gradient limits set for sediment attenuation. The underlying assumptions of the Sediment Attenuation Index are presented in Table 5.3.

Table 5.3: Confidence in the assumptions relating to the sediment attenuation index

Assumption	Confidence	Comment
The slope threshold for reducing sediment mobility is 5%	High	Schulze (1989)
The topography of the terrain can be adequately modelled to find areas that may attenuate sediment delivery to streams	Moderate	The relative values of the results of the curvature analysis need to be investigated, to determine thresholds
Areas of undefined flow depict areas of low sediment mobility	Low	This analysis 'error' produced by the GIS stream delineation routines needs to be tested in less extreme terrain, where such areas are present in the analysis results

5.2 USING THE INDICES TO INFORM MANAGEMENT DECISIONS

There are two components in the application of the derived indices to inform management decision. The first is using the indices to identify the priority areas for intervention, and the second is making site specific recommendations based on the sediment supply risk and the delivery risk associated with the specific priority site.

5.2.1 Identifying priority areas

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. An area of moderate, or even low, erosion potential (SSI value) drained by particularly short watercourse, may well be at greater risk than a long watercourse draining an area of high erosion potential, because the sediment load to the watercourse is determined by the length over which the mobilised sediment is distributed. This realization has driven the enhancement of the results by relating the derived sediment supply and delivery risk indices to an associated watercourse. This gives rise to indices that are more useful indicators of priority.

The development of these new indices requires the delineation of catchments across the study area, and the establishment of the length of stream associated with each catchment. Finally, the mean SSI and mean DRI need to be established per catchment, and related to the associated stream length to develop the priority indicators. The technical process to achieve this is described below.

A stream network was derived from the DEM using the flow accumulation function in ArcView Spatial Analyst. A derived stream network was used, rather than the observed network, because the generalisation that occurs during the interpolation of a digital terrain model may result in an offset between observed features, and their position in the modelled landscape.

Streams are defined by setting a drainage area threshold above which surface flow is regarded as a watercourse, as described in Section 3.3.3. Thresholds of three and five hectares were investigated. The first resulted in 982 streams and catchments being defined, the second resulted in 582 streams and catchments. The five-hectare threshold was selected because the 443 streams eliminated by the larger threshold were all less than 30m (3 raster cells) in length. Although the number of sub-catchments across the study area is still high, it must be remembered that these catchments are not management units, they are only a method for translating the landscape-based indices into a stream-based hydrological risk indices.

In order to establish these streamside risk indices, it is necessary to know the catchment area of each relevant stream, and the length of stream draining the catchment. Once

catchments have been defined, the length of stream draining the catchment can be calculated by a simple overlay analysis, or cell count in a raster linear network.

The indices for a defined stream can be established using the following equation:

$$Index_{SR} = \frac{Index_{LS}}{SL} \quad (16)$$

where

$Index_{SR}$ = streamside risk index

$Index_{LS}$ = catchment mean of landscape based index (i.e. SSI or DRI)

SL = stream length draining catchment

The results of this analysis for the SSI and DRI are presented in Figure 5.2 and Figure 5.3. By comparing these two figures with Figure 3.13 and Figure 4.11 respectively it is apparent that the priority areas, where the streamside index score is in the higher categories, are different to those that would have been identified had the basic sediment supply and delivery risk indices been used. Initially, these individual streamside indices were combined to form a single index that addresses both the sediment supply and sediment delivery concerns to maximize the efficacy of any management interventions. The method for deriving this integrated index is described below.

The SSI index is based on predicted erosion potential, while the DRI is an index that was normalized to a score out of 10 from the outset. In order to be able to combine these indices without the SSI confounding these results, the scores need to be normalized into a single comparable range of values, without compromising the data resolution. To accomplish this the values for both streamside risk factors were normalized to a score out of 100. It was assumed that the resultant dataset would be most useful in prioritising sites for management intervention since it identifies areas with high potential for sediment production and efficient delivery mechanisms that are hydrologically connected with short stream reaches.

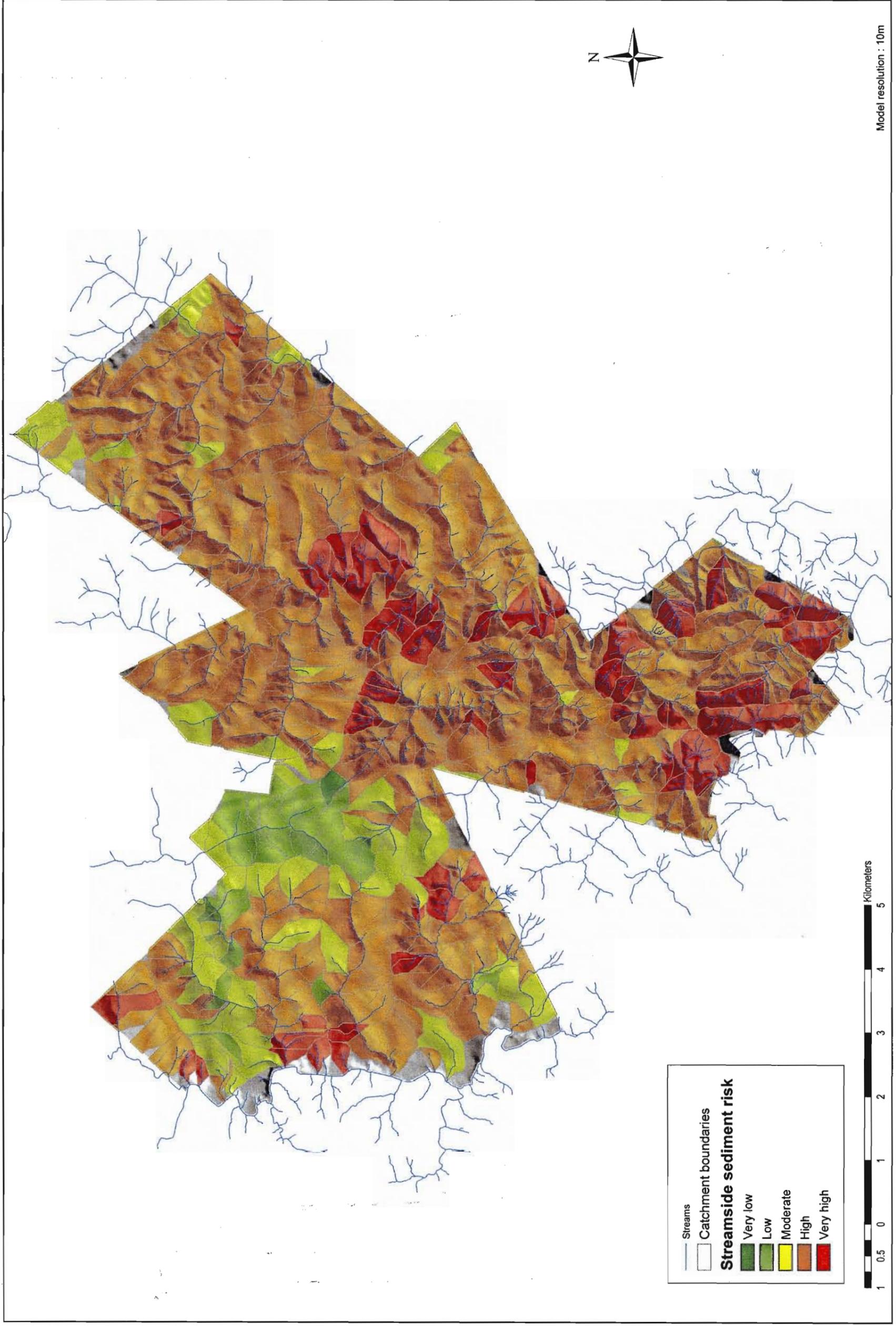


Figure 5.2: Streamside sediment risk per delineated catchment

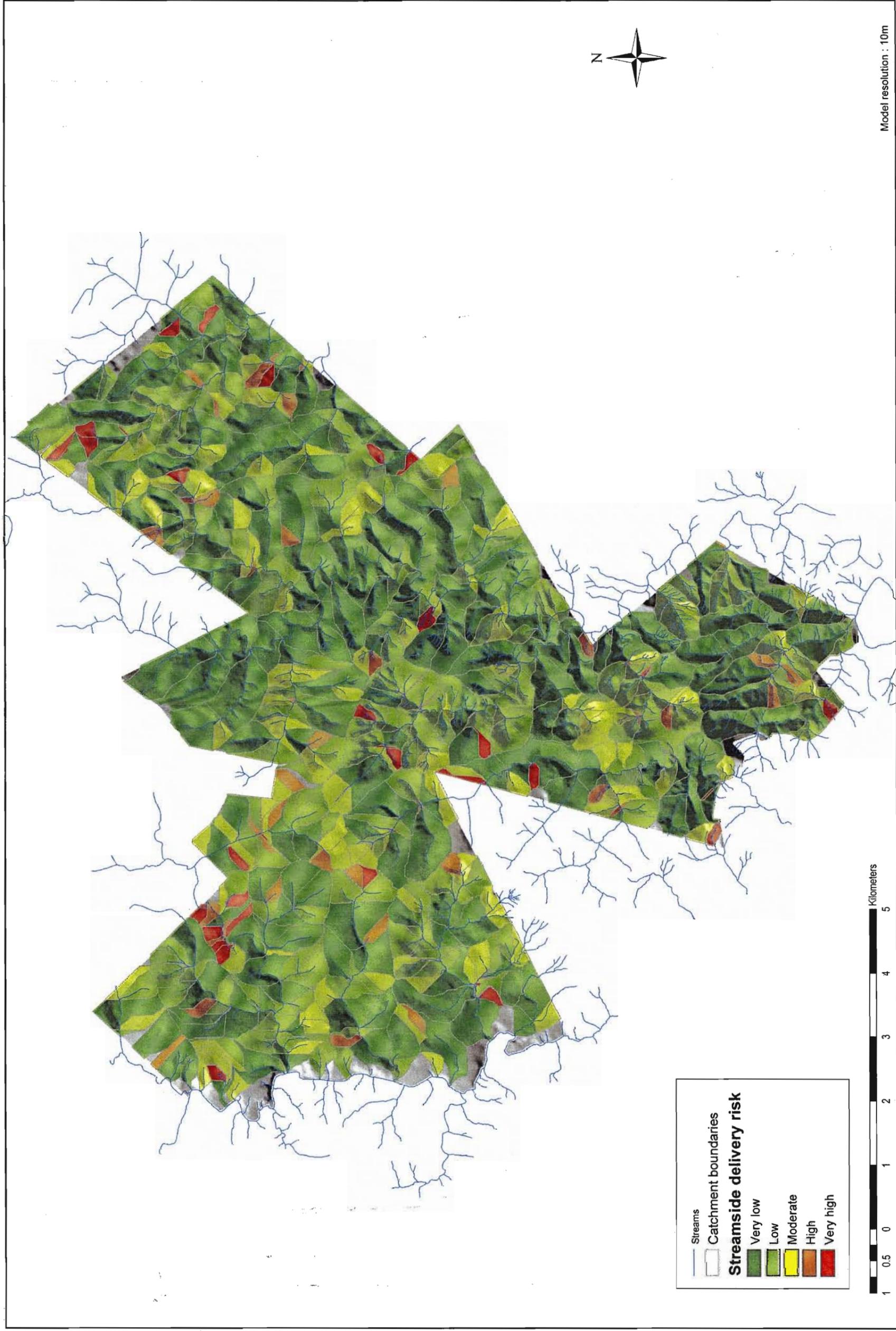


Figure 5.3: Streamside delivery risk per delineated catchment

However, since the DRI identifies specific positions in the landscape where sediment delivery to streams is likely to be particularly efficient, the validity of calculating a mean value for a stream length was questioned. Consequently, the combined streamside risk index based on the mean values of sediment supply and delivery risk was discarded. The revised method of application is to use the streamside Delivery Risk Index to establish the priorities for erosion control, and to use the Delivery Risk Index to guide the development management strategies so that the delivery risk hotspots within the priority areas are properly managed and attenuated. Figure 5.4 shows the streamside sediment risk index with the delivery hotspots highlighted.

5.2.2 Recommending a buffer width

While identifying priorities in the landscape for sediment control is important, it is necessary to make a buffer width recommendation that can be implemented in the identified priority sites. Buffer width recommendations need to consider both the amount of sediment that is likely to be delivered as well as the localized topography within which the delivery occurs. Karssies and Prosser (2001) present a method for determining buffer width requirements, based on the mechanisms of sediment trapping within buffers. Although not developed specifically for forestry conditions it is the only known method for deriving buffer widths, based on topography and sediment supply that can be readily applied in a GIS environment. In its simplest form it can be presented by the equation below.

$$w = 2 + 0.636A - \frac{0.12}{\tan \theta} \quad (17)$$

where

- w = buffer width recommendation
- A = annual soil loss ($\text{t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$)
- θ = gradient (degrees)

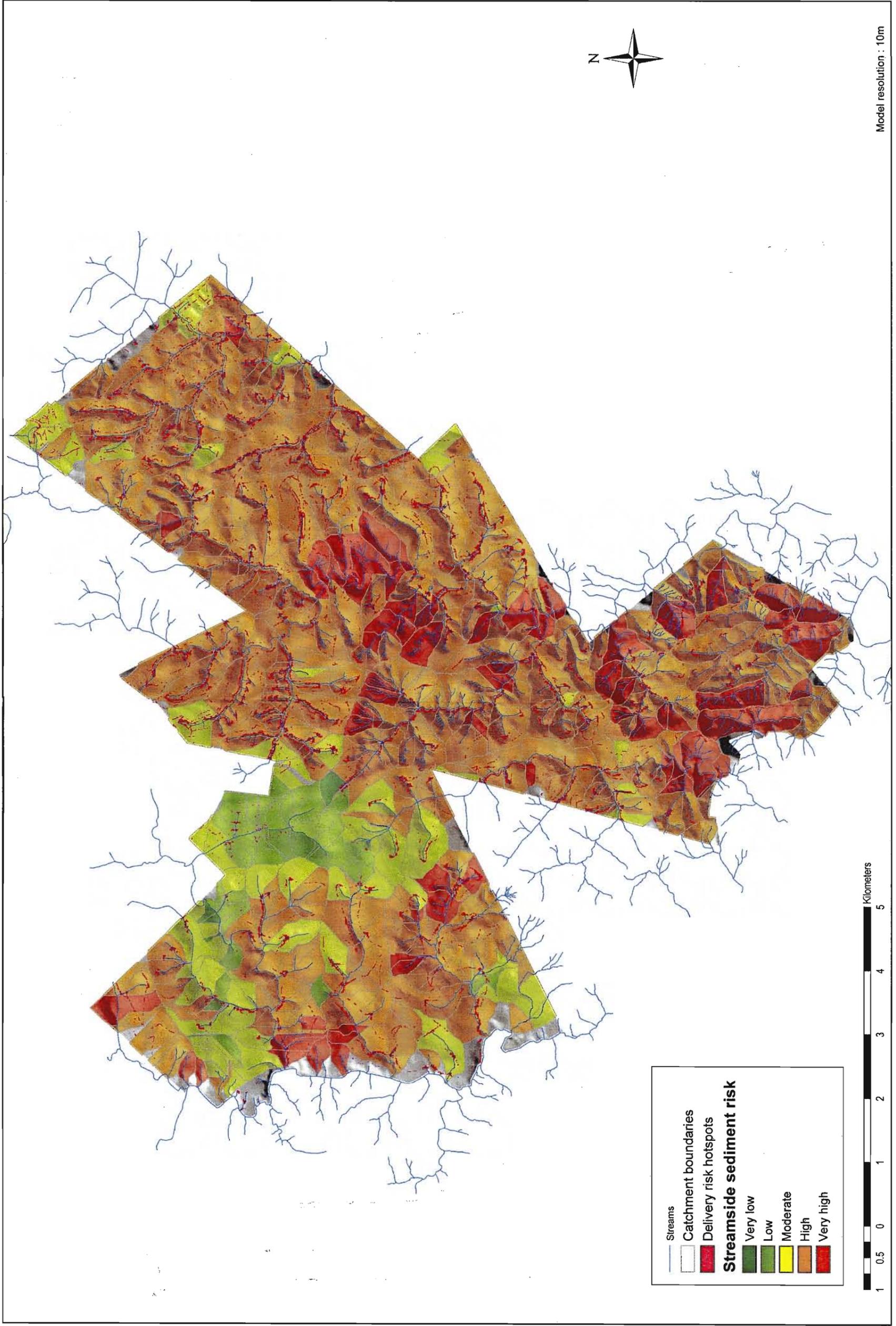


Figure 5.4: Streamside sediment risk per delineated catchment with delivery risk hotspots highlighted

Using the same set of catchments as were used to determine the streamside risk indices, this equation can be implemented easily. The Sediment Supply Index provides a worst-case scenario for potential sediment supply. The index is not a quantitative measure of sediment supply but a measure of the potential erodibility based on soil and topographic factors only. Using the SSI will result in extremely wide buffer width recommendations. These recommendations would be wrong since they are based on invalid input data. It was therefore necessary to add the C-factor into the sediment supply derivation to develop a more realistic assessment of the actual amount of sediment produced. This does not undermine the utility of the original index in establishing priorities in the landscape; it only serves to enable realistic buffer width recommendations to be developed.

The C-factor was determined using the methods described by Smithers *et al.* (1995). The unplanted areas were assumed to be grassland in moderate condition. Afforested areas were assumed to have a mulch layer of 25mm with a loose and friable soil texture (based on observation during the field trips). Smithers *et al.* (1995) provide a range of initial SCS curve numbers for different hydrological soil groupings and landcover classes. Based on the above assumptions an initial SCS curve number was determined for each combination of hydrological soil grouping and cover. This initial curve number was input into the equation for determining the C-factor based only on the initial SCS curve number, presented by Smithers *et al.* (1995).

These factors were incorporated into the erosion modelling procedures. The resultant dataset was used to determine the mean sediment supply (considering landcover) for each of the small catchments using the zonal-statistics functionality in ArcView Spatial Analyst. Mean slope per catchment was determined in the same way. This supplied the two inputs into the buffer width equation (Eqn. 17). The resultant buffer width recommendations were applied to the streams. The results are depicted in Figure 5.5. Additionally, standard buffer widths of 20m and 30m were modelled, to compare the amount of planted area lost by implementing the derived buffers versus buffers compliant with industry standards and legal requirements. Table 5.4 presents the amount of currently planted area that is lost using each of the methods described.

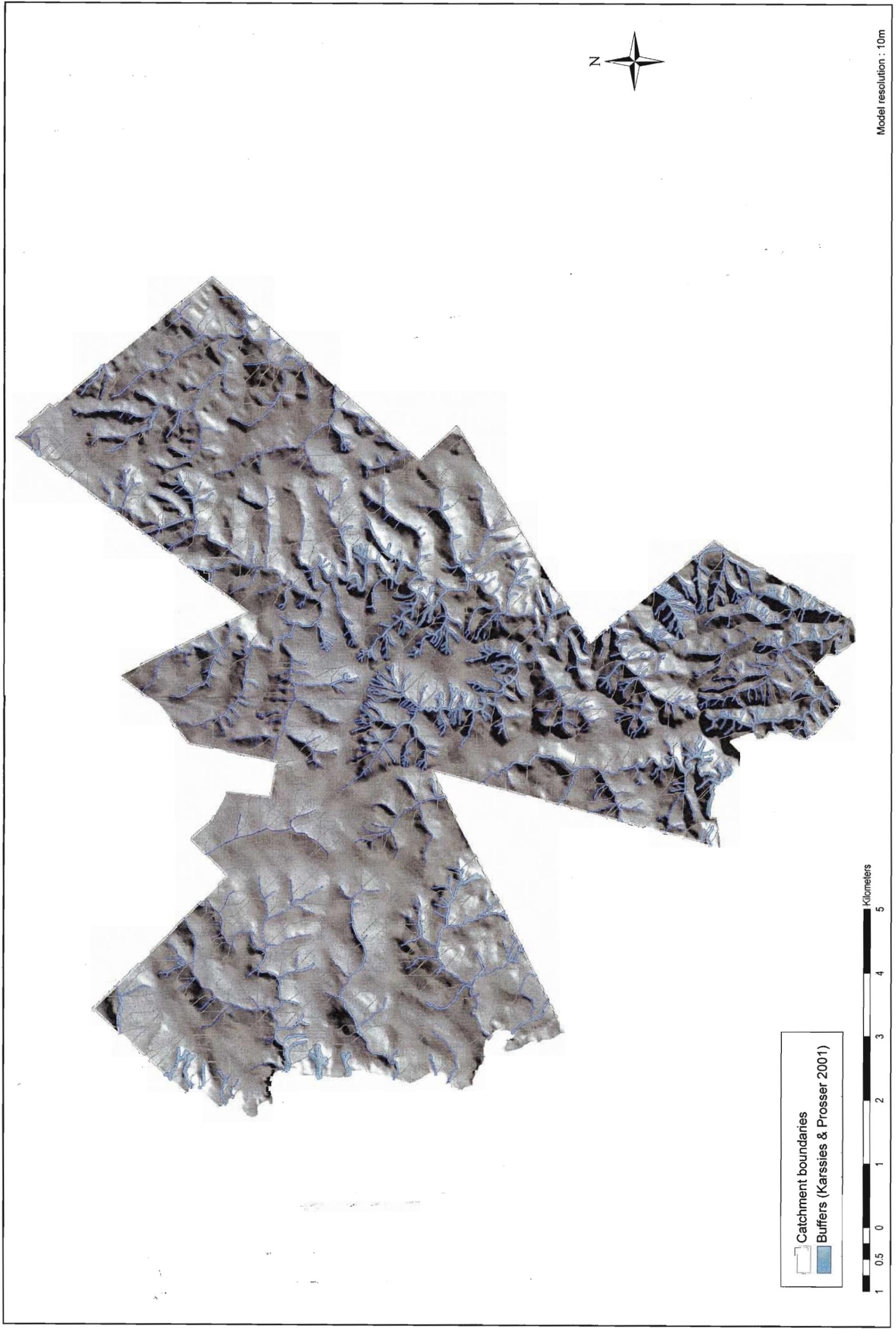


Figure 5.5: Buffered streams using the widths derived by the application of the method developed by Karssies and Prosser (2001)

It must be noted that the Karssies and Prosser (2001) widths are based solely on the requirement of sediment attenuation. The results are useful in cases where the existing buffer is either wider or narrower than the derived buffer width recommendation. In areas where the existing buffer is narrower than the recommended width, it will be necessary to widen it to at least the minimum recommended width and ensure that the condition of the vegetation is maintained for optimal sediment trapping. Where the existing buffer exceeds the minimum recommended width, it is a matter of ensuring a strip of vegetation that equals or exceeds the recommended width, is maintained for optimal sediment trapping within the existing buffer.

Table 5.4: Planted area lost under different buffer width scenarios

Buffer width scenario	Total planted area lost
Standard 20m buffers	186.8 ha
Standard 30m buffers	370.8 ha
Karssies & Prosser (2001) buffers	91.7 ha

These results suggest that, on average, for the study area the existing buffer standards around watercourses are adequate for sediment control. The critical factor is thus the condition of the vegetation within the buffer area. It must be noted though that the steep headwater streams are often inadequately protected, while the lower order watercourses are over protected. This result corresponds to Bren's (1999b) observation that identified upslope convergent areas as areas that are usually under protected.

5.2.3 Site-specific recommendations

An effective erosion management strategy requires that two aspects of the erosion process be considered. The first aspect is not the focus of this dissertation and relates to the management of erosion at the sediment source. However, the results of the spatial modelling do have application in this regard. Onsite erosion control is discussed briefly below. The direct modelling results themselves, presented as a continuous surface, are suitable for the identification of priority areas for on-site erosion control.

5.2.3.1 Onsite erosion control

In commercial forestry areas, on-site erosion control measures are primarily governed by the season during which an area may be harvested, and the

management of the timber residue, or slash. The Guidelines for Environmental Conservation Management in Commercial Forests in South Africa (Forestry Industry Environmental Committee 1995: 3) state, “(i)n the interest of mineral recycling and soil conservation, slash should be left to decompose where possible”. The use of slash as an erosion reduction measure is particularly contentious since it increases the fire risk on a plantation considerably. Where a harvested area with the slash removed or burnt in a controlled manner essentially acts as a fire protection feature, a harvested area where the slash has been left as an erosion control measure is a fire risk. The dilemma presented to forestry managers is presented in Table 5.5.

Table 5.5: Issues arising from the use of slash as an erosion control measure

Erodible areas	Burn slash	Stack slash	Risk / Benefit
Dry season harvesting	✓	✗	<ul style="list-style-type: none"> • Fire risk minimized, provided weather condition permit safe burning of slash • Erosion potential reduced, provided no unseasonal events occur
Wet season harvesting	✓	✗	<ul style="list-style-type: none"> • Fire risk minimized • Erosion risk maximized
Dry season harvesting	✗	✓	<ul style="list-style-type: none"> • Fire risk maximized • Erosion risk minimized
Wet season harvesting	✗	✓	<ul style="list-style-type: none"> • Fire risk reduced • Erosion risk reduced, provided on-site management measure are effective

The optimal solution to the problem would be if the timber residue could be processed on-site in such a way as to minimize the fire risk without compromising its utility in erosion control. The on-site chipping and focused spreading of slash may be a solution. The modelling results, can inform the development of slash management strategies for each harvesting unit. The resolution of the modelling results could be used to identify critical areas for erosion control within each compartment. By deploying slash as an erosion control method only where it is necessary, the creation of a continuous combustible surface across the entire compartment can be avoided, significantly reducing the fire risk. Such high-resolution management is however difficult to implement, and a cost-benefit analysis would need to be performed to assess the viability of this approach. The forestry industry worldwide has adopted policies to ensure environmental sustainability. In achieving this, and conforming to it's own standards and

maintaining access to international markets, the implementation of management actions, such as the one described above, may become obligatory.

Figure 5.6 presents an example of how the procedure described above may be implemented. For illustrative purposes, an area with a range of SSI values was selected. Priority areas were defined based on generalizing polygons describing the occurrence the top three categories of the sediment supply index. The red numbers in the map refer to Figures 5.7 to 5.10, which are photographs taken during field trips. The small black numbers are the compartment identifiers. It should be noted that the photographs are taken during winter, making the vegetation gradients less distinct.

Figure 5.7 shows the location of the gully identified in the map as photo point 1. Figure 5.8 shows three views of the gully within the compartment. It is interesting that although there are no significant topographic factors at play, the SSI indicated the location of the gully as a significantly higher risk than the surrounding area. The wetland area associated with the riparian zone dominates Figure 5.9, identified by photo point 2. The existence of the riparian wetland, and its condition are critical in this situation since the likelihood of stream incision is high. In the photograph, it is apparent that incision has occurred.

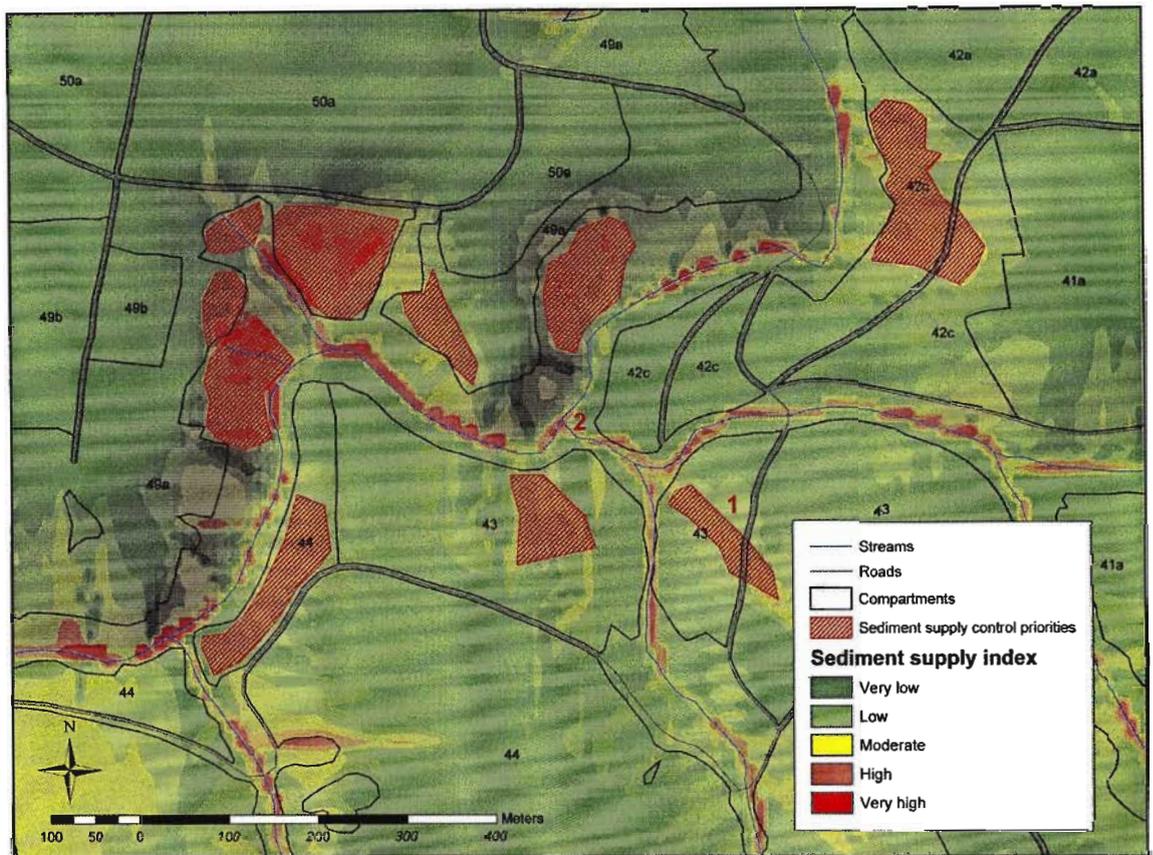


Figure 5.6: Identifying priority areas for on-site erosion control



Figure 5.7: Location of the gully identified by photo point 1 within the landscape



Figure 5.8: Three views of a gully within a compartment, located in a position identified as having a high SSI value (photo point 1)



Figure 5.9: Erosion within the riparian zone and stream incision associated with photo point 2

5.2.3.2 *Off-site erosion control*

The second aspect of erosion control is focused on intercepting the sediment during the transport phase, reducing the amount of sediment that is delivered to

watercourses. The DRI can be used to identify the specific hotspots within each priority areas identified using the method described in Section 5.2.1. Figure 5.10 presents an example for the same area presented in Figure 5.6. Specific remediation can be devised using corporate BMPs or industry standard guidelines. These may include recommendations regarding the size or condition of buffer zones. Management intervention may involve the installation of new, or cleaning of existing, culverts. It may require that stretches of the road be resurfaced.

Erosion control interventions should be informed by optimising the topographic assets in the vicinity by utilizing the sediment attenuation potential surface. Figure 5.11 shows the areas within the landscape where the potential for sediment attenuation exists. The highlighted priority areas have been identified, by consider the localised delivery risk and supply risk. Although priority areas may be set, it is important to manage all areas identified as having sediment attenuation potential to optimise the benefit these areas provide.

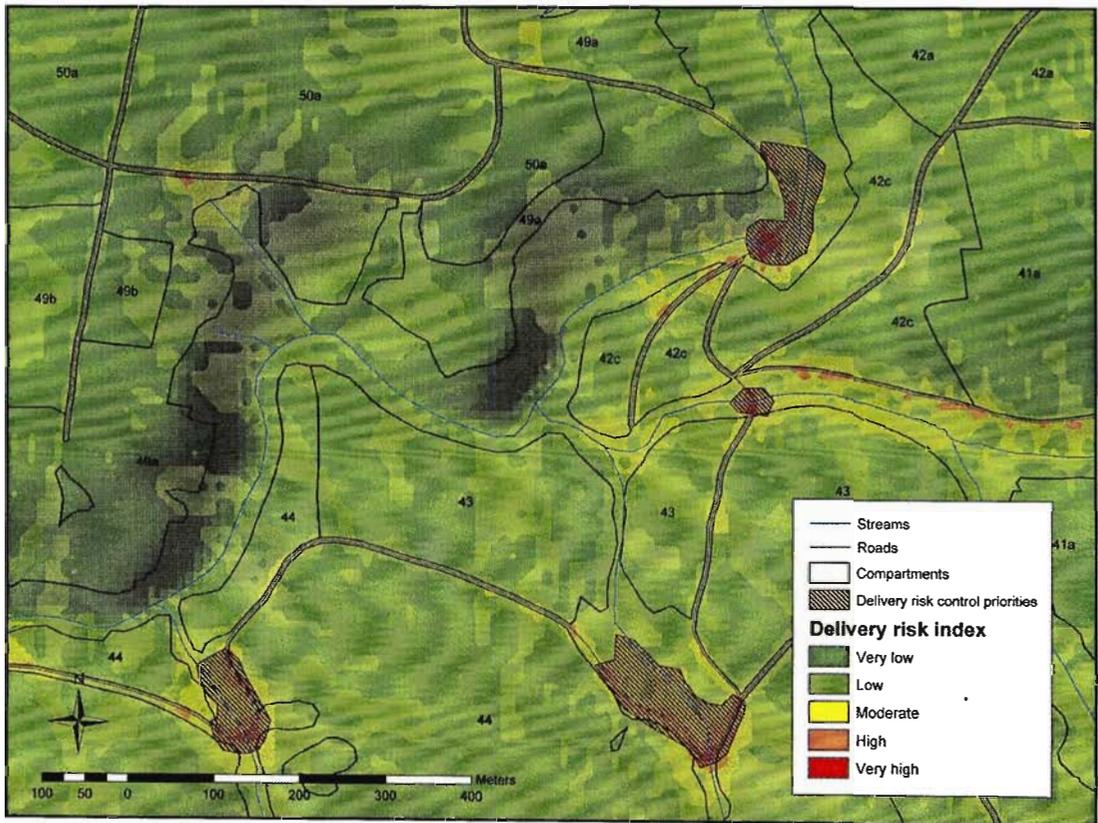


Figure 5.10: Identifying priority areas for off-site erosion control adjacent to compartments

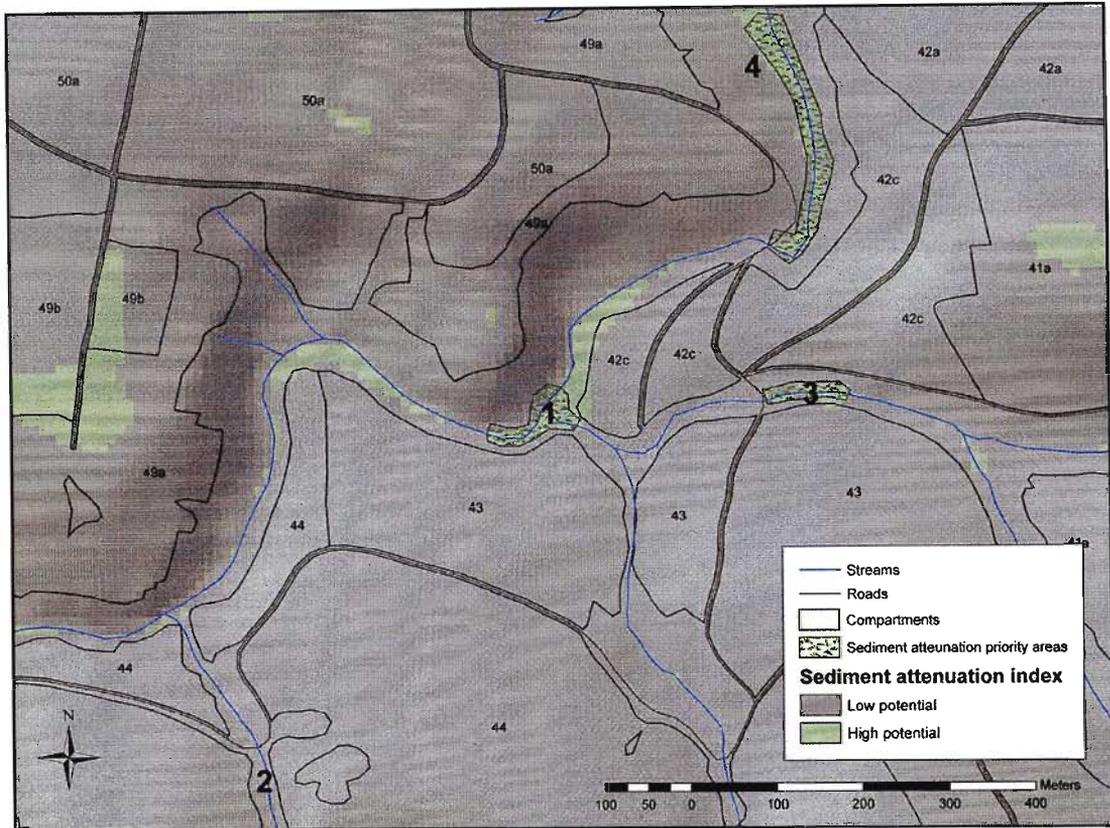


Figure 5.11: Identifying topographic sediment attenuation areas

The areas identified correspond strongly with the location of wetlands within the area. Large black numbers depicted in Figure 5.11 correspond to the location of photographs presented in Figure 5.12 to 5.14.

Figure 5.12 shows the large riparian wetland system identified using the Sediment Attenuation Index (SAI) that corresponds to photo point 1. Figure 5.13 shows another wetland system, corresponding to photo point 4. Unlike in the micro-catchment the shape and extent of the identified areas seem accurate. This is due to the size of the features being more suited to the resolution of the modelling routines. For the same reason, the model did not identify a number of wetland systems that were observed in the field. These systems were all narrow, and associated with low to moderate gradient, convergent areas in the landscape. The width of the systems was between 3m and 5m. Given the modelling resolution of 10m, it is not surprising that these areas systems were not identified. It is likely that had the modelling resolution been finer they would have been identified. Figure 5.14 presents one such system, and corresponds to photo point 2.



Figure 5.12: Riparian wetland system identified by the SAI (Photo point 1)



Figure 5.13: Riparian wetland system identified by SAI (Photo point 4)



Figure 5.14: Typical narrow wetland system not identified by the SAI

Figure 5.15 corresponds to photo point 3. It shows the degraded area upstream from a river crossing. This area was identified using the SAI as a potential sediment trap. The gradient and topographic characteristics make this site an excellent candidate site for testing the results of SAI by encouraging the establishment wetland vegetation, thereby enhancing the sediment attenuation potential of the site.



Figure 5.15: Degraded watercourse identified as a sediment attenuation site using the SAI (Photo point 3)

CHAPTER 6: CONCLUSIONS & RECOMMENDATIONS

The current role of the forestry sector as an economic contributor is recognized, as well as its potential to contribute to the upliftment and economic empowerment of rural communities (DWAF 1995). However, there is a concomitant realization of the potential environmental impact of forestry activities. Particularly, the impact of commercial forestry on water quantity and quality is of concern in South Africa. Increasing public awareness of environmental issues is compelling industries to ensure that their activities are conducted in a responsible and sustainable manner. 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.

6.1 CONCLUSIONS

The focus of this dissertation is to examine sediment production in forestry areas and ways of managing its impacts. In this chapter the research undertaken will be evaluated against the eight objectives that were established in Section 1.6. The strengths and weaknesses of the approaches developed will be highlighted, and are used to identify further research needs.

The first two objectives of the research were to present the current understanding of erosion in commercial forests and to review the potential of riparian buffers zones as sediment control mechanisms. Chapter 2 presented the environmental obligations of the forestry industry as they relate to soil erosion and the impact it has on adjacent water resources. South African legislation was presented which clearly placed the onus for managing water and soil resources on the land-user. The environmental policies of selected national and international forestry companies were examined, highlighting their stated objectives relating to erosion control. These control methods are usually realized through the development of best management practices. A number of these practices were considered, all of which contained specific recommendations that could inform the development of the approach presented in the later chapters of the dissertation. Although there is consensus regarding the issues, in all the material reviewed, there appears to

relatively little research focused on establishing the impact of forestry on soil erosion quantitatively. The noteworthy exception to this is the research conducted by the Cooperative Research Centre for Catchment Hydrology in Australia. Their work provided much of the source material on which the development of the methods presented in this dissertation are based. The paucity of similar research highlights the need for focused research on the impact of forestry on the environment, particularly with regard to plantation forestry.

Buffer zones were identified as an effective way to manage sediment delivery to streams, assuming that the activities of the forestry industry will mobilize sediment in the landscape. Australian research was presented detailing the efficiency of buffer zones and the conditions under which they operate optimally. Three methods for delineating riparian buffer zones were presented. The historical and current methods of establishing widths of buffer zones in South Africa were reviewed. The most significant conclusion in this regard is that, in the light of the research undertaken by the CRC that was presented in Section 2.3, the widths of riparian buffer zones in South Africa are adequate for sediment control. The critical issue is that these buffer zones are managed to optimise their efficiency as erosion control mechanisms in the landscape.

Established approaches to modelling sediment yield were identified in Chapter 3. These range from the prevalent USLE-based models to the complex process-based model. The USLE-based models were favoured for application in the dissertation given the generally data-poor status of commercial forestry areas in South Africa. Within the family of USLE models, the various instances were examined. Three historic spatial applications of these models were presented. A computer-based spatial modelling system was developed that implemented the USLE in its original form, in the RUSLE form (Renard, Foster, Weesies & McCool 1991) and using the flow accumulation method presented by Moore and Burch in 1986. Problems relating to identifying the areas suitable for applying the USLE were overcome by developing a method of identifying areas of low sediment mobility in the landscape. The flow accumulation (Moore & Burch 1986) method was selected as the basis for further development of this research because it is claimed to account for various erosion mechanisms more effectively in non-prototype conditions than the RUSLE. The results of

the modelling undertaken corresponded well to the 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 research occurred. From the perspective of establishing management priorities the implementation of process-based models is unlikely to enhance significantly the results achieved using the simpler, empirical models. However, the modelling needs to be tested in other areas, particularly in less rugged terrain, to evaluate its performance in differing conditions.

While existing models formed the basis for assessing sediment supply areas, there were no similar models for assessing the methods and risks associated with the delivery of sediment to streams. The known contributing factors such as the topographic continuity and the various forms of interaction between roads and streams were identified based on the literature reviewed. Methods of identifying the position of these areas of interaction within the landscape were developed. In some instances this was easily achieved, but in others a number of assumptions needed to be made. Additionally, it was necessary to assume a level of risk associated with each identified factor. A sensitivity analysis tested the sensitivity of the proposed method using three sets of suppositions about the significance of each factor. Although the results differed, the identification of specific 'hotspots' in a test catchment yielded the same results. A method for identifying areas in the landscape that could be utilized as natural sediment traps was developed. Although the modelling resolution constrained the level of detail in the results, the method yielded results that were verified as valid during field trips. These methods are presented in Chapter 4.

The value of any modelling exercise is determined by the applicability of the results to real-world problems. The fifth objective of the research was focussed on integrating the results of the preceding objectives to identify priority areas for managing sediment delivery to streams in commercial forestry areas. The approach adopted was two-fold. Firstly, it was necessary to integrate the two risk factors, supply and delivery, in order to highlight priorities across the entire study area extent. It was realized that the continuous surfaces derived from the modelling were not particularly appropriate in this regard. Relating both these risk factors to a hydrological unit, and incorporating the concept of hydrological load

into the development of a new set of indices, enabled the identification of priority areas to be identified more efficiently and precisely. Modelling based on these units permitted stream reach specific buffer recommendations to be made. Each aspect of the modelling, sediment supply, sediment delivery and sediment attenuation, was examined for a representative commercial forestry area. The utility of the continuous surfaces was realized in the development of strategies for managing compartments with specific reference to the areas within them that are likely to erode, the risk associated with the mobilized sediment as it moves across the landscape and the potential to use the topography of the area to minimize the amount of sediment entering a watercourse.

Unfortunately, it was found that the data generally available within the forestry industry, was either incomplete or inappropriate for use in the procedures developed. However, national datasets, admittedly at a lower resolution, are available. These were used for the case study. There would be merit in investigating the level of improvement in the application of the developed methodology, based on the use of higher resolution data. However, it must be emphasized that available data appears to be adequate for the application of the method, and for achieving the objectives of the research.

6.2 RECOMMENDATIONS

This section will, firstly, present specific recommendations regarding each of the indices developed. Secondly, a number of general research needs identified during the course of the research will be identified.

6.2.1 The sediment supply index

- The effect of improved data resolution needs to be investigated. This should inform the data collection strategies of the forestry industry in future. This consideration is particularly relevant to the development of USLE K factor.
- Improved digital terrain analysis methods identified in Section 5.1.1 should be implemented, to improve the derivation of the sub-factors.
- The assumptions of the method for identifying areas of low sediment mobility presented in Table 3.1 are functional, but tenuous. Investigations into the

relationship between the values of the results of the curvature analysis and the actual terrain need to be established more precisely.

- Further fieldwork to verify the results should be undertaken, for example mapping of observed soil erosion and topsoil loss surveys.
- The principle that Class A watercourses need no particular protection needs to be evaluated in the light of the findings of the research.

6.2.2 The delivery risk index

- Generally, little research has been done on the interaction of the contributing features, although the effects of each are fairly well known in isolation of one another. Research should be conducted to improve the understanding of the interaction between roads, streams and topography, and its effect on sediment delivery.
- Quantitative research will inform the process of assigning risk values to the sub-factors, which are currently based on assumption derived from the literature, or coarse dualistic categories.
- A method for modelling road-surface erodibility, without resorting high-precision data collection, needs to be developed. The objective would be to eliminate the road-facet bias of the method used in this study, in favour of a method that is based on topographically continuous road units.
- The assumptions made, in the light of the paucity of relevant data, relating road surface condition to road class need to be investigated.
- The thresholds used for establishing road-stream adjacency need enhancement. Incorporating the gradient of the landscape between the features, as well as the curvature of the terrain, will improve the derivation of this sub-factor.
- The assumption that only topographically convergent areas are significant in sediment delivery to streams must be investigated. The incorporation of gradient in to the sub-factor topographic delivery efficiency will enhance the results.
- The inclusion of existing culverts into the process for assessing connectivity would improve the development of this index. Unfortunately these data are not readily available.

6.2.3 The sediment attenuation index

- The relationship between the values of the results of the curvature analysis and the actual terrain needs to be established more precisely.
- The method should be applied in an area where the contribution of the method for identifying areas of undefined flow may be assessed.
- The utility of the improved digital terrain analysis methods identified in Section 5.1.1 should be investigated.

6.2.4 Integration of the results

- The assumptions for developing the streamside risk indices need verification.
- The utility of the buffer width determination routines for forestry conditions needs to be investigated.
- The application of improved digital terrain analysis methods would result in improved delineation of stream networks, which would in turn provide better information on which the streamside risk indices are based.
- The proposed method should be implemented in its entirety for a test site, and sediment delivery monitored over a period of time, to evaluate its utility.

The results of the research undertaken for this dissertation suggest that the application of spatial modelling procedures can assist in identifying priority areas within commercial forestry plantations for erosion control. The application of the results, at both landscape and compartment levels, enable tactical and operational management strategies to be developed. As the approach was developed using readily available datasets, and with the operational needs of the industry as a departure point, it is hoped that this contribution in the pursuit of sustainable forestry is implemented.

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The National Water Act (Act No. 36 of 1998)

The Conservation of Agricultural Resources Act (Act No. 43 of 1998)

The National Environmental Management Act (Act No. 107 of 1998)

The National Forests Act (Act No. 84 of 1998)

The Forests Act (Act No. 122 of 1984)

APPENDIX 1: Environmental policy documents



**If you buy timber or forest products with the FSC mark
- you will not leave your mark on the environment**

MONDI ADHERES TO THE FOLLOWING

FSC PRINCIPLES AND CRITERIA

1. COMPLIANCE WITH LAWS AND FSC PRINCIPLES - Forest management shall respect all applicable laws of the country in which they occur, and international treaties and agreements to which the country is a signatory and comply with all FSC Principles and Criteria.
2. TENURE AND USE RIGHTS AND RESPONSIBILITIES - Long term tenure and use rights to the land and forest resources shall be clearly defined, documented and legally established.
3. INDIGENOUS PEOPLES' RIGHTS - The legal and customary rights of indigenous peoples to own, use and manage their lands, territories, and resources shall be recognized and respected.
4. COMMUNITY RELATIONS AND WORKER'S RIGHTS - Forest management operations shall maintain or enhance the long-term social and economic well-being of forest workers and local communities.
5. BENEFITS FROM THE FOREST - Forest management operations shall encourage the efficient use of the forest's multiple products and services to ensure economic viability and a wide range of environmental and social benefits.
6. ENVIRONMENTAL IMPACT - Forest Management shall conserve biological diversity and its associated values, water resources, soils, and unique and fragile ecosystems and landscapes, and, by so doing, maintain the ecological functions and the integrity of the forest.
7. MANAGEMENT PLAN - A management plan - appropriate to the scale and intensity of the operations - shall be written, implemented, and kept up to date. The long term objectives of management, and the means of achieving them, shall be clearly stated.
8. MONITORING AND ASSESSMENT - Monitoring shall be conducted to assess the condition of the forest, yields of forest products, chain of custody, management activities and their social and environmental impacts.
9. MAINTENANCE OF HIGH CONSERVATION VALUE FORESTS - Management activities in high conservation value forests shall maintain or enhance the attributes which define such forests. Decisions regarding high conservation.
10. PLANTATIONS - Plantations shall be planned and managed in accordance with Principles and Criteria 1 - 9, and Principle 10 and its Criteria, While plantations can provide an array of social and economic benefits, and can contribute to satisfying the world's needs for forest products, they should complement the management of, reduce pressures on, and promote the restoration and conservation of natural forests.

For further information regarding Mondi Ltd, FSC or any of the certified products mentioned above, please contact:

Public Affairs Officer -
Mondi Ltd

Marketing Manager -
Mondi Forests

Development Engineer -
Mondi Paper

Divisional Tech
Manager -

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Website:
[www.mondi.co](http://www.mondi.co.za)

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ROOTED IN RESPONSIBLE FORESTRY PRACTICE

Mondi Limited, the South African forest products giant, has long been at the forefront of sustainable plantation forestry. One of the first companies to be FSC (Forest Stewardship Council) certified, it is currently the largest certified plantation forest company in the world.

As an integral part of the Forest Products Division of London-based Anglo American plc, Mondi Limited is committed to the practice of forest operations that are environmentally acceptable, socially beneficial and economically viable. Mondi exemplifies the progressive approach towards certification adopted by the South African forest industry;. More than two-thirds of the country's plantation are certified, giving South Africa the highest percentage of certified forests worldwide.

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WHAT IS CERTIFICATION?

The certification of forests and forest products emerged during the 1990's as an environmental initiative to halt the destruction of the world's forests. Certification encompasses an independent regular assessment of an organisation's forest management practices to measure compliance with a range of internationally recognised social, economic and environmental standards. Certification provides the consumer with the assurance that forest products originate from well-managed forests.

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WHY FSC?

The oldest and "gold standard" of certification systems is the Forest Stewardship Council. Founded by environmentalists in 1993 (and backed by the World Wide Fund for Nature), FSC has emerged as a dominant and demanding performance-based certification system. The FSC has a leading position in forest certification, having gained significant recognition in those markets where certified products are demanded. As interest in certification has increased, so too have the number of systems, greatly confusing the consumer. Mondi favours FSC certification, as it is strongly independent, actively supported by environmentalists and sets increasingly demanding standards. The consumer is assured that products from FSC-certified forests are sustainable.

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Environment | Environmental policy



Sappi recognises that responsible environmental management of natural resources, linked with social responsibility and sound economic performance, are the requirements of sustainable development. Therefore the company is committed to the responsible management of its activities and to continuous improvement of its environmental performance.

To give effect to this policy, Sappi will cultivate, throughout its operations, an attitude of responsibility to the natural environment and will practise these principles:

Compliance

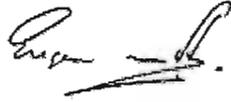
- Meet or exceed the applicable environmental requirements
- Practise sustainable forestry consistent with international and/or regional standards

Performance improvement and monitoring

- Implement internationally recognised environmental management systems such as ISO 14001 and/or regional equivalents in all operational units
- Continuously improve its environmental performance
- Use the best practicable means to reduce waste and emissions and the specific use of water and energy per ton of product produced
- Participate in developing regulations and standards and set our own standards, where we find it applicable, based on analyses of environmental impacts and cost effective technologies
- Request suppliers of goods and services to apply equivalent environmental standards
- Assess and mitigate the environmental impacts of new projects
- Conduct regular environmental audits and management reviews
- Monitor compliance of the group's activities with its environmental policy, standards, targets and procedures

Training and communication

- Effectively train all employees and contractors whose activities have a significant impact on the environment to ensure that the group policy is understood, implemented and maintained
- Make environmental performance a key issue in measuring managerial performance
- Communicate this policy and other environmental matters openly with stakeholders, interest groups, authorities and communities



Eugene van As
Executive Chairman
Sappi Limited

02 August 1999

Date

Sappi is the world's leading producer of coated fine paper and dissolving pulp

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sappi

Environment | Forest certification



Sappi is the foremost forest products group in Africa, the world's leading producer of coated woodfree paper and the largest international producer of dissolving pulp, used primarily in the manufacture of viscose fabric. We have mills and offices situated throughout the world and are a major landowner in Southern Africa, supplying our mills with raw materials from our own tree farms and independent growers.

Sappi Forest Products own and manage approximately 500,000 hectares of commercial tree farming land, of which 110,000 remains unplanted. We are committed to protecting our natural resources by managing our tree farms in a responsible manner on a sustainable basis.

Sappi was one of the first in the forest products industry to recognise the on-going importance of sound environmental management, developing an Environmental Conservation Code and instituting the annual Environmental Audit in 1989. In 1995, we initiated the implementation of the internationally recognised ISO 14001 Environmental Management System and following extensive identification of environmental aspects and impacts, revised our environmental policy in 1997. We were accredited with ISO 14001 certification in April 1999.

The Otter Trophy is presented by the Wildlife and Environment Society every year to the Sappi tree farm achieving the highest audit score.



Sappi Forests' Environmental Audit programme is just one aspect of the group's



In terms of the environmental audit, the siting and maintenance of roads is subject to stringent guidelines.

environmental management system. This environmental practice provides standards for the environmental management of Sappi's tree farms and an audit system to monitor the effective application of the code in all tree farming operations.

The environmental audit programme covers every aspect of timber farming that has an impact on the environment, including:

Planning

In planning silviculture operations, certain environmental considerations have to be taken into account. These include:

- The listing and mapping of sensitive soils
- The mapping of wetlands and streams
- The completion of environmental impact reports for all previously afforested areas to ensure that the next planting in the same area complies with best environmental practices
- The completion of environmental impact reports for any activity such as forest roads, timber loading depots, new plantations, dams and hiking trails

Silviculture operations

Environmental standards for a number of activities are checked including:

- Planting restrictions in terms of distances from water, wetlands and other sensitive areas
- Soil protection using appropriate land preparation techniques to minimise disturbance, particularly on slopes
- Records of chemicals used, e.g. fertiliser and herbicides

Roads

Road construction can cause some streams to become overloaded with silt. To prevent this, when a road is constructed it requires:

- An environmental impact assessment
- An environmental management plan identifying types of construction, restrictions for vehicles and equipment, siting of gravel pits and weather conditions during which construction may not proceed

Road maintenance requires:

- Continuous monitoring of the state of the road and its associated drainage
- Records of written rehabilitation plans
- Quality of road maintenance in terms of these plans

Harvesting

Environmental standards for harvesting activities include:

- Operational plan
- Pre-harvest site inspection to identify any special environmental features, such as streams, indigenous forests and cultural sites
- Code of practice for harvesters
- Post harvest inspection to check the compliance rehabilitation, anti-erosion structures on extraction routes, the number of open road drains and records of removal volumes



Sappi supports the South African Crane Working Group (SACWG), a working group of the Endangered Wildlife Trust. SACWG is the national co-ordinating body for crane conservation in South Africa. Projects include education and awareness programmes, a Wattled Crane breeding programme and Blue Crane satellite tracking. Sappi sponsors satellite transmitters for tracking Blue Cranes, South Africa's national bird featured here. This is to help determine the migration routes and breeding and wintering grounds of these nomadic birds in order to develop a comprehensive conservation strategy for them.

Management of natural areas

Natural areas are susceptible to invasion by alien commercial trees and associated weeds. Accurate annual plans of operation must reflect:

- Budget control, extent of infestation, target date for initial completion of weed control and method of weed control

In addition, management plans for the natural areas need to demonstrate:

- Fauna and flora species check lists
- Natural assets register
- Poaching control and hunting records
- Natural Heritage sites together with sites of conservation significance
- Records of control burning

Social

At Sappi, we believe that one of South Africa's greatest environmental challenges is poverty. As a major rural and urban employer, we are empowering communities not only through jobs, but also through social initiatives, education and the development of entrepreneurial skills.

Our approach is co-operative, and we work in partnership with communities and organisations. In terms of the environmental audit, the following factors are taken into consideration:

- List of land claims
- Records of contacts with local communities
- Permits granted for multiple use activities e.g. cattle grazing,

collection of slash-wood, cutting of thatch grass, mushroom harvesting, hiking, fishing and picnicking

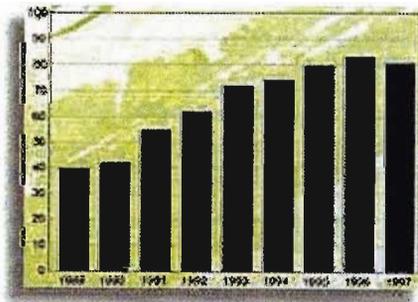
Impact on water

Afforestation can have a negative impact on stream flow when trees are planted too close to rivers and wetlands. Since the inception of environmental auditing in 1989, and the identification of invaded wetlands and rivers as priority areas for rehabilitation, Sappi has cleared and maintained over 15,000 hectares of land. This programme, which has cost approximately R30 million, has had beneficial effects for downstream users, as well as the riverine and wetland eco-systems themselves.

All over the world, raptors, such as this Long-Crested Eagle has come under diminishing habitats and the indiscriminate use of poisons. By sponsoring the Forest Raptor Project and adopting the recommendations in our environmental management programme, we are contributing to the understanding of raptors and are helping to secure the future of these magnificent birds of prey.



Impact on biodiversity



Growth in audit scores since the introduction of the environmental audit.

As an indication of our commitment to biodiversity conservation, Sappi has set aside over 10,000 hectares of our natural areas as formal Natural Heritage sites (recognised by the Department of Environmental Affairs and Tourism) and Sites of Conservation Significance (recognised by the provincial nature conservation agencies).

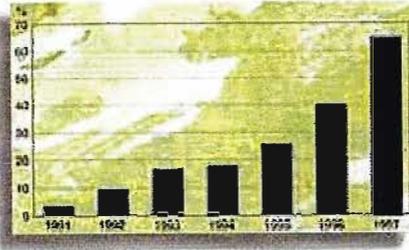
The increase, over time, of these sites as biodiversity hotspots is a reflection of the company's efforts to continuously improve our environmental performance.

The audits have resulted in all our tree farms developing a data base of species and have highlighted the diversity of fauna and flora on our land.

Scoring and results

After every annual audit we have held an annual review and implemented an action plan to address shortcomings

identified on each tree farm. With the revision of the audit to reflect ISO 14001 requirements, these shortcomings are now identified as major or minor corrective actions (CAR's). These CAR's are now the subject of an annual management review.



Sites of conservation significance and Natural Heritage sites combined.



Sappi Forests clear their riverine areas on an ongoing basis. To date approximately 15,000 hectares of riverine land has been cleared of invading alien plants and trees.

Over the years, the scoring of the performance audit has changed to reflect new knowledge and standards. Inevitably, this has resulted in stricter requirements. Despite this, the audit results have indicated a continuous improvement in environmental performance. One of the most encouraging aspects of the audit is the enthusiastic support from the foresters who compete keenly for the Otter Trophy, presented annually by the Wildlife and Environment Society of Southern Africa to the tree farm achieving the highest scores.

Throughout Sappi, there is a commitment to the responsible management of our lands and the conservation of natural resources. Our forestry managers share a deep-rooted commitment to the land and it is largely due to their efforts that the environmental audit results show a steady improvement.

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Boise's Environmental Policy

Philosophy

All employees at Boise Cascade Corporation must be committed to ensuring that the company's operations comply with both the letter and intent of all applicable environmental laws and regulations and pose no significant risk to human health or environment. The company will continue to build on its strong record of fulfilling this commitment. Boise will continuously improve its environmental performance through economically sound and technologically practical processes that are based on the best available science and which produce meaningful, measurable environmental improvements.

Scope

This policy applies to all employees and operations of Boise Cascade Corporation, including wholly owned or majority-owned subsidiaries as well as joint ventures and foreign operations for which the company has management control in the United States and around the world.

Provisions

Boise will:

- Ensure that its operations comply with both the letter and intent of all environmental laws and regulations.
- Conduct training programs necessary to inform employees of this policy and their respective responsibilities for environmental compliance and management.
- Integrate environmental considerations into business planning and decision making at existing locations and in planning new operations.
- Set meaningful and measurable goals for environmental performance and environmental management systems and track progress toward these goals.
- Continuously improve its environmental management systems and environmental performance through practices such as pollution prevention and efficient use of resources.
- Communicate the company's environmental performance and its strong commitment to environmental responsibility to its directors, employees, shareholders, customers, suppliers, and the communities in which it operates.
- Promptly fulfill its legal obligations to disclose potential environmental hazards posed by its operations.
- In the event of a company incident or accident which causes or has the potential to cause significant adverse impacts to the environment or human health, the company will respond appropriately and timely, including curtailing operations if necessary.
- Conduct periodic self-evaluations of its compliance and environmental management systems.
- Constructively work with government agencies, trade associations, and others to develop practical and effective environmental laws and regulations that result in meaningful, measurable environmental improvements.
- Support research on the environmental impacts of raw materials, products, processes, discharges, emissions, and wastes.

Responsibility

Division Managers - Division managers have oversight responsibility for environmental performance and compliance within their divisions.

Location Managers - Location managers have direct responsibility for environmental compliance and performance, including implementing this policy at their respective locations.

Timberlands Managers - Timberlands managers have direct responsibility for environmental compliance and performance on company-owned and leased timberlands and in the performance of public and private timber sale contracts.

Public Policy and Environment - The Public Policy and Environment Department has responsibility for working with government agencies, trade associations, and other parties to monitor and develop practical and effective environmental laws and regulations. This Department provides guidance and assistance to division and location personnel on environmental compliance, permitting, training, environmental due diligence, and changes in environmental management practices. The Department is responsible for managing sensitive sites that are not under the jurisdiction of operations. At least quarterly, the vice president of Public Policy and Environment ensures that the company's overall environmental performance is reported to the Board of Directors. Public Policy and Environment has specific responsibility for establishing, implementing, and maintaining appropriate environmental self-evaluation programs for compliance and environmental management systems, appropriate environmental training programs, and a central environmental information collection and reporting system.

Employees - All Boise employees are expected to understand their responsibilities for environmental compliance and management. They must comply with the letter and intent of this policy and the environmental laws and regulations relevant to their respective jobs.

Violations

Violations of this policy and of environmental laws and regulations can have a serious, adverse, and lasting effect on the environment and the company. A violation of this policy by any employee is sufficient grounds for disciplinary action, including demotion, reduction in pay, or dismissal.

Updated 05/00

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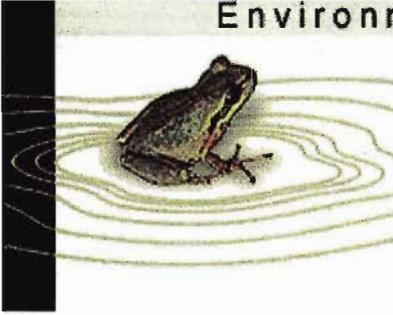
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Environment



OUR role as environmental stewards is one of the most important we play.

Weyerhaeuser is a leader in an industry whose activities rely on natural resources. Our journey toward becoming "the best" includes unique and serious environmental responsibilities.

Since 1971, our environmental policy has outlined our commitments and guided our behavior. A similar policy guides our efforts to protect the health, safety and well-being of Weyerhaeuser people. We've highlighted those policies in our [Annual Environment, Health and Safety Report](#).

In 1999, we committed to aligning all of our timberlands and manufacturing operations to the ISO 14001 [Environmental Management System](#) standard by the year 2005. This will help ensure that reliable processes are in place to further improve our environmental performance and to meet regulatory and stakeholder requirements in the years ahead. It will also help us achieve our environmental goals of [Practicing Sustainable Forestry](#), [Reducing Pollution](#) and [Conserving Natural Resources](#).



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Policy



At Weyerhaeuser, we are proud of our continuing innovations and ongoing commitment to maintaining a balance between the demands of industry and the needs of the environment.



It is Weyerhaeuser's core policy that employees at all levels will work to ensure that we comply with applicable environmental laws, regulations and other requirements to which the company commits, and to continually improve our environmental performance wherever we do business.

Employees are accountable for ensuring compliance with applicable laws and for managing and operating our businesses to conform with the company's goals of:

- Practicing sustainable forestry.
- Reducing pollution.
- Conserving natural resources through recycling and waste reduction.

In countries where applicable environmental laws are less stringent than those in the United States and Canada, we will operate in a manner comparable to North American requirements.

Alignment to our values

This core policy aligns with the company value: **Citizenship.**

Expectations
Employee Responsibilities
Manager's and Team Leader's Responsibilities

Expectations

In conducting our business, we are committed to:

- Understanding and responding to public health and environmental impacts of our operations and our products.
- Ensuring that employees are trained and are empowered to actively participate in the company's environmental management process.
- Actively supporting environmental research and technological advancement and, where appropriate, adopting innovative practices and technology.
- Promoting the development and adoption of environmental laws, policies and regulations that are balanced, are technologically sound and use incentive-based approaches for improving environmental performance.
- Managing forestlands for the sustainable production of raw materials



- Managing forestlands for the sustainable production of raw materials while protecting water quality; fish and wildlife habitat; soil productivity; and cultural, historical and aesthetic values.
- Continually improving our processes for reducing wastes and emissions to the environment.
- Conserving energy and natural resources by maximizing recycling and by-product reuse.
- Using the company's environmental management systems to manage the environmental aspects of all timberlands and manufacturing operations.
- Adopting internal standards for situations not adequately covered by law or regulation or where we believe more stringent measures are necessary to protect the environment.

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Environment Policy



We are committed to responsible stewardship of the environment throughout our operations.

We will:

- Comply with or surpass legal requirements.
- Comply with other environmental requirements to which the company is committed.
- Set and review environmental objectives and targets to prevent pollution and to achieve continual improvement in our environmental performance.
- Create opportunities for interested parties to have input to our forest planning activities.
- Practice forest management that recognizes ecological processes and diversity and supports integrated use of the forest.
- Promote environmental awareness throughout our operations.
- Conduct regular audits of our environmental management system.
- Communicate our environmental performance to our Board of Directors, shareholders, employees, customers and other interested parties.

D.L. Emerson
President and Chief Executive Officer

P.J.G. Bentley
Chairman

July 21, 1999





☐ Certification

Canfor is committed to the responsible stewardship of the forest resources entrusted to our care. In keeping with this commitment, Canfor is implementing a very deliberate and comprehensive certification strategy for its forestlands and operations positioning the company as a North American leader.

Canfor is one of the few forest companies to have completed the certification of all of its forestlands to the ISO 14001 standard and it represents the largest certification of its kind in North America. Canfor's pulp mills also have been certified to both the ISO 9001 and 14001 standard.

Building on its ISO certification, Canfor has also certified all of its area based tenures to the CSA Sustainable Forest Management standard. Canfor is very proud of this accomplishment as the standard is particularly stringent and requires public participation in developing the standard.

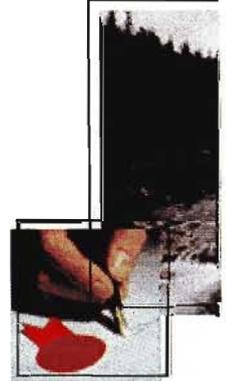
Canfor's certification strategy is ongoing. We continue to work towards certification of our volume based tenures to the CSA standard and we continue to monitor the Forest Stewardship Council (FSC) regional standards development process. Subsequently, Canfor has been preparing its area-based tenures for FSC certification. In accordance with FSC certification guidelines, Canfor's FSC certifier, KPMG Forest Certification Services Inc., has developed the evaluation criteria for Canfor's FSC certification initiative and has made it available to all interested stakeholders and individuals to solicit public input.

Canfor is also the first forest company to certify one of its mills to the Canadian Standards Association (CSA) Chain of Custody for Forest Products. The CSA chain of custody charts the progress of forest products from their point of origin, the certified forest area, through all stages in the manufacturing process, to the point at which they are delivered to the customer. This allows Canfor's Grande Prairie sawmill, a dimension lumber operation, to apply the CSA chain of custody mark on the packaging of its products.

In February 2002, Canfor enrolled as a participant in the SFISM program indicating the company's intention to pursue certification under the American Forest & Paper Association – launched standard. The SFISM program is an exacting standard of environmental principles, objectives and performance measures that integrates the perpetual growing and harvesting of trees with the protection of wildlife, plants, soil and water quality and a wide range of other conservation goals. The SFISM program was launched by the American Forest & Paper Association (AF&PA) in 1995. An independent External Review Panel, comprised of representatives from the environmental, professional, conservation, academic and public sectors reviews the program and advises AF&PA on its progress.

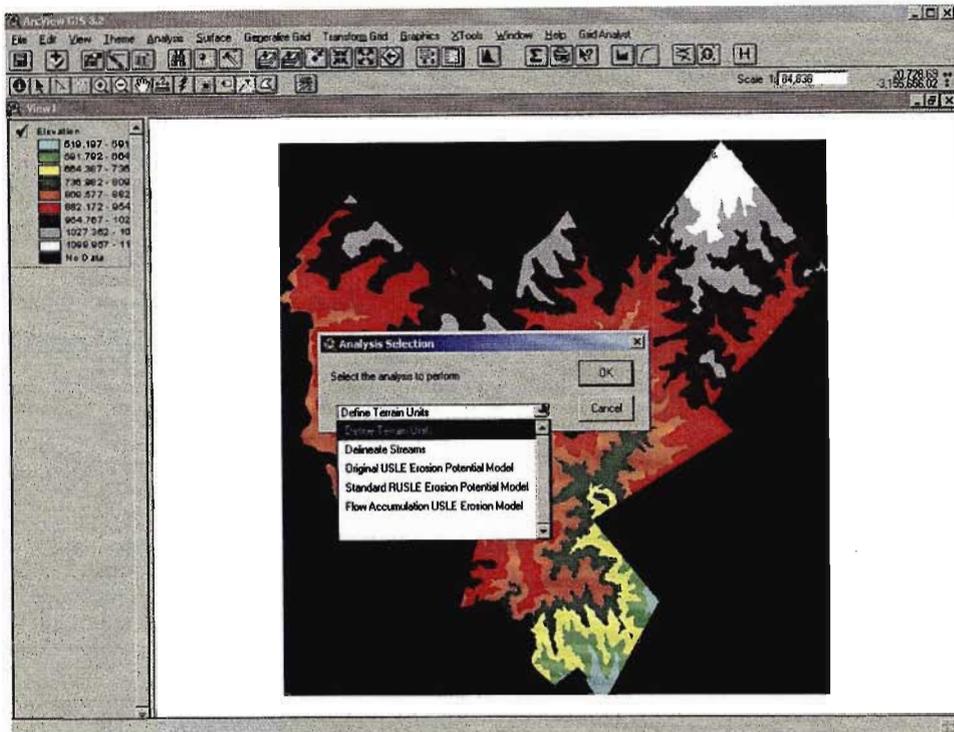
Through all of these initiatives, Canfor continues to provide the independent proof of our environmental performance to our customers and to our stakeholders.

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APPENDIX 2: User interface and Avenue scripts

User interface to erosion modeling routines in ArcView



Scripts:

Where the scripts developed by others have been integrated into the model, the acknowledgements of this contribution are as included in the scripts by the original author.

GRID.ANALYSISCHOICE

```
theOptions = List.Make
theOptions.Add("Define Terrain Units")
theOptions.Add("Delineate Streams")
theOptions.Add("Original USLE Erosion Potential Model")
theOptions.Add("Standard RUSLE Erosion Potential Model")
theOptions.Add("Flow Accumulation USLE Erosion Model")
aSelection = MsgBox.ChoiceAsString(theOptions, "Select the analysis to perform", "Analysis Selection")
```

```
If (aSelection = theOptions.Get(0)) then Av.Run("Grid.TerrainDefine", Self) exit
elseif (aSelection = theOptions.Get(1)) then av.Run("Grid.StreamCreate", Self) exit
elseif (aSelection = theOptions.Get(3)) then av.Run("Grid.StandardUSLE", Self) exit
elseif (aSelection = theOptions.Get(4)) then av.Run("Grid.FlowAccumulationUSLE", Self) exit
'elseif (aSelection = theOptions.Get(5)) then av.Run("Grid.FlowAccumulationUSLE", Self) exit
exit
ElseIf (aSelection = Nil) then exit
End
```

GRID.CURVATURE

```
theProject= av.GetProject
theview = av.GetActiveDoc

'grid.MakeElevActive

theView = av.GetActiveDoc
theThemeList = theView.GetThemes
theGridList = {}
for each t in theThemeList
```

```

t.SetActive(False)
if (t.Is(GTHEME)) then theGridList.Add(t)
end
end

theChoice = MsgBox.Choice(theGridList, "Select the Elevation grid from the list","Select
Elevation Grid")
theChoice.SetActive(True)

SlopeFn = "d:/db/work/mhlatuze/slope1".AsFileName
ProCurvFn = "d:/db/work/mhlatuze/ProCurv1".AsFileName
PlanCurvFn = "d:/db/work/mhlatuze/PlanCurv1".AsFileName
AspectFn = "d:/db/work/mhlatuze/Aspect1".AsFileName

Curvature = theChoice.GetGrid.Curvature(ProCurvFn, PlanCurvFn, SlopeFn, AspectFn)

'Create and Display the Curvature Grid
'CurvTheme = GTheme.Make(Curvature)
'CurvTheme.SetName ("Curvature")
'theView.AddTheme (CurvTheme)

GRID.DEMFILL
' Name: Spatial.DEMFill
'
' Title: Creates a grid theme by filling all sinks in another grid theme.
'
' Topics: Spatial Analyst, Hydrologic modeling
'
' Description: Takes a grid theme and fills all sinks, areas of
' internal drainage, contained within it. The aGrid.FlowDirection,
' aGrid.Sink, aGrid.Watershed, aGrid.ZonalFill, and aGrid.Con
' requests is used to fill the sinks. The process of filling
' sinks can create sinks, so a looping process is used until all
' sinks are filled. One cell sinks are not filled. Sinks of
' any depth are filled.
'
' Requires: The Spatial Analyst extension to be loaded. The script
' also requires an active view with an active grid theme that
' represents a surface. The grid theme should be the only active
' theme in the view.
'
' Self:
'
' Returns:

theView = av.GetActiveDoc

' fill active GTheme
theTheme = theView.GetActiveThemes.Get(0)

' fill sinks in Grid until they are gone
elevGrid = theTheme.GetGrid
sinkCount = 0
numSinks = 0
while (TRUE)
    flowDirGrid = elevGrid.FlowDirection(FALSE)
    sinkGrid = flowDirGrid.Sink
    if (sinkGrid.GetVTab = NIL) then
        ' check for errors
        if (sinkGrid.HasError) then return NIL end
        sinkGrid.BuildVAT
    end
    ' check for errors
    if (sinkGrid.HasError) then return NIL end
    if (sinkGrid.GetVTab <> NIL) then
        theVTab = sinkGrid.GetVTab
        numClass = theVTab.GetNumRecords
        newSinkCount = theVTab.ReturnValue(theVTab.FindField("Count"),0)
    else
        numClass = 0
        newSinkCount = 0
    end
    if (numClass < 1) then
        break
    elseif ((numSinks = numClass) and (sinkCount = newSinkCount)) then

```

```

        break
    end
    waterGrid = flowDirGrid.Watershed(sinkGrid)
    zonalFillGrid = waterGrid.ZonalFill(elevGrid)
    fillGrid = (elevGrid <
(zonalFillGrid.IsNull.Con(0.AsGrid,zonalFillGrid))).Con(zonalFillGrid,elevGrid)
    elevGrid = fillGrid
    numSinks = numClass
    sinkCount = newSinkCount
end

' create a theme
theGTheme = GTheme.Make(elevGrid)

' set name of theme
theGTheme.SetName("Filled_"+theTheme.GetName)

' add theme to the view
theView.AddTheme(theGTheme)
theGTheme.SetActive(true)
theTheme.SetActive(false)

' save data set
g = theGTheme.GetGrid
def =
FileName.Make(FileName.Merge(FileName.GetCWD.AsString,g.GetSrcName.GetFileName.GetBaseName)
.AsString)
aFN = SourceManager.PutDataSet(GRID,"Save Data Set: " + theGTheme.GetName,def,FALSE)
status = Grid.GetVerify
Grid.SetVerify(#GRID_VERIFY_OFF)
if (g.SaveDataSet(aFN).Not) then
    Grid.SetVerify(status)
end
Grid.SetVerify(status)

av.Run("Grid.AnalysisChoice", Self)

```

GRID.DEMMODELLING

```

aResponse = msgBox.LongYesNo("Have the sinks in the DTM been filled?","Fill sinks", False)
If (aResponse = True) then Av.Run("Grid.AnalysisChoice", Self)
Else If (aResponse = False) then av.Run("Grid.DemFill", Self)
ElseIf (aResponse = Nil) then exit
end
end

```

GRID.DEPOSITION

```

theView = av.GetActiveDoc

'Get datasets
Procurv = theView.FindTheme("Profile Curvature").GetGrid
Plancurv = theView.FindTheme("Planform Curvature").GetGrid
Curv = theView.FindTheme("Curvature").GetGrid
Terrain = theView.FindTheme("Terrain units").GetGrid
Slope = theView.FindTheme("Slope").GetGrid

'Extract relevant areas
Flow = Terrain = 5
LowSlope = Slope < 5
Conc1 = Procurv < 0
Conc2 = Plancurv < 0
Conc3 = Curv < 0

ConcAll = Conc1 + Conc2 + Conc3

ConcSlope = ConcAll * Lowslope

Dep1 = Concslope + Flow

Dep2 = (Dep1 = 0)

Deposition = Dep2.FocalStats(#GRID_STATYPE_MIN, NbrHood.MakeRectangle(2,2,False), True)

'Create and Display the Deposition Grid
DPTTheme = GTheme.Make(Deposition)

```

```
DPTheme.SetName ("Deposition Areas")
theView.AddTheme (DPTheme)
```

GRID.FLOWACCAREA

```
'Calculate Erosion using Flow Accumulation USLE
```

```
theView = Av.GetActiveDoc
SlopeD = theView.FindTheme("Slope (degrees)").GetGrid
kfactor = theView.FindTheme("Terrain-Landtypes").GetGrid.Lookup("kfactor")
FlowDir = theView.FindTheme("Flow Direction").GetGrid
Elev = theView.FindTheme("Elevation").GetGrid
```

```
'Check If depostion areas have been extracted
DepTest = theView.FindTheme("Deposition Areas")
```

```
If (DepTest= Nil) then
```

```
  'Get datasets for deposition area extraction
```

```
  Procurv = theView.FindTheme("Profile Curvature").GetGrid
```

```
  Plancurv = theView.FindTheme("Planform Curvature").GetGrid
```

```
  Curv = theView.FindTheme("Curvature").GetGrid
```

```
  Terrain = theView.FindTheme("Terrain units").GetGrid
```

```
  Slope = theView.FindTheme("Slope (degrees)").GetGrid
```

```
  'Extract Deposition areas
```

```
  'Flow = Terrain = 5
```

```
  LowSlope = Slope < 5
```

```
  Conc1 = Procurv < 0
```

```
  Conc2 = Plancurv > 0
```

```
  Conc3 = Curv < 0
```

```
  ConcAll = Conc3 + Conc2 + Conc1
```

```
  ConcSlope = ConcAll * Lowslope
```

```
  Dep1 = Concslope
```

```
  Dep2 = (Dep1 = 0)
```

```
  Deposition = Dep2.FocalStats(#GRID_STATYPE_MIN, NbrHood.MakeRectangle(2,2,False),
```

```
True)
```

```
  'Create and Display the Deposition Grid
```

```
  DPTheme = GTheme.Make(Deposition)
```

```
  DPTheme.SetName ("Deposition Areas")
```

```
  theView.AddTheme (DPTheme)
```

```
else Deposition = DepTest.GetGrid
```

```
end
```

```
'EroDem = (Deposition = 0).SetNull(Elev)
```

```
EroFLDir = Elev.FlowDirection(true)
```

```
FAccSuit = EroFLDir.FlowAccumulation(nil)
```

```
'Convert Slope in degrees to slope in radians
```

```
SlopeR = SlopeD * 3.1415926535 / 180
```

```
Cellsize = terrain.getCellSize
```

```
Fact1 = ((FAccSuit * Cellsize) / 22.13).Pow(0.4)
```

```
F1Theme = GTheme.Make(Fact1)
```

```
F1Theme.SetName ("Factor 1")
```

```
theView.AddTheme (F1Theme)
```

```
Fact2 = ((SlopeR.Sin) / 0.0896).Pow(1.3)
```

```
F2Theme = GTheme.Make(Fact2)
```

```
F2Theme.SetName ("Factor 2")
```

```
theView.AddTheme (F2Theme)
```

```
SlopeLength = Fact1 * Fact2
```

```
'Create and Display the SlopeLength Grid
```

```
LSTheme = GTheme.Make(SlopeLength)
```

```
LSTheme.SetName ("FlowAcc LS Factor")
```

```
theView.AddTheme (LSTheme)
```

```
'Calculate instream topographic erosion potential
```

```
InStrPot = kfactor * SlopeLength * 38.AsGrid
```

```
'Create and Display the Erosion potential Grid
```

```
InStrTheme = GTheme.Make(InStrPot)
```

```
InStrTheme.SetName ("Instream Topographic Erosion Potential")
```

```
theView.AddTheme (InStrTheme)
```

GRID.FLOWACCUMULATIONUSLE

```
'Calculate Erosion using FlowAccumulation
```

```

theView = Av.GetActiveDoc
SlopeD = theView.FindTheme("Slope (degrees)").GetGrid
kfactor = theView.FindTheme("Terrain-Landtypes").GetGrid.Lookup("kfactor")
FlowAcc = theView.FindTheme("Flow Accumulation").GetGrid
terrain = theView.FindTheme("Terrain Units").GetGrid

'Extract areas for FlowAcc Analysis
'FASuit = terrain = 5
'FAccSuit = (FASuit = 0).Setnull(FlowAcc)

'Convert Slope in degrees to slope in radians
SlopeR = SlopeD * 3.1415926535 / 180

Cellsize = terrain.getCellSize

Fact1 = ((FlowAcc * Cellsize * Cellsize) / 22.13).Pow(0.4)
F1Theme = GTheme.Make(Fact1)
F1Theme.SetName ("Factor 1")
theView.AddTheme(F1Theme)

Fact2 = ((SlopeR.Sin) / 0.0896).Pow(1.3)
F2Theme = GTheme.Make(Fact2)
F2Theme.SetName ("Factor 2")
theView.AddTheme(F2Theme)

SlopeLength = Fact1 * Fact2

'Create and Display the SlopeLength Grid
LSTheme = GTheme.Make(SlopeLength)
LSTheme.SetName ("FlowAcc LS Factor")
theView.AddTheme(LSTheme)

'Calculate instream topographic erosion potential
InStrPot = kfactor * SlopeLength * 38.AsGrid

'Create and Display the Erosion potential Grid
InStrTheme = GTheme.Make(InStrPot)
InStrTheme.SetName ("Instream Topographic Erosion Potential")
theView.AddTheme(InStrTheme)

GRID.LTYPETERRAIN.COMBINE
'combine Ltype Grid and Clipped Terrain units
theView = av.GetActiveDoc
ThemeList = theView.GetThemes

NewList = MsgBox.MultiList(Themelist, "Select the Terrain and Landtype Grids", "Grid
Selection")

Theme1 = NewList.get(0).GetGrid
Theme2 = NewList.get(1).GetGrid
CombineList = {}
CombineList.Add(Theme2)
TerLtype = Theme1.Combine(CombineList)

'Make and add new theme
TerLtypeTheme = GTheme.Make(TerLtype)
TerLtypeTheme.SetName ("TerLtype")
theView.AddTheme(TerLtypeTheme)

GRID.MOREANALYSIS
theResponse = MsgBox.YesNo("Would you like to perform more analysis?", "Further analysis",
True)
if (theResponse = True) then av.Run("Grid.AnalysisChoice", Self)
ElseIf (theResponse = False) then exit
End

GRID.RUSLE
'Calculate Erosion using standard RUSLE

theView = Av.GetActiveDoc
SlopeD = theView.FindTheme("Slope (degrees)").GetGrid
SlopeP = theView.FindTheme("Slope (percent)").GetGrid
kfactor = theView.FindTheme("Terrain-Landtypes").GetGrid.Lookup("K-factor")
Elev = theView.FindTheme("Elevation").GetGrid

```

```

'Check If deposotion areas have been extracted
DepTest = theView.FindTheme("Deposition Areas")
If (DepTest= Nil) then
  'Get datasets for deposition area extraction
  Procurv = theView.FindTheme("Profile Curvature").GetGrid
  Plancurv = theView.FindTheme("Planform Curvature").GetGrid
  Curv = theView.FindTheme("Curvature").GetGrid
  Terrain = theView.FindTheme("Terrain units").GetGrid
  Slope = theView.FindTheme("Slope (degrees)").GetGrid
  'Extract Deposition areas
  'Flow = Terrain = 5
  LowSlope = Slope < 5
  Conc1 = Procurv < 0
  Conc2 = Plancurv > 0
  Conc3 = Curv < 0
  ConcAll = Conc3 + Conc2 + Conc1
  ConcSlope = ConcAll * Lowslope
  Dep1 = Concslope
  Dep2 = (Dep1 = 0)
  Deposition = Dep2.FocalStats(#GRID_STATYPE_MIN, NbrHood.MakeRectangle(2,2,False),
True)
  'Create and Display the Deposition Grid
  DPTheme = GTheme.Make(Deposition)
  DPTheme.SetName ("Deposition Areas")
  theView.AddTheme(DPTheme)
else Deposition = DepTest.GetGrid
end

'Calculate flowlength
EroDem = (Deposition = 0).SetNull(Elev)
EroFLDir = EroDem.FlowDirection(true)
EroFLLen = EroFLDir.FlowLength(nil, True)

'Create and Display the EroFLLen Grid
ELTheme = GTheme.Make(EroFLLen)
ELTheme.SetName ("Flow Length (excluding Deposition)")
theView.AddTheme(ELTheme)

'Convert Slope in degrees to slope in radians
SlopeR = SlopeD * 3.1415926535 / 180
SLRTheme = GTheme.Make(SlopeR)
SLRTheme.SetName ("Slope (radians)")
theView.AddTheme(SLRTheme)

'Caclulate Slope Steepness Factor
Slope1 = (10.8.AsGrid * (SlopeR.Sin)) + 0.03.AsGrid
Slope2 = (16.8.ASGrid * (SlopeR.Sin)) - 0.5.ASGrid

Temp1 = (SlopeP < 9.ASGrid).Con(Slope1, 0.AsGrid)
SL1Theme = GTheme.Make(Temp1)
SL1Theme.SetName ("Slope Steepness factor < 9")
theView.AddTheme(SL1Theme)
Temp2 = (SlopeP >= 9.ASGrid).Con(Slope2, 0.ASGrid)
SL2Theme = GTheme.Make(Temp2)
SL2Theme.SetName ("Slope Steepness factor >=9")
theView.AddTheme(SL2Theme)

SSFact = Temp1 + Temp2

'SSFact = (Deposition = 0).SetNull(SSTemp)

'Create and Display the SSFact Grid
SSFTheme = GTheme.Make(SSFact)
SSFTheme.SetName ("Slope Steepness factor")
theView.AddTheme(SSFTheme)

'Slope Length Factor: Calculate beta factor for
BFact = (slopeR.Sin) / (0.0896.ASGrid * ((3.AsGrid * (slopeR.Sin).Pow(0.8)+ 0.56.ASGrid)))
'Create and Display the BetaFact Grid
BFFTheme = GTheme.Make(BFact)
BFFTheme.SetName ("Beta Factor")
theView.AddTheme(BFFTheme)

```

```

'Slope Length Factor: Calculate Exponent M
ExpM = BFact / (1.AsGrid + BFact)
'Create and Display the Exponent Grid
EXPTheme = GTheme.Make(ExpM)
EXPTheme.SetName ("Exponent")
theView.AddTheme(EXPTheme)

'Slope Length Factor
SLFact = (EroFLLen / 22.1.AsGrid).Pow(ExpM)
'Create and Display the Slope Length Factor
SLFTheme = GTheme.Make(SLFact)
SLFTheme.SetName ("Slope Length factor")
theView.AddTheme(SLFTheme)

'Calculate LS Factor
LSFact = SLFact * SSFact
'Create and Display the LSFact Grid
LSFTheme = GTheme.Make(LSFact)
LSFTheme.SetName ("LS Factor")
theView.AddTheme(LSFTheme)

'Calculate Topographic Erosion Potential
TopoEroPot = KFactor * LSFact * 38.AsGrid
'Create and Display the TopoEroPot Grid
TEPTheme = GTheme.Make(TopoEroPot)
TEPTheme.SetName ("Topographic Erosion Potential (RUSLE)")
theView.AddTheme(TEPTheme)

```

GRID.SELECTELEV

```

'grid.SelectElev

theView = av.GetActiveDoc
theThemeList = theView.GetThemes
theGridList = {}
for each t in theThemeList
    t.SetActive(False)
    if (t.Is(GTHEME)) then theGridList.Add(t)
end
end

'Get path for saving datasets
_path = MsgBox.Input("Enter the path for saving datasets", "Enter path",
"d:\db\work\mhlatauze\tcq\grid")
If (_path = Nil) then exit
end

theChoice = MsgBox.Choice(theGridList, "Select the Elevation grid from the list", "Select
Elevation Grid")
If (theChoice = Nil) then exit
else theChoice.SetActive(True)
end

av.Run("Grid.DEMModelling", Self)

```

GRID.STANDARDUSLE

```

'Calculate Erosion using standard USLE

theView = Av.GetActiveDoc
theSlope = theView.FindTheme("Slope (percent)").GetGridkfactor =
theView.FindTheme("Terrain-Landtypes").GetGrid.Lookup("k-factor")
FlowDir = theView.FindTheme("Flow Direction").GetGrid
Elev = theView.FindTheme("Elevation").GetGrid

'Check If deposition areas have been extracted
DepTest = theView.FindTheme("Deposition Areas")
If (DepTest= Nil) then
    'Get datasets for deposition area extraction
    Procurv = theView.FindTheme("Profile Curvature").GetGrid
    Plancurv = theView.FindTheme("Planform Curvature").GetGrid
    Curv = theView.FindTheme("Curvature").GetGrid
    Terrain = theView.FindTheme("Terrain units").GetGrid
    Slope = theView.FindTheme("Slope (degrees)").GetGrid
'Extract Deposition areas
    Flow = Terrain = 5
    LowSlope = Slope < 5

```

```

Conc1 = Procurv < 0
Conc2 = Plancurv < 0
Conc3 = Curv < 0
ConcAll = Conc1 + Conc2 + Conc3
ConcSlope = ConcAll * Lowslope
Dep1 = Concslope + Flow
Dep2 = (Dep1 = 0)
Deposition = Dep2.FocalStats(#GRID_STATYPE_MIN, NbrHood.MakeRectangle(2,2,False),
True)
'Create and Display the Deposition Grid
DPTheme = GTheme.Make(Deposition)
DPTheme.SetName ("Deposition Areas")
theView.AddTheme(DPTheme)
else Deposition = DepTest.GetGrid
end

EroDem = (Deposition = 0).SetNull(Elev)
EroFLDir = EroDem.FlowDirection(true)
EroFLLen = EroFLDir.FlowLength(nil, True)

'Create and Display the EroFLAcc Grid
ELTheme = GTheme.Make(EroFLLen)
ELTheme.SetName ("Flow Length (excluding Deposition)")
theView.AddTheme(ELTheme)

'Add Rainfall Erosivity data

aSlope = theSlope / 100
FactA = EroFLLen / 22.1
FactB = ((430.AsGrid * (aSlope.pow(2))) + (30.AsGrid * aSlope) + 0.43)

LS1 = (((FactA.pow(0.3))* FactB) / 6.613)
LS2 = (((FactA.pow(0.4))* FactB) / 6.613)
LS3 = (((FactA.pow(0.5))* FactB) / 6.613)

Ans1a = (theSlope < 3.AsGrid)
Ans1aTheme = GTheme.Make(Ans1a)
Ans1aTheme.SetName ("Ans1a")
theView.AddTheme(Ans1aTheme)

Ans1b = (Ans1a = 1).Con(LS1, 0.AsGrid)
Ans1Theme = GTheme.Make(Ans1b)
Ans1Theme.SetName ("Ans1")
theView.AddTheme(Ans1Theme)

Ans2aa = (theSlope > 3.AsGrid)
Ans2ab = (theSlope < 5.Asgrid)
Ans2ac = Ans2aa + Ans2ab
Ans2a = (Ans2ac = 2)
Ans2aTheme = GTheme.Make(Ans2a)
Ans2aTheme.SetName ("Ans2a")
theView.AddTheme(Ans2aTheme)

Ans2b = (Ans2a = 1).Con(LS2, 0.AsGrid)
Ans2Theme = GTheme.Make(Ans2b)
Ans2Theme.SetName ("Ans2b")
theView.AddTheme(Ans2Theme)

Ans3a = (TheSlope > 5.AsGrid)
Ans3aTheme = GTheme.Make(Ans3a)
Ans3aTheme.SetName ("Ans3a")
theView.AddTheme(Ans3aTheme)

Ans3b = (Ans3a = 1).Con(LS3, 0.AsGrid)
Ans3Theme = GTheme.Make(Ans3b)
Ans3Theme.SetName ("Ans3")
theView.AddTheme(Ans3Theme)

SlopeLength = Ans1b + Ans2b + Ans3b

'Create and Display the SlopeLength Grid
LS3Theme = GTheme.Make(SlopeLength)
LS3Theme.SetName ("USLE LS Factor")
theView.AddTheme(LS3Theme)

```

```

'Create and Display the K-factor Grid
'KFTheme = GTheme.Make(kfactor)
'KFTheme.SetName ("K-Factor")
'theView.AddTheme(KFTheme)

Eropot = kfactor * SlopeLength * 38.AsGrid

'Create and Display the Erosion potential Grid
EPTheme = GTheme.Make(Eropot)
EPTheme.SetName ("Topographic Erosion Potential (Standard USLE)")
theView.AddTheme(EPTheme)

'av.Run("grid.MoreAnalysis", Self)

GRID.STREAMCREATE
theView = av.GetActiveDoc

'Get Datasets
FlowAccGrid = theView.FindTheme("Flow Accumulation").GetGrid
FlowDirGrid = theView.FindTheme("Flow Direction").GetGrid

' extract streams from flow accumulation
streamGrid = (flowAccGrid < 500.AsGrid).SetNull(1.AsGrid)
StreamGTheme = GTheme.Make(StreamGrid)
StreamGTheme.SetName ("Raster Streams")
theView.AddTheme(StreamGTheme)

'perform stream ordering create vector network and add theme
StreamOrderGrid = StreamGrid.StreamOrder(FlowDirGrid, False)
StreamLine = StreamOrderGrid.StreamtoPolyLineFtab("streamnet".AsFileName, FlowDirGrid,
True, Prj.MakeNull)
StreamSourceName = SrcName.Make("streamnet.shp")
StreamTheme = Theme.Make(StreamSourceName)
StreamTheme.SetName("Stream Network")
theView.AddTheme(StreamTheme)

aResponse = MsgBox.YesNo("Do you want to define catchments?", "Catchment Delineation",
True)
if (aResponse = True) then
'delineate stream links
streamLinkGrid = streamGrid.StreamLink(flowDirGrid)
'delineate watersheds for each stream link
watershedGrid = flowDirGrid.Watershed(streamLinkGrid)
'Create and display the Watershed Grid
WatershedGTheme = GTheme.Make(WatershedGrid)
WatershedGTheme.SetName ("Watershed")
theView.AddTheme(WatershedGTheme)
end

'Delete interim datasets
Grid.DeleteDataSet("FlowDirGrid".AsFileName)
Grid.DeleteDataSet("FlowAccGrid".AsFileName)
Grid.DeleteDataSet("StreamGrid".AsFileName)
Grid.DeleteDataSet("StreamOrderGrid".AsFileName)

av.run("Grid.MoreAnalysis", Self)

GRID.TERRAINDEFINE
theView = av.GetActiveDoc

ThemeList = theView.GetActiveThemes
theTheme = ThemeList.Get(0)

ElevGrid = theTheme.GetGrid

'Calculate FlowDirection

FlowDir = ElevGrid.FlowDirection(false)

'Create, display and save the FlowDirection Grid
FDTheme = GTheme.Make(FlowDir)
FDTheme.SetName ("Flow Direction")

```

```

theView.AddTheme(FDTheme)
FDName = _path.AsString + "\FlowDir"
FlowDir.SaveDataset (FDName.AsFileName)

'Calculate FlowAccumulation

FlowAcc = FlowDir.FlowAccumulation(Nil)

'Create, display and save the FlowAccumulation Grid
FATheme = GTheme.Make(FlowAcc)
FATheme.SetName ("Flow Accumulation")
theView.AddTheme(FATheme)
FAName = _path.AsString + "\FlowAcc"
FlowAcc.SaveDataset (FAName.AsFileName)

'Calculate Slope in degrees
SlopeD = ElevGrid.Slope(Nil, False)
SLDTheme = GTheme.Make(SlopeD)
SLDTheme.SetName ("Slope (degrees)")
theView.AddTheme(SLDTheme)
SLDName = _path.AsString + "\Slopedeg"
SlopeD.SaveDataset(SLDName.AsFileName)

'Calculate Slope in percent
SlopeP = ElevGrid.Slope(Nil, True)
SLPTheme = GTheme.Make(SlopeP)
SLPTheme.SetName ("Slope (percent)")
theView.AddTheme(SLPTheme)
SLPName = _path.AsString + "\Slopeper"
SlopeP.SaveDataset(SLPName.AsFileName)

'Calculate Curvature
ProCurvFn = (_path.AsString + "\ProCurv").AsFileName
PlanCurvFn = (_path.AsString + "\PlanCurv").AsFileName

Curvature = ElevGrid.Curvature(ProCurvFn, PlanCurvFn, Nil, Nil)

'Create, display and save the Curvature Grid
CVTheme = GTheme.Make(Curvature)
CVTheme.SetName ("Curvature")
theView.AddTheme(CVTheme)
CVName = _path.AsString + "\Curvature"
Curvature.SaveDataset(CVName.AsFileName)

'Load and display Profile and Planform Curvature
ProCSrc = Grid.MakeSrcName(ProCurvFn.AsString)
ProCGrid = Grid.Make(ProCSrc)
ProCThm = GTheme.Make(ProCGrid)
ProCThm.SetName("Profile Curvature")
theView.AddTheme(ProCThm)
PlanSrc = Grid.MakeSrcName(PlanCurvFn.AsString)
PlanGrid = Grid.Make(PlanSrc)
PlanThm = GTheme.Make(PlanGrid)
PlanThm.SetName("Planform Curvature")
theView.AddTheme(PlanThm)

'Define Ridges

Ridge1 = (FlowAcc < 1.AsGrid).Con(1.AsGrid, 0.AsGrid)

Ridge2 = Ridge1.FocalStats(#GRID_STATYPE_MEAN, NbrHood.MakeRectangle(3,3,False), True)

Ridge3 = (Ridge2 > 0.5.AsGrid).Con(1.AsGrid, 0.AsGrid)

Ridge4 = Ridge3.Thin(True, False, True, 50)

Ridge5 = (Ridge4 = 0.AsGrid).SetNull(Ridge4)

Ridge = (Ridge5 = 1.AsGrid).Con(1.AsGrid, 0.AsGrid)

'Define Gullys

```

```

Gully1 = (FlowAcc > 75.AsGrid).Con(1.AsGrid, 0.AsGrid)
Gully2 = Gully1.Thin(True, False, True, 100)
Gully3 = (Gully2 = 1.AsGrid).Con(1.AsGrid, 0.AsGrid)
Gully4 = Gully3.FocalStats(#GRID_STATYPE_Max, NbrHood.MakeRectangle(3,3,False), True)
Gully = (Gully4 = 0.AsGrid).SetNull(Gully4)

'Calculate Euclidean Distance to ridges
Euc2Ridge = ridge.EucDistance(Null, Null, Null)

'Calculate Euclidean Distance to gullies
Euc2Gully = Gully.EucDistance(Null, Null, Null)

'Calculate relative position between ridges and gullies
Position = (Euc2ridge / (Euc2ridge + Euc2gully))

'Calculate Terrain Units
Terrain11 = (Position.IsNotNull).Con(5.Asgrid,99.Asgrid)
Terrain1 = (Terrain11 = 99.AsGrid).SetNull(Terrain11)

Terrain21 = (Position < 0.25.AsGrid).Con(1.AsGrid,99.AsGrid)
Terrain22 = (SlopeD < 20.AsGrid).Con(1.AsGrid,99.AsGrid)
Terrain23 = Terrain21 + Terrain22
Terrain24 = (Terrain23 = 2.AsGrid).Con(1.AsGrid, 99.AsGrid)
Terrain2 = (Terrain24 = 99.AsGrid).SetNull(Terrain24)

Terrain31 = (Position = 1.Asgrid).Con(5.AsGrid, 99.Asgrid)
Terrain3 = (Terrain31 = 99.AsGrid).SetNull(Terrain31)

Terrain41 = (Position > 0.85.AsGrid).Con(1.AsGrid, 0.AsGrid)
Terrain42 = (Curvature < 0.1.AsGrid).Con(1.AsGrid, 0.AsGrid)
Terrain43 = Terrain41 + Terrain42
Terrain44 = (Terrain43 = 2.AsGrid).Con(1.AsGrid, 0.Asgrid)
Terrain45 = Terrain44.FocalStats(#GRID_STATYPE_MEAN, NbrHood.MakeRectangle(3,3,False),
True)
Terrain46 = (Terrain45 < 0.6).Con(3.AsGrid, 99.AsGrid)
Terrain4 = (Terrain46 = 99.AsGrid).SetNull(Terrain46)

'Merge the Interim Grids
TerrainGridList = {}
TerrainGridList = {Terrain2, Terrain4}
Terrain5 = Terrain3.Merge(TerrainGridList)

Terrain6 = (Terrain5.IsNotNull).Con(3.Asgrid, Terrain5)
Terrain = (ElevGrid.IsNotNull).SetNull(Terrain6)

'Create and Display the Terrain Grid
TerrainTheme = GTheme.Make(Terrain)
TerrainTheme.SetName ("Terrain units")
theView.AddTheme(TerrainTheme)
TerName = _path.AsString + "\Terrain"
Terrain.SaveDataset(TerName.AsFileName)

>Delete interim datasets
Grid.DeleteDataSet("Ridge".AsFileName)
Grid.DeleteDataSet("ridge1".AsFileName)
Grid.DeleteDataSet("Ridge2".AsFileName)
Grid.DeleteDataSet("Ridge3".AsFileName)
Grid.DeleteDataSet("Ridge4".AsFileName)
Grid.DeleteDataSet("Ridge5".AsFileName)
Grid.DeleteDataSet("Gully".AsFileName)
Grid.DeleteDataSet("Gully1".AsFileName)
Grid.DeleteDataSet("Gully2".AsFileName)
Grid.DeleteDataSet("Gully3".AsFileName)
Grid.DeleteDataSet("Gully4".AsFileName)
Grid.DeleteDataSet("Terrain1".AsFileName)
Grid.DeleteDataSet("Terrain11".AsFileName)
Grid.DeleteDataSet("Terrain2".AsFileName)
Grid.DeleteDataSet("Terrain21".AsFileName)

```

```
Grid.DeleteDataSet("Terrain22".AsFileName)
Grid.DeleteDataSet("Terrain23".AsFileName)
Grid.DeleteDataSet("Terrain24".AsFileName)
Grid.DeleteDataSet("Terrain3".AsFileName)
Grid.DeleteDataSet("Terrain31".AsFileName)
Grid.DeleteDataSet("Terrain4".AsFileName)
Grid.DeleteDataSet("Terrain41".AsFileName)
Grid.DeleteDataSet("Terrain42".AsFileName)
Grid.DeleteDataSet("Terrain43".AsFileName)
Grid.DeleteDataSet("Terrain44".AsFileName)
Grid.DeleteDataSet("Terrain45".AsFileName)
Grid.DeleteDataSet("Terrain46".AsFileName)
Grid.DeleteDataSet("Terrain5".AsFileName)
```

```
Av.Run("Grid.MoreAnalysis", Self)
```

GRID.WATERSHED

```
' Name:  wshed_point.ave
'
' Date:  25/Feb/2000
' Updated: 20/Apr/2000
'         14/Aug/2001 (minor changes)
' Author:  Fridjof Schmidt
'         no.spam.please@gmx.net
'         bug reports and suggestions welcome
'
' Title:  Delineates watersheds using a point theme as the pour point input
'
' Topics:  Spatial Analyst, Hydrologic Modeling
'
' Description:  Run this script from a view.
' You will be asked to select a point theme representing the
' pour points (outlets), and a grid theme representing elevation.
' The point theme will be converted to a temporary grid, the extent
' and cell size of which will be set to the elevation grid's extent and
' cell size.
' Sinks will be identified and filled upon request.
' Flow direction and flow accumulation will be created as temporary grids.
' Alternatively, they can be selected if they have been computed already.
' The pour points will be snapped to the maximum flow accumulation based
' on a snap distance you specify (default is 3 times the cell size).
' Please note that watersheds may overlay in reality while they don't
' in the results of this script. Overlaying watersheds can be created
' manually by copying, pasting + joining adjacent watershed polygons.
' The script borrows code from scripts included in the Hydrologic
' Modeling extension that comes with the Spatial Analyst, and from other
' ArcView system scripts.
'
' Requires:  Spatial Analyst extension must be loaded.
' A view with at least one point and one grid theme must be active.
'
' Self:
'
' Returns:
```

```
' Delineate Watersheds from a Point Theme
```

```
theScript = "Watersheds from Point Theme"
theView = av.GetActiveDoc
computeStr = "-- compute --"

themeList = theView.getthemes
if (nil = themeList) then
    return nil
end
if (themeList.count < 2) then
    MsgBox.Warning("At least 2 themes must be present in the view",theScript)
    return nil
end

'Choose the point theme
pointlist = list.make
```

```

for each atheme in themelist
  if (atheme.canselect=true) then
    if (atheme.getftab.findfield("Shape").gettype = #FIELD_SHAPEPOINT) then
      pointlist.add(atheme)
    end
  else
    end
end
thePointTheme = MsgBox.ChoiceAsString(pointlist,"Please select a point theme
representing"++
                                "the POUR POINTS.",theScript)
if (thePointTheme=Nil) then
  return nil
end

'Choose the elevation grid theme
gridlist = list.make
for each atheme in themelist
  if (atheme.GetClass.GetClassName = "GTheme") then
    gridlist.add(atheme)
  end
end
theElevTheme = MsgBox.ChoiceAsString(gridlist,"Please select a grid theme representing"++
                                "ELEVATION.",theScript)
if (theElevTheme=Nil) then
  return nil
end
theElevGrid = theElevTheme.GetGrid

theFlowDirTheme = computeStr
theFlowAccTheme = computeStr
if (gridlist.count > 1) then
  'Choose a flow direction grid theme if applicable
  gridlist = {computeStr} + gridlist
  theFlowDirTheme = MsgBox.ChoiceAsString(gridlist,"FLOW DIRECTION: please specify whether
to compute"++
                                "a new grid OR select an existing one",theScript)
  if (theFlowDirTheme=Nil) then
    exit
  end
  if (gridlist.count > 3) then
    'Choose a flow accumulation grid theme if applicable
    theFlowAccTheme = MsgBox.ChoiceAsString(gridlist,"FLOW ACCUMULATION: please specify
whether to compute"++
                                "a new grid OR select an existing one",theScript)
    if (theFlowAccTheme=Nil) then
      return nil
    end
  end
end
end

' convert selected features of Point Theme to Grid
thePointFTab = thePointTheme.GetFTab

' make a list of fields
fl = {}
for each f in thePointFTab.GetFields
  if (f.IsVisible and (f.IsTypeNumber or f.IsTypeString)) then
    fl.Add(f)
  end
end

' check if valid conversion field exists
if (fl.Count = 0) then
  MsgBox.Warning("No valid conversion field exists.",theScript)
  return NIL
end

'set extent and cell size for conversion
cellSize = theElevGrid.GetCellSize
box = theElevGrid.GetExtent

' obtain field to convert with
theValueField = MsgBox.List(fl,"Please select a field for obtaining the cell values:",
                                "Conversion Field:" ++ thePointTheme.GetName)
if (theValueField = NIL) then
  return NIL
end

```

```

elseif (theValueField.IsTypeString) then
  ' make list
  stringlist = list.make
  theBitmap = thePointFTab.GetSelection
  if (theBitmap.Count = 0) then
    totalNumRecords = theBitmap.GetSize
    theBitmap = thePointFTab
  else
    totalNumRecords = theBitmap.Count
  end
  for each r in theBitmap
    stringlist.add(thePointFTab.ReturnValueString(theValueField,r))
  end
  stringlist.RemoveDuplicates
  doString = TRUE
else
  doString = FALSE
end

' actually do conversion
aPrj = theView.GetProjection
theSrcGrid = Grid.MakeFromFTab(thePointFTab,aPrj,theValueField,{cellSize, box})

if (theSrcGrid.HasError) then
  MsgBox.Warning("Error:" ++ thePointTheme.GetName ++ "could not be converted to a
grid",theScript)
  return NIL
end

' Get snap distance
SnapDist = 3 * cellSize
status = TRUE
while (status)
  SnapDist = MsgBox.Input("Enter the maximum distance in map units to snap pour points"++
"to the flow accumulation grid.",theScript, SnapDist.AsString)
  if (SnapDist = NIL) then
    return NIL
  elseif (SnapDist.IsNumber) Then
    status = FALSE
  else
    status = TRUE
    MsgBox.Warning("The 'snap distance must be a number.",theScript)
  end
end

'Create a flow direction grid
if(theFlowDirTheme = computeStr) then
  theFlowDir = theElevGrid.FlowDirection(FALSE)
  ' Check for Sinks on The currently selected elevation grid's direction grid
  theSinkGrid = theFlowDir.Sink
  if ((theSinkGrid.getVTab = NIL).Not) Then
    'YesNo to fill sinks
    fillStat = MsgBox.YesNo(TheSinkGrid.GetVTab.GetSelection.GetSize.AsString++
"sinks were identified!" +nl+" "+NL+
"Do you want to fill the sinks? (recommended)",
theScript,true)

    'Fill sinks
    if(fillStat) then
      ' fill sinks in Grid until they are gone
      sinkCount = 0
      numSinks = 0
      while (TRUE)
        if (theSinkGrid.GetVTab = NIL) Then
          ' check for errors
          if (theSinkGrid.HasError) Then
            MsgBox.Warning("Error in sink grid",theScript)
            return NIL
          end
          theSinkGrid.BuildVAT
        end
        ' check for errors
        if (theSinkGrid.HasError) Then
          MsgBox.Warning("Error in sink grid",theScript)
          return NIL
        end
        if (theSinkGrid.GetVTab <> NIL) Then
          theVTab = theSinkGrid.GetVTab
        end
      end
    end
  end
end

```

```

        numClass = theVTab.GetNumRecords
        newSinkCount = theVTab.ReturnValue(theVTab.FindField("Count"),0)
    else
        numClass = 0
        newSinkCount = 0
    end
    if (numClass < 1) Then
        break
    elseif ((numSinks = numClass) and (sinkCount = newSinkCount)) Then
        break
    end
    theWater = theFlowDir.Watershed(theSinkGrid)
    zonalFillGrid = theWater.ZonalFill(theElevGrid)
    fillGrid = (theElevGrid <
(zonalFillGrid.IsNull.Con(0.AsGrid, zonalFillGrid))).Con(zonalFillGrid, theElevGrid)
    theElevGrid = fillGrid
    numSinks = numClass
    sinkCount = newSinkCount
end
' Create new flow direction grid
theFlowDir = theElevGrid.FlowDirection(FALSE)
end 'fillStat
end 'Check for no sinks
else
    theFlowDir = theFlowDirTheme.GetGrid
end

' Create a flow accumulation grid
if (theFlowAccTheme = computeStr) then
    theFlowAcc = theFlowDir.FlowAccumulation(NIL)
else
    theFlowAcc = theFlowAccTheme.GetGrid
end

theWater = theFlowDir.Watershed(theSrcGrid.SnapPourPoint(theFlowAcc, SnapDist.AsNumber))

if (theWater.HasError) then
    MsgBox.Warning("Error in watershed grid", theScript)
    return NIL
end

theVTab = theWater.GetVTab
theValue = theVTab.FindField("Value")
if (doString.Not) then
    toField = theValue
    theValue.SetAlias(theValueField.GetAlias)
else
    theSValue = Field.Make(theValueField.GetName, #FIELD_CHAR, theValueField.GetWidth, 0)
    theSValue.SetEditable(TRUE)
    if (theVTab.StartEditingWithRecovery) then
        theVTab.BeginTransaction
        theVTab.AddFields({theSValue})
        for each r in (1..theVTab.GetNumRecords)
            ' theString = thePointFTab.ReturnValue(theValueField, theVTab.ReturnValue(theValue, r-
1)-1)
            theString = stringList.Get(theVTab.ReturnValue(theValue, r-1)-1).AsString
            theVTab.SetValue(theSValue, r-1, theString)
        end
        theVTab.EndTransaction
    end
    theVTab.StopEditingWithRecovery(TRUE)
    toField = theSValue
    theValue.SetVisible(False)
end

' create a theme and add it to the view
theGTheme = GTheme.Make(theWater)
' check if output is ok
if (theWater.HasError) then
    MsgBox.Warning("Error in watershed grid", theScript)
    return NIL
end

theGTheme.SetName("Watersheds of"++ThePointTheme.GetName)
theView.AddTheme(theGTheme)
theLegend = theGTheme.GetLegend
theLegend.Unique(theGTheme, theValueField.GetName)

```

```

if (thePointFTab.IsBase and thePointFTab.IsBeingEditedWithRecovery.Not) then
  if (MsgBox.YesNo("Join attributes of" ++ thePointTheme.GetName ++ "to the
grid?",theScript,FALSE)) then
    theVTab.Join(toField,thePointFTab,theValueField)
    theGTheme.UpdateLegend
  end
end

' save watershed grid
if (MsgBox.YesNo("Do you want to save" ++ theGTheme.GetName ++ "as a
grid?",theScript,false)) then
  def = av.GetProject.MakeFileName("wshed", "")
  aFN = SourceManager.PutDataSet(GRID,"Save Watershed Grid",def,TRUE)
  if ((aFN = NIL).Not) then
    status = Grid.GetVerify
    Grid.SetVerify(#GRID_VERIFY_OFF)
    if (theWater.SaveDataSet(aFN).Not) then
      MsgBox.Warning("Unable to save the watershed grid.",theScript)
      Grid.SetVerify(status)
    else
      Grid.SetVerify(status)
    end
  end
end

'export to shapefile
if (MsgBox.YesNo("Do you want to export" ++ theGTheme.GetName ++ "to a shape
file?",theScript,true)) then
  if (theGTheme.CanExportToFtab.Not) then
    MsgBox.Warning("Error occurred while exporting" ++ theGTheme.GetName)
    return nil
  end
  def = av.GetProject.MakeFileName("wshed", "shp")
  def = FileDialog.Put(def, "*.shp", "Convert " + theGTheme.getName)
  if ((def = NIL).not) then
    theFTab = theGTheme.ExportToFtab(def)
    ' For Database themes, which can return a nil FTab sometimes
    if (theFTab=nil) then
      MsgBox.Warning("Error occurred while converting to shapefile."+NL+
"Shapefile was not created.",theScript)
      return nil
    end
    theValue = theFTab.FindField("Gridcode")
    theId = theFTab.FindField("Id")
    if (doString.Not) then
      theValue.SetName(theValueField.GetName)
    else
      theSValue = Field.Make(theValueField.GetName,#FIELD_CHAR,theValueField.GetWidth,0)
      theSValue.SetEditable(TRUE)
      theSValue.SetVisible(TRUE)
      if (theFTab.StartEditingWithRecovery) then
        theFTab.BeginTransaction
        theFTab.AddFields({theSValue})
        for each r in (1..theFTab.GetNumRecords)
          ' theString =
thePointFTab.ReturnValue(theValueField,theFTab.ReturnValueNumber(theValue,r-1)-1)
          theString = stringList.Get(theFTab.ReturnValue(theValue,r-1)-1).AsString
          theFTab.SetValue(theSValue,r-1,theString)
        end
        theFTab.RemoveFields({theValue,theId})
        theFTab.EndTransaction
      end
      saveEdits = TRUE
      theFTab.StopEditingWithRecovery(saveEdits)
    end

    shpfld = theFTab.FindField("Shape")

    ' build the spatial index
    theFTab.CreateIndex(shpfld)

    ' create a theme and add it to the View
    fthm = FTheme.Make(theFTab)

    if (MsgBox.YesNo("Do you want to add" ++ fthm.getName ++"to the view?",theScript,true))
then
      theView.AddTheme(fthm)

```

```
    end  
  end  
end
```

```
theView.GetWin.Activate
```