AN EROSION AND SEDIMENT DELIVERY MODEL FOR SEMI-ARID CATCHMENTS

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ABSTRACT

Sedimentation has become a significant environmental threat in South Africa as it intensifies water management problems in the water-scarce semi-arid regions of the country. As South Africa already allocates 98% of available water, the loss of storage capacity in reservoirs and degraded water quality has meant that a reliable water supply is compromised. The overall aim of this thesis was to develop a catchment scale model that represents the sediment dynamics of semi-arid regions of South Africa as a simple and practically applicable tool for water resource managers. Development of a conceptual framework for the model relied on an understanding of both the sediment dynamics of South African catchments and applicable modelling techniques. Scale was an issue in both cases as most of our understanding of the physical processes of runoff generation and sediment transport has been derived from plot scale studies. By identifying defining properties of semi-arid catchments it was possible to consider how temporal and spatial properties at higher levels emerged from properties at lower levels. These properties were effectively represented by using the Pitman rainfall-runoff model disaggregated to a daily timescale, the Modified Universal Soil Loss Equation (MUSLE) model incorporating probability function theory and through the representation of sediment storages across a semi-distributed catchment. The model was tested on two small and one large study catchment in the Karoo, South Africa, with limited observed data. Limitations to the model were found to be the large parameter data set and the dominance of structural constraints with an increase in catchment size. The next steps in model development will require a reduction of the parameter data set and an inclusion of an in-stream component for sub-catchments at a larger spatial scale. The model is applicable in areas such as South Africa where water resource managers need a simple model at the catchment scale in order to make decisions. This type of model provides a simple representation of the stochastic nature of erosion and sediment delivery over large spatial and temporal scales.

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Unless otherwise stated, this thesis presents the authors own work.

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1 INTRODUCTION

1.1 Introduction and project overview

Reservoir sedimentation is a global problem leading to large reductions in reservoir storage capacity. De Villiers & Basson (2007) suggest that the average life-span of reservoirs has reduced to just 35 years. Storage reservoirs in South Africa are experiencing a similar trend, largely as a consequence of high sediment yields within their catchment areas. This is a major environmental and economic concern as it intensifies water management problems in the water scarce semi-arid regions of the country. As South Africa already allocates 98% of available water, the loss of storage capacity in reservoirs and degraded water quality has meant that a reliable water supply is compromised.

The importance of reservoir sedimentation was first highlighted in South Africa in 1901 when the basin of the newly constructed Camperdown Dam rapidly accumulated sediment (Rooseboom & Lotriet, 1992). Following this realisation numerous studies have led to there being remarkably good data on long-term sedimentation rates in major reservoirs (Rooseboom & Lotriet, 2010). It is apparent that the real challenge is relating these sediment yields to catchment erosion and sediment delivery data (Boardman, 2012) as there is a large amount of variability over both temporal and spatial scales. At the catchment scale erosion rates may vary with soil type, slope angle and vegetation cover, with system connectivity creating another layer of complexity, making it incredibly difficult to link sediment yield with erosion rates.

Soil erosion by water is considered to be one of South Africa's major environmental problems (Le Roux et al., 2008), due in part to landscape and soil conditions making the country susceptible to erosion. Although erosion is a natural process, it may be accelerated by human influences. This, linked to the negative impacts of erosion on soil productivity has meant that there has been significant focus on the issue by the government with regards to erosion as a form of land degradation. The governmental focus on land degradation originated in the early part of the nineteenth century for the arid parts of the country where observed declines in vegetation cover and associated soil loss was attributed primarily to overgrazing (Boardman, 2012). This view was encouraged by Acocks (1953), with a primary focus on the Eastern Cape. By 1999 the first national review of the land degradation problem rejected this focus on the Eastern Cape (Hoffman & Ashwell, 2001; Hoffman et al., 1999) as it was apparent that a multitude of environmental factors were important for different reasons in different regions. This highlighted the complexity involved in identifying the driver of land degradation and more importantly the driver of soil erosion by water.

A historical perspective of how the government has dealt with this problem can be seen by tracking the development of the water act, as a legislative provision to protect the country's water resources. Initially the Water Act of 1956 (Act 54 of 1956) dealt with point source discharges as the main issue of concern in the country but by the 1980's water resource managers were becoming increasingly aware that certain land use activities resulted in significant nonpoint pollution problems (Quibell et al*.,* 2003). This culminated in a new National Water Act (Act 36 of 1998) making provisions for managing land use activities within an Integrated Catchment Management (ICM) approach. This also included the relationship between flow and water quality as the Act included a provision for an ecological Reserve, or the quality and quantity of water required to maintain aquatic ecosystems. It is therefore necessary to have a method to measure these components. The evolution of the water law has meant that water resource managers have been given the policy and legal framework to manage land use activities that increase a catchments sediment yield. Implementation has been constrained by a lack of both financial and human resources as limitations in the availability of methods for assessing the water quality (including sediment) components of ecological Reserve determinations (Slaughter, 2011).

Before soil erosion prevention or mitigation can take place, the spatial scale of the problem needs to be identified. The Department of Agriculture as well as the Water Research Commission have funded a number of regional projects with this issue in mind. Initially a regional map was developed by Rooseboom et al. (1992) to provide spatial data on sediment yield by using geographical information systems. This map, the Sediment Delivery Potential Map (SDM), as well as following attempts to present the spatial extent of erosion (Erosion Susceptibility Map (ESM) (Pretorius,1995), Predicted Water Erosion Map (PWEM) (Pretorius, 1998), South African National Biodiversity Institute (SANBI) land degradation review (Garland et al., 2000)) have not managed to effectively represent erosion and sediment yield at catchment scales. Recently the SDM has been reviewed (Rooseboom & Lotriet, 1992; Msadala et al., 2010) and new data and techniques have been used to improve estimates. This Revised Sediment Yield Map for South Africa is useful at a regional scale but still lacks the accuracy necessary to make decisions at a catchment scale.

There are examples of landforms in the South African semi-arid landscape which have an important influence on the connectivity of the sediment system. The effects of runoff are clearly seen through the existence of degraded land, badlands and gullies in the semi-arid regions of South Africa. Badlands are widely spread from the Eastern Cape (Kakambo & Rowntree, 2003; Kakembo et al., 2009; Boardman et al., 2003; Boardman & Foster, 2008; Kaey-Bright & Boardman, 2009) to KwaZulu-Natal (Watson, 2000; Clarke et al., 2003) and

Swaziland (Price Williams et al., 1982; Dardis, 1990). These landforms are comprised of an intricate network of gullies and are considered an active part of the landscape, acting as a sediment source in certain catchments. Gullies or 'dongas' are also a widespread feature of South Africa's semi-arid landscape but these systems may not always be considered 'active' as is the case in the Sneeuberg where gully systems seem little changed over several years (Boardman & Foster, 2008; Keay-Bright, 2006; Keay-Bright & Boardman, 2006), although they do act as conduits during frequent flood events.

1.2 Erosion and sediment delivery modelling

Natural systems are very complex and a major limitation in modelling the generation and transport of sediments is an inadequate understanding of the processes involved. Quantifying the spatial distribution of these processes is particularly complex due to the difficulty in obtaining and verifying information on sediment sources, pathways, transport rates and delivery (Merritt et al., 2003). More than two decades ago prominent researchers Wolman (1977) and Walling (1983) called for research to be continued towards an increased understanding of the sediment delivery processes in order to link on-site erosion to sediment yield at the basin outlet. This developed from the recognition that the sediment yield at the basin outlet would not reflect the gross soil erosion within the basin due to depositional losses, made clear in Meade's (1982) statement that "any sediment particle entrained by a river is not likely to spend a large amount of time being transported but would spend a great deal of time in storage".

Since then sediment models have become more complex, placing greater emphasis on representing important physical processes over large spatial scales. Model results have indicated that this strategy may provide predictions that are moderately good for total discharge at a catchment outlet but models would then rely on extensive calibration (Jetten et al., 2003). The issue of scale is typically dealt with through distributed models by dividing a catchment into cells or grids. Complications arise in part because of high data requirements but mainly due to a poor understanding of the complex interactions between different processes at a larger scale (Jetten et al., 2003; De Vente & Poesen, 2005; Nearing & Hairsine, 2011). In some cases lumped regression based models may perform better, owing to the inherent uncertainty associated with increased numbers of parameters (Zhang et al., 1996; Risse et al., 1993). These complex models are also not useful in data poor South African catchments where it would be difficult to measure all the parameters required and where calibration is almost impossible because of the lack of observed sediment transport data.

Implementing water quality assessment in South Africa is constrained by water resource managers not having the training or resources to use complex models, indicating that simpler, easier to understand models may be more appropriate (Slaughter, 2011). An alternative approach would be to use statistical distributions and uncertainty methods, whereby a catchment would be classified based on distributions of functional responses and physical characteristics. In hydrological modelling this has been proved useful as distribution function models are easy to implement and require much less computer time than fully distributed models (Beven, 2001). Application of this approach to sediment models was first developed by Moore (1984) and it was based on the idea that the range of responses in a catchment area can be related to the probability distribution of conceptual stores without any explicit account of the physical characteristics that control the distribution of responses (Beven, 2001).

Scale is a significant challenge in sediment modelling in particular in semi-arid landscape such as South Africa. For rills and gullies sediment entrainment and sediment travel distance are considered functions of flow, which does not increase linearly but rather with catchment area (Parsons et al., 2004). The intermittent nature of flow in semi-arid areas also acts to disconnect a catchment. The degree of connectedness of a catchment can be related to flow through this conceptualisation as flow is the driver of sediment entrainment and movement. As the catchment scale increases it can be expected that landscape units such as gullies and badlands exert more influence on the sediment yield as they may act as conduits and sources of sediment. These concepts need to be represented in a sediment model but unfortunately the data limitations in South Africa means that a more conceptual overview is required for this thesis.

This thesis progresses from investigating the theory behind the important processes in semi-arid catchments and incorporates the investigation of sediment models that fall somewhere between simple and complex models in order to develop a conceptual model for semi-arid catchments that may be implemented by water resource managers. A potential gap in available sediment models is the representation of temporary storage at the catchment scale. The representation of this characteristic will be an important feature of a sediment model for semi-arid catchments.

1.3 Research aim, objectives, outcomes and design

The overall aim of this study is to develop a catchment scale model that represents the sediment dynamics of semi-arid regions in South Africa. Water resource managers require quantifiable results in order to make decisions regarding the sedimentation of important storage reservoirs, but in order to do this a qualitative understanding of the catchment is necessary. A desktop study of the important sediment source, sink and transfer processes in semi-arid catchments will be conducted in order to develop this qualitative understanding. Limitations to currently available erosion and sediment delivery models will also be identified via a literature review. Once a conceptualisation of a semi-arid catchment is developed an erosion and sediment delivery model will be developed and tested for semi-arid catchments.

1.3.1 Research objectives

The specific objectives of this research are to:

1. Develop a catchment scale conceptual model that incorporates sediment erosion, storage and delivery processes.
2. Translate the conceptual model into a mathematical model that can be linked to an existing rainfall-runoff model. This objective includes the selection of an appropriate rainfall-runoff model that will provide the necessary rainfall, catchment runoff and stream flow data to drive the sediment model.
3. Test and calibrate the model for small catchments using available long-term sediment yield data from farm dams.
4. Apply the model to a large catchment for which long-term sediment accumulation data is available.

1.3.2 Research outcomes

The erosion and sediment delivery model has been designed to target a research gap in South Africa and more specifically in semi-arid catchment management where sedimentation has become a major issue. Available models are either too complex for South Africa's data poor environment or do not account for important processes within a semi-arid catchment. Although the erosion and sediment delivery model will be tested on small catchments it will also be applicable to larger catchments, providing a useful tool for water resource managers.

1.3.3 Research design

The outlined project objectives will be met by dividing the project into three main themes (Figure 1.1). The first theme, focusing on modelling the semi-arid catchment system, is a theoretical framework consisting of two chapters: the literature review of the sediment dynamics of semi-arid catchments and of previous approaches to erosion and sediment modelling. The second theme, focusing on the development of an erosion and sediment delivery model, takes the theory developed in the proceeding theme and applies it to create a new sediment model for semi-arid catchments. The study area and methodology of the model will be discussed within this theme. The third theme will focus on the application of the model.

1.3.3.1 Theoretical framework for the erosion and sediment delivery model

The theoretical framework for the conceptual erosion and sediment delivery model will have two literature review chapters: the sediment dynamics of semi-arid catchments and erosion and sediment delivery models. The first chapter will highlight the important source, sink and transport processes in semi-arid catchments, with an influence on erosion and sediment delivery, and the second chapter will focus on the erosion and sediment models that could be used in semi-arid catchments. The important points and limitations identified in each section will provide the insight necessary to develop a conceptualisation of an erosion and sediment delivery model. This may be considered the development of the underlying model structure for an erosion and sediment delivery model.

1.3.3.2 Developing an erosion and sediment delivery model

This section will include two chapters: the study area considered for the testing and application of the model and the methodology behind the development and testing of the model. The methodology behind the development of the model will include model development, testing and application. The development of the underlying model structure will be based on the literature reviews of sediment dynamics and existing simulation approaches as described in the theoretical framework. Model development will also include determining the governing equations, the linkages among them and the parameter values. Model testing will include using data from two small catchments in the Karoo, with parameter sensitivity being conducted and evaluated. The model would then be applied to a large catchment in the Karoo to test its applicability in larger catchments.

1.3.3.3 Applying the erosion and sediment delivery model

The applicability of the model in semi-arid catchments will be discussed and the developed model will be critically assessed on the basis of its data requirements, limitations and uncertainties. Conclusions and recommendations will be considered for further testing and development of the model.

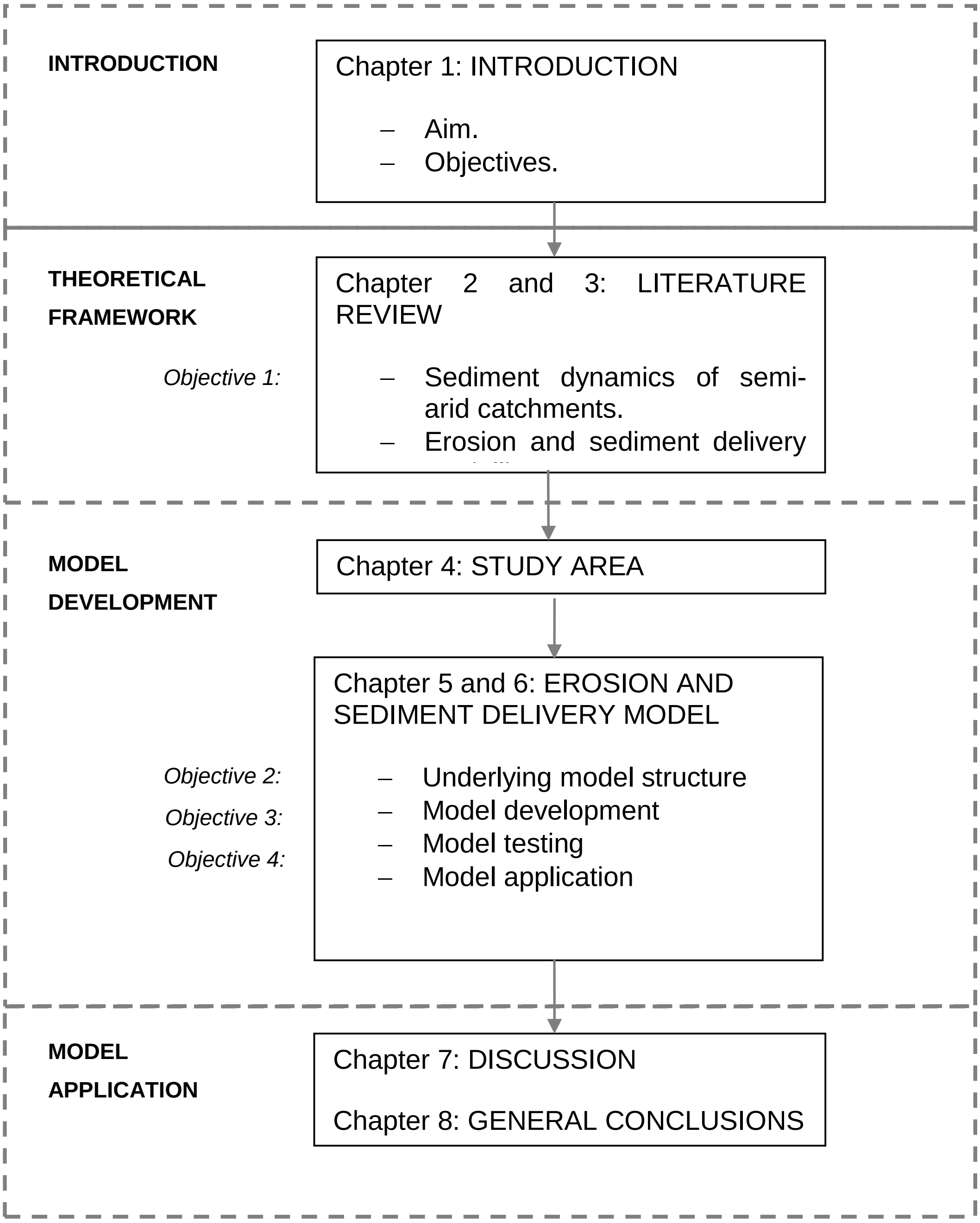


Figure 1.1 Thesis outline.

2 LITERATURE REVIEW: SEDIMENT DYNAMICS OF SEMI-ARID CATCHMENTS

The aim of this literature review is to provide a summary of the present knowledge of both erosion and sediment delivery processes in semi-arid catchments. This chapter outlines important erosion and sediment delivery processes as well as the factors that influence these processes, while the following chapter deals with the models that are currently available to represent them. The outcomes of both reviews will inform the first research objective of development of a catchment scale conceptual erosion and sediment delivery model.

2.1 Introduction

Much of our understanding of the physical processes of both runoff generation and sediment mobility has been derived from plot studies (i.e. Wischmeier & Smith, 1978). However, it is clear that additional processes are relevant at larger scales and that these processes affect catchment scale sediment delivery rates (De Vente & Poesen, 2005; Wolman, 1977; Walling, 1983; Walling, 1988). Identifying emergent properties may be a means of considering how spatial and temporal organisation at higher levels emerged from many physical and biological processes acting at lower levels (Wasson, 2002). Emergent properties are difficult to predict due to the many interactions between components of a system, which increases with the number of components as the scale increases.

2.2 Scale issues in soil erosion research

Scale dependency in erosion and sediment delivery has been identified as an important problem throughout the literature. In the 1970's researchers made well documented statements about the need for research to be directed towards an understanding of the linkage between the on-site rates of erosion and the sediment yield at the drainage basin outlet (Wolman, 1977; Robinson, 1977; Meade, 1982; Walling, 1983). This concept developed from the recognition that the sediment yield at the basin outlet would not reflect the gross soil erosion within the basin due to depositional losses (Walling, 1988). It was clear that sediment particles entrained by water erosion would more than likely spend a short amount of time being transported, and in fact more time in storage (Meade, 1982). The discontinuity of sediment progress through the drainage basin was related to a 'jerky conveyor belt" by Ferguson (1981) as sediment was considered to move through the basin, being deposited further downstream with the potential to be reworked as a sediment source.

At the plot scale the landscape is spatially distributed with a mosaic of sources and sinks. Vegetation may be considered to be the main factor at this scale, determining hydrological and erosion response at different temporal scales (Cammeraat et al., 2005). Soil loss is also closely related to rainfall due to the detaching power of raindrops and through the contribution of rain to overland flow. Critical conditions affecting runoff generation and erosion at the finer scale are rainfall intensity (Cammeraat, 2004) and antecedent soil moisture content (Cantón et al., 2001). Bare patches of soil will act as a source for runoff and sediments, trapped by vegetated patches and acting as sinks (Cantón et al., 2011). Hydrological connectivity is decreased, with only extreme rainfalls saturating sinks and contributing to runoff and connectivity.

Generally as the spatial scale increases different controlling factors and erosion processes interact and different water and sediment sources appear. At the finer scale low energy (sheet or rill erosion) processes take place and past a certain threshold more non-selective erosion processes (gullying) progressively appear before depositional features become dominant (Cantón et al., 2011). Hooke (2003) identified erosion in gullies and banks as the main slope-to-channel sediment source. When ephemeral gullies become permanent they act to couple the hillslope with the channel network (Hooke, 2003), whilst deposition in fans and footslopes significantly reduces connectivity (Faulkner et al., 2008).

In a similar way, our understanding of hillslope and channel runoff generation processes developed rapidly during the 1970's (Hewlett & Hibbert, 1967; Dunne, 1978; Ward, 1984). Runoff can be generated through rainfall intensity exceeding soil infiltration rates, through rainfall falling on saturated soil surfaces or through the re-emergence of sub-surface flow. The actual processes occurring at any specific site are also highly variable and depend on similar factors as soil erosion processes (i.e. climate, topography, soils and vegetation). Quantifying site specific runoff generation processes and how they affect sediment detachment and entrainment processes is therefore very difficult at scales larger than small hillslope plots.

2.3 Dealing with scale in semi-arid catchments

Cammeraat (2004) and De Vente & Poessen (2005) have both experimentally demonstrated area specific runoff and erosion rates which can be attributed to the influence of sinks at different scales. Whilst the finer scale processes of soil particle detachment and entrainment are well understood (Toy et al., 2002; Lal, 2001; Morgan et al., 2005), quantification at all but very small spatial scales remains difficult due to the large number of variables involved, their interactions and their high degree of spatial variability (De Vente & Poesen, 2005). Spatial and temporal variation of processes in semi-arid catchments make generalisations about patterns of runoff generation, and sediment transfer, extremely difficult (Hughes, 2008).

The consideration of the complexity of erosion and sediment delivery processes led Wasson (2002) to propose a 'top-down' approach to its analysis. Wasson (2002) considered that this would "immediately lift the modeller's gaze" above the detail of low level process, by focusing on the high level properties that need to be understood if catchment management is to be effective. A top-down approach could also be related to the hierarchical classification framework commonly used as a basis for river classification systems (i.e. as presented by Cammeraat (2002)). Rowntree & Wadeson (1998) adapted the scheme presented by American ecologists (Frissell et al., 1986) for application to South African rivers. This classification is based on the geomorphological basis that the structure and dynamics of a river system are determined by the surrounding catchment, with landform structure at one level being driven by processes at a higher level (Rowntree, 2012). At the same time, each higher level is comprised of a collection of lower level units. Although hierarchical systems are built with the bottom-up approach, they are driven from the top down (Rowntree, 2012). This hierarchy places catchments as the landscape unit that provides a source of water and sediment to the channel network.

In particular defining the emergent properties of semi-arid catchments requires the presentation of the characteristics of such regions. This introduces the concept that dryland fluvial environments are distinctively different to humid environments (Bull & Kirkby, 2002; Nanson et al., 2002; Knighton & Nanson, 2002; Tooth, 2013). The term 'drylands' refers to hyperarid, arid, semi-arid and dry-subhumid environments; often occurring in warm, low-altitude regions (Tooth & Nanson, 2011). Knighton & Nanson (1997) originally ascribed a set of characteristics to dryland rivers. This analysis of their distinctiveness drew upon research, conducted up until the mid-1980s, in a limited range of environmental contexts (Leopold et al., 1964; Reid & Frostick, 1987; Graf, 1988; Lewin et al., 1995), which left out much larger areas of drylands with tectonically stable uplands and vast, lower relief plains (Tooth & Nanson, 2011). Since then dryland fluvial research has extended into these settings and has provided a broader range of examples from which to draw (Tooth & Nanson, 2011; Tooth, 2013).

In general what should be noted is that river systems are the integrated product of their environmental setting, which consists of various factors subject to various spatial and temporal changes (Tooth & Nanson, 2011). As large parts of dryland fluvial environments are still poorly known Tooth & Nanson (2011) assessed how different combinations of factors can give rise to different dryland river styles. One of the regions studied was southern

Africa as it was considered to have extensive drylands with several types of river systems ranging from moderate-size, moderate gradient rivers to moderate-size, low gradient rivers. Tectonic, structural, lithological and palaeo-climatic factors have had a significant influence on the development of the fluvial system in this region (Tooth et al., 2002; Tooth et al., 2004; Grenfell et al., 2009), which has been different to that experienced in other regions.

Although Tooth & Nanson (2011) define regional differences in dryland rivers there are still certain aspects of such systems that can be generalised. In this respect hydrology and sediment transport, with their associated processes, are defining characteristics of dryland regions. Rowntree (2012) defines the regional and local drivers of river systems in South Africa in relation to this concept. At a regional scale catchment runoff and sediment yield provide the main inputs into the channel network with the longitudinal profile determining the energy available for erosion and sediment transfer, whilst at the local scale channel form adjusts to downstream manifestations of these factors as well as to local constraints of underlying geology and riparian vegetation (Rowntree, 2012). The predominance of an erosion or sediment transport process depends on the spatial scale, topographic thresholds, rainfall, initial soil moisture content, and soil biological activity (Cammeraat, 2002); and the spatial configuration of land use, land cover, topography and lithology (De Vente et al., 2007). Above certain thresholds, when rill erosion, gully erosion, bank erosion and mass movements are initiated, connectivity will increase until slope gradient decreases and sediment yield becomes transport-limited (De Vente & Poesen, 2005). These factors as well as those defined by Tooth & Nanson (2011) and Tooth (2013), will be discussed below in order to develop a conceptualisation of defining or emergent properties for erosion and sediment delivery in semi-arid catchments.

2.3.1 Climatic drivers

Climate is one of the main controlling variables in a fluvial system as it impacts on both hydrology and vegetation (Schumm, 2005). It is therefore considered a driver of the hydrological characteristics considered emergent properties of semi-arid catchments.

2.3.1.1 Hydrology

Knighton & Nanson (1997) presented a conceptualisation of the diversity within arid systems in terms of a continuous scale of flow occupancy, with ephemeral stream flow at the one end and perennial flow at the other. Dryland rivers may be on either end of this scale but irregular rainfall events and depressed water tables have meant that most are commonly ephemeral, with channels normally remaining dry and only occasionally transporting water (Tooth, 2013). These rivers may further be subdivided into endogenous, where rivers have headwaters in humid mountain areas and have perennial flow, and exogenous, where rivers have semi-arid or arid headwaters and have ephemeral flow (Knighton & Nanson, 1997). Most Karoo rivers fall within this category (Rowntree, 2012). Both exogenous and endogenous dryland rivers have a tendency for downstream decreases in flow volume, normally as a result of transmission losses from floodwater infiltrating into channel boundaries, overbank flooding and evaporative losses (Thornes, 1977; McCarthy & Ellery, 1998). Many dryland rivers will also fail to travel the entire length of the channel (Hughes & Sami, 1992) and it has been proposed that in ephemeral rivers the dynamics of channel pools, in reference to frequency of connectivity and storage levels, will be just as important as flow (Bunn et al., 2006).

The amount and timing of precipitation influences whether a river is perennial or ephemeral, and as such influences the flow of sediment. The nature of the drainage system would therefore influence the sediment cascade. Semi-arid systems have characteristically low annual precipitation and high evaporative losses, which result in low annual runoff totals, with inter-annual variability of runoff increasing as annual totals increase (McMahon, 1979). Given the spatial variability of rainfall events, catchment area may not reliably provide an accurate measure of runoff (Reid & Frostick, 1997). For instance smaller runoff events in semi-arid areas tend to be isolated in time and space, therefore only small areas of the catchment produce runoff, relating to how much of the catchment is considered effective (Rowntree, 2012). Rarely runoff events may extend over the entire catchment, making the whole catchment effective.

A recent study has focused on the climatic controls on drainage basin processes in South Africa whereby two drainage systems on equivalent lithologies, in contrasting climatic conditions were compared (Grenfell et al., 2014). The Seekoei River Floodplain and Gordonville valley fill site, in the Great Karoo, experienced less than half the annual precipitation of the Nsonga River Floodplain and Hlatikhulu valley fill in the Kwa-Zulu Natal Foothills. Although attention is usually focused on the amount of precipitation an area receives, the seasonality or variability of the precipitation may have a more notable impact, especially when considering ephemeral flow. Climatically the Karoo is more arid than Hlatikhulu, with more “flashier” and variable rainfall, which would be reflected in the flow (Grenfell et al., 2014). The river form in the Karoo is impacted by this variable flow, in that as opposed to the sinuous, meandering river form of the Hlatikhulu River, the sporadic flow in the Karoo cannot maintain a meandering channel and rivers tend to rather maintain a relatively straight planform. There is not constant recycling of sediment in the floodplain as sediment is not transported past resistant dolerite dykes. Channel width and depth may adjust, resulting in floodouts, infilling channels and distributary switching. Gully-floodout dynamics may be the precursor to anabranching. In general the authors found that sediment moves through the Karoo floodplain in infrequent bursts each time a floodplain channel is rejuvenated by a switch at the floodplain head on a floodout. Given the infrequent flow, it is likely that sediment stays in temporary storages within the Karoo floodplain for longer periods, in comparison to the storage time of humid regions.

2.3.1.2 Vegetation

As has been mentioned above, climate has an impact on both hydrology and vegetation. There is a positive feedback between vegetation and infiltration rates in semi-arid regions where water stress acts as important control over vegetation growth (Beven, 2002). Vegetation may act as a protective covering for soil from the impacts of rainfall and be a dominant control on runoff generation in semi-arid areas (Wainwright, 1997). Factors affecting vegetation growth will have a significant impact on infiltration rates. The density of vegetation cover, which increases with water availability, will offset the possibility of increased runoff generation with increased rainfall (Beven, 2002). As vegetation cover in semi-arid areas may become a pattern of bare and vegetated patches, runoff is highly discontinuous owing to non-uniform infiltration (Ludwig et al., 2005). In semi-arid regions where vegetation is sparse, high concentrations of suspended sediment load may be expected (Langbein & Schumm, 1958; Walling & Kleo,1979).

2.3.2 Topographic drivers

Topographic drivers relate to the short-term and long-term controls that landscape characteristics have in semi-arid catchments. The concept that runoff yield decreases with increasing area has been related to changes in lithology and channel width and increasing possibilities for valley storage at the watershed scale and non-uniform infiltration and spatial variability of vegetation and soil surface properties at a smaller scale. For erosion and sediment delivery this relationship is less clear. De Vente & Poesen (2005) have developed a conceptual model to explain sediment delivery at the basin scale but the local conditions and their spatial distributions are important factors that need to be accounted for. It has been proposed by other authors that the explanation for a decline in sediment yield with increasing basin area is, quite simply, because it takes longer for particles to travel greater distances (Parsons et al., 2006). Although Parsons et al. (2006) have demonstrated that sediment yield decreases with plot lengths above 7 meters, due to limited travel distance of individual entrained particles and by the decline in runoff coefficient as plot length increases, at larger scales additional erosion processes such as gully erosion, mass movement and bank erosion can become active and increase area specific sediment yield. Parsons et al. (2004) also identified that for both interrill and rill and gully erosion, sediment flux has a notable spatial variability. The authors found that for interrill erosion, measurements made at the plot scale will grossly overestimate erosion for whole hillslopes. For rill erosion the opposite is true, as the greater the distance down the rill that the measurement is made, the greater the apparent erosion rate. The notion that active erosion and transport process as well as sediment sinks are strongly related to spatial scale is the important point to grasp from these concepts.

Rivers will continually rework and deposit sediment over different time scales. The time scale of this change is important as long-term evolution of a landscape is controlled by different factors than those that bring about short-term change. In the short term deposition of sediment is under the influence of transport or supply limitation. In the long-term imposed boundary conditions of geologic influences such as tectonic and base level controls shape relief, slope, valley confinement and associated patterns of aggradation and degradation along a river (Brierley et al,, 2008). Over both time scales climate would provide a fluctuating boundary condition within which rivers operate.

In the short term diminished discharge can be considered to be due to transmission losses and a decline in slope, resulting in the stream power and sediment transport capacity decreasing. This would lead to sediment deposition. Stream power, as related to the bed area or shear stress at the bed surface, determines whether a river will erode, transport or deposit its suspended sediment load. In headwater reaches, channels are frequently discontinuous as the catchment area is too small to generate sufficient discharge to maintain a channel capable of transporting the amount of sediment supplied to it (Grenfell et al., 2014). In basic terms the decrease of discharge and slope in a downstream direction will result in according decreases in stream power. Following a decrease in stream power, excess sediment is deposited. Once sediment is deposited the transport capacity of flow increases and a channel may reform. Once a channel has formed other controls, such as climate, geology and tectonics become important. Bull (1979) outlined the importance of grade in rivers as when there are sections of a river at or near the threshold of critical power these sections are sensitive to changes of climate, base-level and anthropogenic factors.

The long term evolution of the South African subcontinent may be considered as an important factor determining river grade. Following two periods of uplift, rivers in the eastern part of the subcontinent developed a long-term state of incision with their channel beds positioned on or close to bedrock (Tooth et al., 2002). As large amounts of the soft Karoo sediments were removed these channels became superimposed upon resistant dolerite dykes and sills (Grenfell et al., 2009). Dolerite forms a stable local base level for a river and hence slows down erosion and the rate of sediment delivery to downstream reaches (Tooth, 2007). On the South African Highveld resistant dolerite outcrops were found to exert strong controls on the nature of river activity not only within the immediate reach, but also in the dominantly alluvial reaches upstream (Tooth et al,, 2004). Grenfell et al. (2014) compared two drainage basins in South Africa with similar lithologies to determine the extent of the control that climate has on fluvial systems. In accordance it can be expected that whilst the underlying geology may have a long-term control on the sediment cascade of semi-arid catchments, in the short-term climatic drivers are more important. It is still important to understand the base-level control when considering the long-term evolution of the landscape and in relation to the development of fluvial landforms such as badlands, floodouts and gully systems.

2.3.3 Catchment connectivity drivers

At the catchment scale soil erosion is a complex set of sediment delivery processes. The "connectivity" of a catchment can be considered as the transfer of energy or matter though a system as a whole, from the uplands of a drainage basin all the way down to its outlet. Any hampering of this transfer of energy or matter may be considered to cause a "disconnect" in the drainage basin. This may be due to ineffective sediment delivery (Walling, 1983) or the decoupling of sediments from slopes and tributaries (Fryirs & Brierley, 1999; Harvey, 2001). Sediment budgeting has often been used in order to identify sink and source areas within a catchment (Slaymaker, 2006; Walling & Collins, 2008) with sediment yield referring to the amount of sediment reaching the catchment outlet.

Fryirs et al. (2007) focused on sediment stores and sinks with regards to connectivity. They stressed the fact that storage of sediment is as important as sediment movement, reflecting the ideas emphasized by Walling (1973) and others over the years. Fryirs (2013) introduced a higher level look at the "sediment delivery problem", originally identified in Walling's (1983) seminal paper, by presenting the concept of "(dis)connectivity in catchment sediment cascades". This concept developed from the Fyirs et al. (2007) conceptual framework for the analysis of the sediment cascade through a catchment that incorporates both the temporal and spatial scales. Fluvial landforms (termed buffers, barriers and blankets) may disrupt longitudinal, lateral and vertical linkages in catchments. Depending on the position of fluvial landforms and their sediment residence time, various parts of a catchment may be actively contributing sediment to the sediment cascade, considered to be analogous to being "switched on", or inactive and "switched off". In semi-arid systems the pattern of source, transfer and sink zones, as well as the level of (dis)connectivity is more likely to reflect the last high magnitude, low frequency event that was able to "flush-out" sediment through the system (Schumm, 1977; Graf, 1988; Trimble, 1995). This event driven disconnectivity reflects the characteristic hydrology of semi-arid catchments.

The concept of hydrological connectivity, as in the physical linkage of water and sediment through the fluvial system, has been increasingly used within the field of hydrology and geomorphology (Hooke., 2006; Bracken & Croke, 2007). In particular it has been useful when identifying areas that function as sinks when modelling runoff and erosion for semi-arid catchments (Lesschen et al., 2008). Lesschen et al. (2008) identify vegetation and micro-topography as influential at the plot scale, whilst concentrated runoff downslope may lead to gully formation. These gullies can act as effective links for transferring water and sediment from hillslope to valley bottoms and channels, increasing the hydrological connectivity (Poessen et al., 2003). Harvey (1974, 1977, 2002, 2012) has conducted many years of research focusing on the degree of coupling in landscapes caused by gullies. In the particular landscape on-slope gully erosion occurs recurrently, from between 30 to 50 runoff events per year (Harvey, 1974), where the relatively low effective catchment area is contained within the active gully network. Every 2–6 years, both the gullies and the alluvial fans are active allowing for a larger effective catchment area and less frequently, once every 30 years, hillslope debri flows occur, resulting in an increase further increasing the effective catchment area (Harvey, 2001). Effective catchment area is significantly increased during a one in 100 year runoff event as all sources in the tributaries are active and the tributaries are directly connected to the trunk stream. Rowntree & Foster (2012) have also noted that gully initiation, during a particular threshold event, was responsible for increased connectivity in a small, high elevation catchment in the Karoo.

The evaluation of gully development rates under various climatic conditions has seen limited attention by researchers as the main focus has traditionally been on sheet and rill erosion (Marzolff et al., 2011). This knowledge gap is mainly caused by the temporal and spatial variation of gully development making it difficult to monitor. For both rill and gully erosion sediment entrainment and travel distance of sediment are functions of flow, and as flow increases with catchment area rather than linearly with distance, measurement is quite difficult (Parsons et al., 2004). Gully erosion is usually caused by intense, infrequent rainfall and the sizes and forms of gullies are often beyond the traditional scale for erosion investigation, whilst development is usually erratic (Marzolff et al., 2011). Gullying also involves a wide range of sub-processes related to water erosion and mass movement, which act to increase the complexity involved in defining them. This cannot be effectively described by highly variable short term data (Marzolff et al., 2011). In general once gullies develop they are considered to increase the connectivity in the landscape as they are considered to be effective links between the upland areas and channels, rapidly transferring overland flow to lower areas (Poesen et al., 2002). This aggravates flooding problems and sedimentation of reservoirs.

Another important physical feature of semi-arid landscapes is the presence of badlands. The term ‘badlands’ describes an intensely dissected natural landscape with limited vegetation, which has been exposed to rapid fluvial erosion (Bryan & Yair, 1982). Particularly in semi-arid landscapes these physical units are representative of a fragile natural equilibrium which has been disturbed. Small-scale features in badlands have short reaction times to erosional processes and may adjust form rapidly, whilst large-scale features may preserve the effects of formative events (Kirkby & Nanson, 1997). Erosion in badlands is so rapid that establishment of vegetation cover is inhibited and in a positive feedback loop, this lack of vegetation enhances erosion (Kirkby & Nanson, 1997). Extremely high drainage densities are regarded as evidence of the dominance of overland flow (Bryan & Yair, 1982). Overland flow occurs in parts of the badlands which produce runoff rapidly even in low flow stages whilst concentrated flow occurs in the numerous gully and rill systems dissecting the landscape feature.

In the Karoo there is evidence for the occurrence of linear gullying and significant badland erosion. In the Sneeuberg, gully systems, considered to have originated as a result of European farming in the area (Keay-Bright & Boardman, 2006), seem to be little changed since the 1940s (Boardman, 2012). At around the 1940s the extent of the gullying had stabilised (Rowntree, 2012) and evidence from dam sediments indicated that gullies have not been a significant source of sediments since this time (Foster et al., 2012). They are considered active in the sense that they move sediment from the hillslopes in frequent floods, but there is little change to their form (Keay-Bright & Boardman, 2006; Boardman & Foster, 2008). These linear gullies would still act as an important sediment transfer system, but they would not be acting as a source of sediments.

Badland areas may act as significant source of sediments at certain points in time. In the Sneeuberg it has been observed that badland areas produce runoff in response to runoff events as low as 10 mm (Keay-Bright & Boardman, 2006). Rowntree & Foster (2012) provide evidence that in the Ganora catchment badland erosion is a significant source of sediment. This is indicative of a very active source of sediments in semi-arid regions and they should not be overlooked as significant landscape features in a catchment.

Sediment accumulation in reservoirs may act as a significant sediment sink in a drainage basin. These accumulations may represent a ‘history book’ of catchment erosion in highly variable semi-arid regions (Foster & Rowntree, 2012). In South Africa accumulation of sediments in large storage reservoirs have been used to construct sediment yield maps and algorithms at a regional scale. A Sediment Yield Map for South Africa by Rooseboom et al. (1992) has been revised by Msadala et al. (2010) based on the sediment yields calculated for over 150 dam catchments, subdivided into nine regions. Smaller farm dams have also been studied in the Karoo, which give a more detailed description of the processes occurring within the catchments (Foster et al., 2012; Rowntree & Foster, 2012; Foster & Rowntree, 2012).

2.4 Concluding remarks

Whilst generalisation and conceptualisation is an important part of making sense of highly complex natural systems, misconceptions can arise as a result of scaling up perceptions from a smaller scale to interpret a much larger scale (Nanson et al., 2002). A method to address this scaling issue is to use a "top-down" approach or by identifying emergent properties. By identifying emerging properties at the higher level, a holistic view of erosion and sediment delivery processes in semi-arid catchments can be obtained. Important emergent properties in semi-arid catchments are presented in Table 2.1. These are considered to be important features of semi-arid systems that have seen little research effort. A catchment scale sediment delivery model should represent such properties if it is to be an effective representation of a semi-arid system.

Table 2.1 The drivers of emergent properties of semi-arid catchments.

Driver	Emergent properties
Climatic drivers	• In relation to variable rainfall, "flashiness" of flow and event driven (dis)connectivity. • In relation to variable vegetation density related to hydrology.
Topographic drivers	• In relation to short term controls of slope and discharge; and long-term controls of geology and tectonics.
Catchment connectivity drivers	• In relation to (dis)connectivity in sediment sources and sinks within the landscape.

3 LITERATURE REVIEW: EROSION AND SEDIMENT DELIVERY MODELS

Scale was identified as an important feature in chapter two as at the catchment scale there is significant spatial and temporal variability of processes. Current sediment delivery models have not dealt with the issue of scale efficiently as modelling approaches have either up-scaled plot models or tried to incorporate as many processes as possible, creating unnecessary complexity. By identifying emergent properties at the catchment scale modellers may be able to use a “top-down” approach to dealing with scale issues. Relating emergent properties of semi-arid catchments provides criteria for an effective erosion and sediment delivery model. The drivers of emergent properties can be considered to be climatic, topographic and connectivity related. These drivers may be represented by using a good hydrological model at an effective time scale with a stochastic erosion model, as well as through using a distributed spatial scale with incorporated sediment storage.

As erosion and sediment delivery models have been advancing in line with societal need it is also necessary to note the purpose behind model development and applicability of models to semi-arid catchments in South Africa. This chapter will present the evolution of sediment delivery modelling both internationally and in South Africa. Currently available modelling strategies will be reviewed in relation to their representation of the properties defined in chapter two and their approach to dealing with the issue of scale. The chapter will conclude by presenting an applicable modelling strategy for semi-arid catchments in South Africa.

3.1 Status quo of sediment delivery modelling in South Africa

Currently, information about soil erosion and its effects on water quality is increasingly sought by water resource managers in South Africa. This Information is required at spatial and temporal scales which reflect the timing and pattern of sediment movement in relation to climatic drivers (Merritt et al., 2003). As Wolman (1977) and Boardman (2006) have presented, the conceptualisation of soil erosion and sediment delivery has advanced over time, as has the complexity of models. Three notable reviews present the international development of erosion and sediment delivery models. The first by Jetten et al*.* (2003) presents the difficulties with calibrating and validating spatially distributed soil erosion models due to the large spatial and temporal variability, as well as uncertainties associated with parameters. Merritt et al*.* (2003) present similar conclusions but add that at the catchment scale, in order to represent reality as closely as possible, sediment delivery models require a rainfall-runoff module, an in-stream module and explicit representation of alternate sediment sources. Aksoy & Kavaas (2005) expand this concept and suggest that erosion and sediment delivery models are extensions of hydrological models and as such should be coupled to existing hydrological algorithms. The authors also suggest that probability based stochastic modelling techniques should be considered, as such a modelling technique could allow for heterogeneity in the physical structure of the watershed by giving important environmental factors probability distribution functions (Kavvas, 1999).

Sediment has long been recognised as one of South Africa's significant water quality problems. For this reason the Department of Agriculture (DoA) and the Water Research Commission (WRC) have funded many regional-based research projects in the country as the spatial extent of the problem needed to be identified. A review of the methodology for monitoring soil erosion in South Africa at a regional scale is presented by Le Roux et al. (2007). The authors identified that some of the challenges that South Africa faces with regards to soil erosion research are limited data availability and that not all erosion types occurring in South Africa are accounted for. This can be seen by the fact that the main approach that researchers have taken in South Africa has been to develop sediment yield maps. Although these maps have provided an important tool in sediment yield prediction they are not effective at a catchment scale, where land and resource management is usually needed.

Water resource management in South Africa has focused both on water quantity and quality assessment. In this regard hydrological models have been used to provide water quantity estimates in ungauged basins. The first comprehensive assessment of South Africa's water resources was conducted by Midgley (1952) and since then there have been four major studies (Pitman, 2011). The third major study introduced the deterministic rainfall-runoff model developed by Pitman (1973) in order to overcome the problem of land use affects (Pitman, 2011). The results from this study, WR90 (Midgley et al., 1994), have proved to be one of the most useful products from the point of view of water management and planning and have provided the default input for a number of other water management tools (Hughes, 2004). This has also been referred to as "the single most valuable contribution to the practical application of the (Pitman) model" (Hughes, 2004). In the most recent 2008 study the previous version of the Pitman model, WRSM90, was upgraded to a windows version, called WRSM2000 (Pitman et al., 2008).

The Pitman model has been the most widely applied hydrological model within the southern Africa region (Wilk & Hughes, 2002). It was developed in the 1970s (Pitman, 1973) as an explicit soil moisture accounting model representing interception, soil moisture and groundwater storages with functions to represent the inflows and outflows (Hughes 2008). The Institute for Water Research (IWR) has added a number of refinements based on assessments by the southern Africa Flow Regimes from International Experimental and Network Data (FRIEND) programme (Hughes, 1995) and subsequently have also added more explicit groundwater recharge and discharge functions (Hughes, 2004). An advantage of the Pitman model is the availability of guidelines for parameter estimation provided by the WR90 study (Midgley et al., 1994). The guidelines can be used to establish initial parameters for almost any climate region of southern Africa, which can then be refined through local calibration (Hughes, 2008). It would be useful to link a sediment delivery model with the Pitman model, as it presents a hydrological model that has proven to be effective in semi-arid South African catchments.

A sediment yield model has also been included as part of the ACRU hydrological model (Schulze, 1989). This model was developed by the Agricultural Catchment Research Unit within the Department of Agricultural Engineering of the University of Natal in South Africa. ACRU is a daily multi-layer soil water budget model. It is a physical conceptual model with variables estimated from physical catchment properties. The model may be used as a point model, lumped in small catchments or distributed in larger catchments. When distributed the model uses a distributed cell method with flows taking place from ‘exterior’ to ‘interior’ cells according to a predetermined scheme. Sediment yields are modeled by using MUSLE in sub-catchments. The rainfall-runoff model then routes the flow and sediment through the catchment. However the model does not include important sediment storage processes. Problems such as over-parameterisation are significant as parameters may be difficult to determine in data poor environments. The model user must also prepare a certain amount of data and information before operating the model. This is not considered to be an effective sediment delivery model for South African catchments.

Another model that has been used recently in a study in South Africa is the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2005). SWAT was used within a context of connectivity in a catchment in South Africa with identified source and sink zones (Le Roux et al., 2013). The model was designed to simulate water, sediment and chemical fluxes in watersheds and large river basins with varying climatic conditions, soil properties, stream channel characteristics, land use and agricultural management. It is a continuous time-scale model which uses readily available inputs on soils, land use, topography, drainage and climate in order to provide outputs on sub-basin scale. The catchment or basin is divided into sub-basins and hydrological response units (HRUs) are used, which are considered homogeneous land areas within the sub-basin with regards to land cover, soil and management combinations. Each HRU has separate calculations with the output being routed to the sub-basin outlets and then to the basin outlet to obtain total basin loadings. A major weakness that was identified with the SWAT model was that it does not consider the processes of deposition during transport from hillslopes to channels and there also needs to be more emphasis on the timescale of sediment movement from different sources.

3.2 Dealing with scale in sediment delivery modelling

The concept of calculating sediment yield at a catchment scale commonly involves a two stage process:

1. Estimating soil erosion or soil loss from an upland area
2. Modification of the gross soil erosion estimate by using a lumped sediment delivery ratio or a distributed approach

Although the beginning part of the last century was primarily directed towards the development of erosion models, the latter half has built upon erosion models conceptualisation to include more advanced sediment delivery models. This has led to the last century being a period of contemplation on the importance of incorporation as many processes as possible versus simple mathematically sound representations. This has come about because of the uncertainty inherent with increasing the number of parameters used in models.

3.2.1 USLE model

Among soil erosion models, the USLE is the most used (and misused) soil loss estimation equation in the world (Kinnell, 2001). The model developed when the United States Soil Conservation Service (SCS) was established to facilitate the transfer of erosion control strategies out of the laboratories and into the farmer’s field. It was developed as a model to predict average annual soil loss from interrill and rill erosion from fields in the eastern USA. The factors for the equation can be considered to be determined for erosivity and erodibility of a unit plot (Figure 3.1). Erosivity relates to the climatic driver of rainfall (considered the rainfall factor) and erodibility relates to the inherent physical characteristics of the soil (the soil erodibility factor) as well as land and crop management (the topography, practice and cover factors).

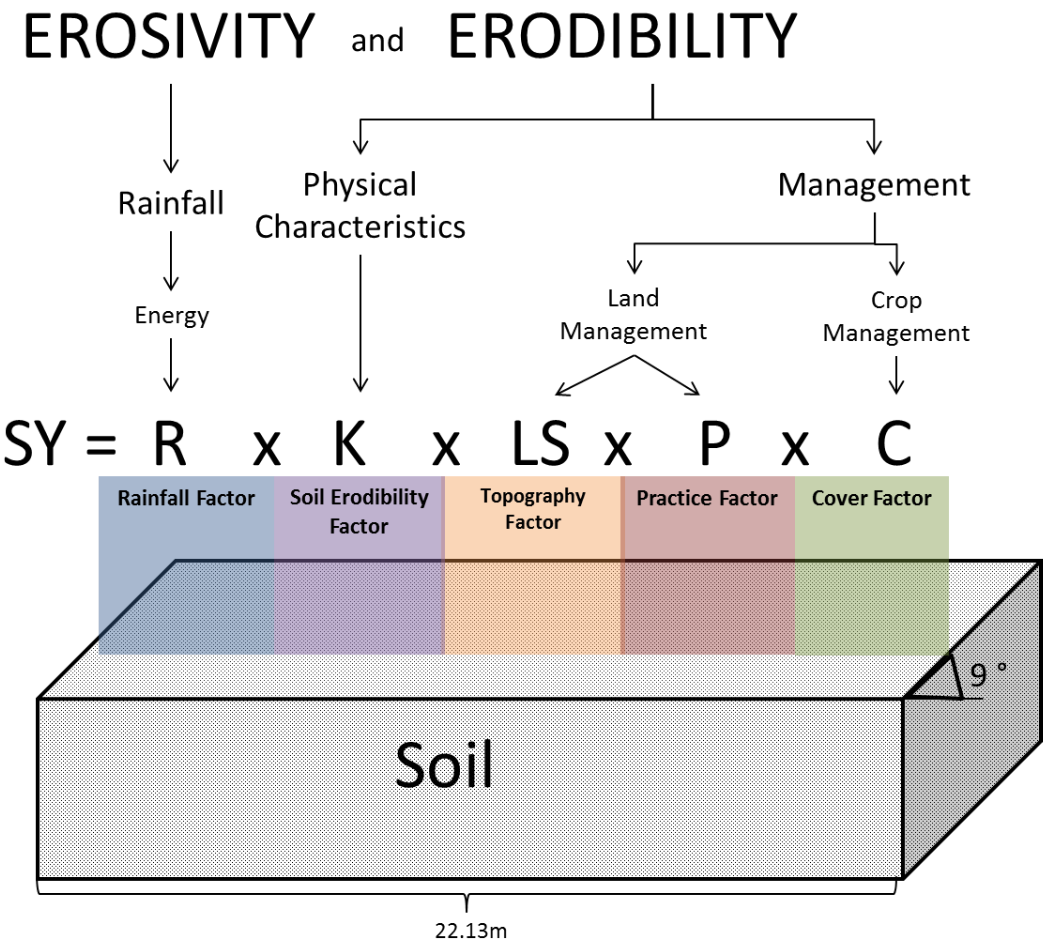


Figure 3.1 A conceptualisation of a standard unit plot with the accompanying USLE description (adapted from Wischmeier and Smith, 1978).

The USLE, with its modifications and revisions, is still used in watershed management to this day (Kinnel, 2001). Many advanced existing erosion and sediment delivery models are based on the USLE (i.e. the Erosion-Productivity Impact Calculator model (EPIC: Williams, 1985); Agricultural Non-Point Source model (AGNPS: Young et al., 1989) and Agricultural Catchment Research Unit model (ACRU: Shulze, 1989)), but their application is limited to the environmental circumstances from which the model was generated (Aksoy & Kavvas, 2005). Other limitations are that the model is not event based and as such it cannot identify the event most likely to result in large scale erosion (Merritt et al., 2003). Gully erosion and deposition processes are not modelled (Zhang et al., 1996) and the use of the model outside of the USA necessitates a large investment of time and resources (Nearing et al., 1994) to estimate parameters. Another problem with the USLE is that there is no direct consideration of runoff, even though erosion depends on sediment being discharged with flow, which varies with runoff and sediment concentration (Kinnell, 2005). Application of the USLE at a larger scale has usually meant that it is used in conjunction with a delivery ratio.

3.2.2 *Sediment delivery ratio*

Early attempts to model sediment delivery can be dated back to the work of Glymph (1954) and Maner & Barnes (1953). Glymph (1954) defined the rate of sediment delivery as "the percentage relationship between annual sediment yield and annual gross erosion in the watershed, the percentage being derived with both sediment yield and erosion being expressed in tons", whilst sediment yield is expressed as the amount of sediment leaving a catchment. A sediment delivery ratio (SDR) was developed to express this percentage relationship (Walling, 1983). Although this ratio was developed as a practical tool for estimating sediment storage at the spatial scale of a catchment and the temporal scale of a year, Parsons et al. (2006) argue that the SDR is unreliable as it is not conceptually sound. They argue that the concept of sediment delivery is a "fallacy" as measurements of sediment passing given points in the landscape are actually measurements of flux or change. Differences in flux would therefore enable the identification of processes leading to spatial and temporal sources and sinks of sediment.

There are also fundamental scaling problems with the SDR. These may be associated with both erosion and sediment yield needing to be expressed in tons in order for their ratio to be calculated. In reality both have typically been expressed in tons/unit area/unit time (Livesey, 1975; Williams, 1977; Ebisemiju, 1990). Sediment yield is expressed per unit area of the catchment upstream of the point of measurement, which bears little relationship to the area from which transported sediment itself is delivered (Parsons et al., 2006; parsons et al., 2014). According to the concept of (dis)connectivity of semi-arid landscapes it is apparent that an entire catchment area is usually only effectively active during infrequent, high magnitude events (Fryirs et al., 2007). Consequently if the concept of event driven (dis)connectivity is to be adhered to, the area that could potentially contribute sediment to the channel over the period of measurement should be used for calculations and not the entire catchment.

3.2.3 *MUSLE model*

Using the SDR in conjunction with gross erosion is tedious and inadequate if one is interested in individual storms (Sadeghi et al., 2014). The storm event factor used by the USLE also often fails to account for the effective rainfall that generates surface runoff, which is an important process in erosion and sediment delivery (Sadeghi et al., 2014). Due to a lack of sediment data in many areas and the general lack of consistency in regional regression relationships, Williams (1975) suggested a modelling approach whereby the SDR would not be necessary. This involved replacing the rainfall energy factor of the USLE with a runoff factor, as characteristics such as drainage area, slope and watershed shape influence runoff rates and delivery ratios in a similar way. Williams (1975) used 778 storm-runoff events collected from 18 small watersheds, with areas varying from 15 to 1500 Ha, slopes from 0.9 to 5.9% and slope lengths of 78.64 to 173.74m (Williams & Berndt, 1977; Haa et al., 1994). This equation, known as the Modified USLE (MUSLE) model, was given in the general form:

$$Sy = a(Qq_p)^b KLSCP \quad \text{(Equation 3.1)}$$

Where *Sy* is sediment yield (in t) on a storm basis for the entire catchment, Q is volume of runoff (in m^3), q_p is the peak flow rate (in $m^3.s^{-1}$) and *K*, *L*, *S* and *P* are, respectively, the soil erodibility (in $t.ha.h.MJ^{-1}.mm^{-1}$), slope length, slope steepness, crop management and soil erosion control practice factors similar to the USLE model, and *a* and *b* are location coefficients. For the area where the equation was developed the coefficients were 11.8 and 0.56 respectively. There have been many disagreements with respects to the dimensionality of MUSLE (Cardei, 2010), owing to the many different watersheds around the world that the model has been applied to. The use of the LS factor is also considered an issue, when considering the views of authors such as Parsons et al. (2004).

A review of the international application of the MUSLE model has been presented by Sadeghi et al. (2014) in order to evaluate the applicable conditions and methods used to determine the MUSLE model variables in research. The trends in the methodology to determine the factors in the MUSLE model indicated that for the erodibility factor most values were obtained by using the Wischmeier & Smith (1978) diagram, with the erodibility estimation methodology not affecting accuracy of results. The topography factor was estimated by the direct use of a topographic map at a scale of 1:50 000 in most studies, with the use of GIS providing an improved performance of model estimates. Crop management and control practice factors were mainly estimated by using existing data, with the incorporation of temporal variation of these factors resulting in significant improvements in performance. The peak flow and volume of runoff were mainly obtained through storm-event basis. It was concluded that application of the MUSLE model may provide reasonable results when applied under appropriate conditions similar to those of the original model or when the model factors are calibrated accordingly.   Although this equation may not be considered to be mathematically sound on its own (Kinnel, 2004), integrating it with a sediment transport model may make more sense.

3.2.4 Advanced modelling

Another method of dealing with scale in sediment delivery is by accounting for erosion and deposition processes more explicitly. The more process-based models have arisen due to the availability of computers which has allowed for more advanced modelling. Since this rapid rise in process based modelling, concerns of over parameterisation and uncertainty have arisen. Problems have also arisen when scaling up traditional erosion models to a scale of above 50 km^2 as has been seen in studies with WEPP (Flanagan & Nearing, 1995), EUROSEM (Morgan *et al.* 1998), USLE (Wischmeier & Smith, 1978) and MUSLE (Young et al. 1989). The main problems for up-scaling are the increased complexity, increase in data requirements and insufficient systems knowledge (De Vente & Poesen, 2005). It has been determined that increasing model complexity could lead to increased prediction uncertainty (Nearing & Hairsine, 2011).

Sediment transport varies over large spatial and temporal scales, making representations of these processes exceedingly difficult. Traditionally models have tended to treat input parameters as lumped over the area needing to be analysed but, with increasing computer power, distributed approaches are now seeing more use. The USLE (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1991) and Erosion-Productivity Impact Calculator (EPIC) (Williams, 1985):models are lumped models that assume spatially homogeneous hillslopes. More advanced models such as the Chemical Runoff and Erosion from Agricultural Management Systems model (CREAMS: Knisel, 1991), WEPP (Flanagen et al., 2001) and EUROSEM (Morgan et al., 1998) act as field scale models that assume a linked system of interill and channel elements. In contrast to lumped models, distributed models reflect the spatial variability of processes and outputs in a catchment. Typically this is achieved through dividing an area into cells. The Limberg soil erosion model (LISEM) (De Roo et al., 1996) and Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al*.,* 1980) models are based on runoff and suspended sediment calculations for grid cells which is then routed to the catchment outlet. These approaches require large amounts of input and are limited by the effects of cell resolution.

Attempts have been made to scale up the MEDALUS model to be used at the catchment to regional scale (Kirkby et al., 1998). The slope catena model of MEDALUS represents four interacting submodels for the atmosphere, vegetation, soil and surface systems. These are defined at a series of points down a hillslope catena, which are connected to overland flow. Field data are then available at three points along a hillslope catena profile, with the catena representing a flow strip. Flows of water and sediment are routed between points and erosion is calculated by differencing the sediment storage equation for each grain size. Long term outputs are determined mainly by interactions between the four submodels. These interactions may be such that plants grow in response to climatic and soil conditions, which in turn lead to changes in overland flow generation, producing greater erosion upslope and greater deposition downslope. These interactions provide a dynamic model for erosion and sediment delivery at the catchment scale. The spatial distribution of the model was based on the subdivision of the catchment into drainage areas, connected through the flow network. Certain subdivisions will represent headwater areas, whilst others will contain a through-flowing main stream. Scaling up from flow strips to larger catchments invariably allows for some loss of resolution and leads to changes in the dominant processes but it is considered that the critical processes are sufficiently understood to allow for this explicit approach. This demonstrates a conceptual linkage between interacting submodels as an approach to dealing with the issue of scale.

3.2.5 Distribution function theory

Wolman's (1977) argument that current erosion and sediment delivery models did not account for stochastic processes influenced an approach developed by Moore & Clarke (1983) and updated by Moore (1984). This approach used distribution function theory which accounts for the stochastic nature of runoff, erosion processes and sediment delivery. Whereas fully distributed models are complex, requiring many parameters, this model attempts to maintain a distributed description of catchment processes in a much simpler way. Models based on this approach use mechanistic representations of important physical processes, with the benefit of being able to calculate the relationship between soil detachment rate and erosion factors from information about probability distribution functions (pdfs) of driving and stabilizing forces (Sidorchuk et al*.,* 2004). The basin sediment model (BSM) (Moore, 1984) was based on the probability distribution moisture model (PDM) of Moore & Clarke (1981), which used a distribution function to represent the spatial variability of runoff generation. Although the precise means of detachment, sediment sources and exact paths for sediment delivery are not defined, a lumped basin model considers mean removal rates, travel times and paths for sediment. The model was also based on the time scale of a day or less, with the intention of representing the transitory nature of erosion and sediment delivery based on rainfall variables.

After the first version of the model two serious failings were identified. The first was that the representation of erosion available for removal was computationally complex and the second was the assumption of instantaneous and total removal of sediment from a storage element once it had been filled with rainfall and begun contributing to direct runoff. The model was re-formulated into a more realistic and simple representation of sediment removal (Moore, 1984). This version of the BSM uses a statistical approach to describe sediment accumulation and removal by runoff, with the rate of removal being dependent on rainfall intensity. Basin sediment yield variations over time were depicted by three functions:

- Sediment availability;
- Sediment removal; and
- Sediment translation.

The *availability function* calculates the supply of sediment available for removal increased with the inter-storm period, the *removal function* represents the detachment of sediment during a storm as the function of sediment availability and storm intensity, and the *translation function* represents the movement of suspended sediment to the basin outlet.

Moore (1984) used the contributing area concept of runoff generation that had been developing over the years. This influenced the concept of hillslope processes contributing to river channel sediment yield only at a smaller spatial scale. Availability of sediment was considered to be related to ease of entrainment as sediment would have a changing susceptibility to water erosion over time. The many factors involved in making sediment available, as well as the changing dominance of these processes at different spatial and temporal scales influenced Moore (1984) to use a model function for sediment availability that was lumped in space. The BSM is consistent with the concepts of hydrological connectivity presented in chapter 2. Increasing catchment connectivity, with increases in effective catchment area, through the breaching of certain landscape units can be considered equivalent to a series of switches which determine which parts of the landscape contribute to the sedimentary cascade over time. The effective catchment area increases as the magnitude of the event increases and as the flow stages increases the fluvial barriers are more readily reworked. High runoff as well as high sediment availability, lead to high sediment production.

3.3 Concluding remarks

Models are meant to be practical tools and as such it is important that the purpose behind the development and intended use be transparent. Managers need to quantify erosion and sediment delivery at temporal and spatial scales in response to hydrological drivers. Management may extend from government agencies, responsible for implementing and maintaining land and water resources, that have considerable technical and scientific expertise, to stakeholders and managers with less modelling expertise. Decisions are usually made at the catchment scale and in South Africa a model needs to be aplicable to users with limited modelling expertise.

Empirical erosion models will tend to over predict sediment delivery and empirical erosion models with the SDR are still simple but prone to errors. More advanced process based models are prone to over parameterisation and uncertainty. These problems may be avoided if an empirical erosion model is used with a sediment transport model. As erosion and sediment delivery models are considered extensions of hydrological models (Aksoy & Kavaas, 2005) it would also be necessary to link to an appropriate hydrological model. Considering that available erosion and sediment delivery models have not been able to effectively describe the stochastic nature of the sediment system, probability based stochastic modelling techniques may be a step in the right direction. Such a modelling technique allows for the heterogeneity in the physical structure of the watershed by probability distribution functions (Kavaas, 1999). This reduces the need for many parameters and provides the space for the stochasticity in processes to be reflected in the model. Jetten et al. (2003) stated that "distributed runoff and erosion modelling needs to move towards a greater interaction between the landscape and the model". It has been emphasised that each particular catchment should be represented by a set of distributed variables, effectively "pruning" superfluous process descriptions that do not improve results and only add uncertainty (Beven, 2002). The optimal model would therefore be dependent on the landscape characteristics and the dominant process operating.

In order to account for the stochastic nature of runoff, erosion processes and sediment delivery, distribution theory may be used. Such a model would maintain a distributed description of catchment processes in a much simpler way. The model may be separated into the following functions:

1. Sediment availability (representing soil loss);
2. Sediment transfer (representing storage), and
3. Sediment removal (representing sediment delivery).

These distribution functions may be associated with an erosion model, such as the MUSLE model, and a hydrological model, such as the Pitman rainfall-runoff model (Table 3.1). This type of model would effectively provide a simple representation of the stochastic nature of erosion and sediment delivery over large spatial and temporal scales, presenting a modelling strategy which addresses key issues identified by Wolman (1977), Walling (1988), Merritt et al. (2003), Aksoy & Kavaas (2005), Jetten et al. (2003), Boardman (2006) and Nearing & Hairsine (2011).

Table 3.1 The emergent properties of semi-arid catchments represented in an erosion and sediment delivery model

Emergent property	Representation in model
Climatic drivers • Spatial and temporal variability of flow • Relationship of vegetation density with hydrology	• Pitman rainfall-runoff model at a daily timescale
Topographic drivers • Short term controls of slope and discharge; and long-term controls of geology and tectonics.	• MUSLE model with distribution function theory
Catchment connectivity drivers • (Dis)connectivity in sediment sources and sinks within the landscape	• Incorporation of sediment storages over a semi-distributed catchment

4 STUDY AREA

This chapter defines the study area used to test the erosion and sediment delivery model. It forms the first chapter in model development as it defines the important features for model calibration and testing. The Karoo, in the Eastern Cape of South Africa, was selected as the study area as it was identified as a semiarid region of South Africa that covers up to 30% of the country's land surface. Two small catchments within this region have also been the focus of significant erosion and sedimentation research over the past decade (Foster et al., 2007, 2008, 2012, Rowntree & Foster, 2012; Foster & Rowntree, 2012). These two catchments will be used for model testing, whilst a larger catchment in the region will be used to test the applicability of the model at a larger scale. An overview of the study area will be given, followed by an analysis of the main characteristics, as defined by chapter two, for each catchment. This will provide the basis for defining the important features for each catchment, which will be used when calibrating the sediment delivery model.

4.1 Introduction

In this dry landscape a reliable water supply is critical for permanent settlement meaning that historically farm dams were an important part of farm development. In the 1800s there were no man made dams in the eastern Karoo, settlements were temporary as they would be made near water sources or pools and when those dried up the farmers needed to move (Palmer, 2012). The first dam in the Graaff-Reinet area of the Karoo was built in 1843 on a farm near Pearston, known today as Cranemere. This dam originated as a 5-ft high earthen wall which would catch water from the surrounding mountains. Its development awakened a new era of water supply in this arid region.

As was characteristic of the Karoo, the proximity of water was an important criterion for settlement location. Although situated in close proximity to the Sundays River, Graaf-Reinet still has a long history of water supply problems. In the 1900s the town was supplied by two temporary dams which had a history of being washed away and furrows being choked with mud (Minaar, 1987). This influenced the decision to build Nqweba Dam (originally named Van Rynevelds Pass Dam) in 1921 but unfortunately this did not provide a readily available supply of water at all times as the dam was heavily affected by alternating droughts and heavy rain. In 1932 the dam overflowed for the first time, but this was followed by a severe drought in 1932/1933 which caused the water to become brackish and highly saline (Minaar, 1987). This was a continuous problem and during the late 1950s drought the dam became empty for the first time (Figure 4.1). The inconsistent water supply was not the only issue and excessive siltation resulted in loss of storage and increased occurrence of spilling.

Silting up of dams is a characteristic of the Karoo, owing to the erodible soils and limited vegetation cover. It is a major problem not only for major storage reservoirs such as the Nqweba Dam but also for small farm dams (Figure 4.2).

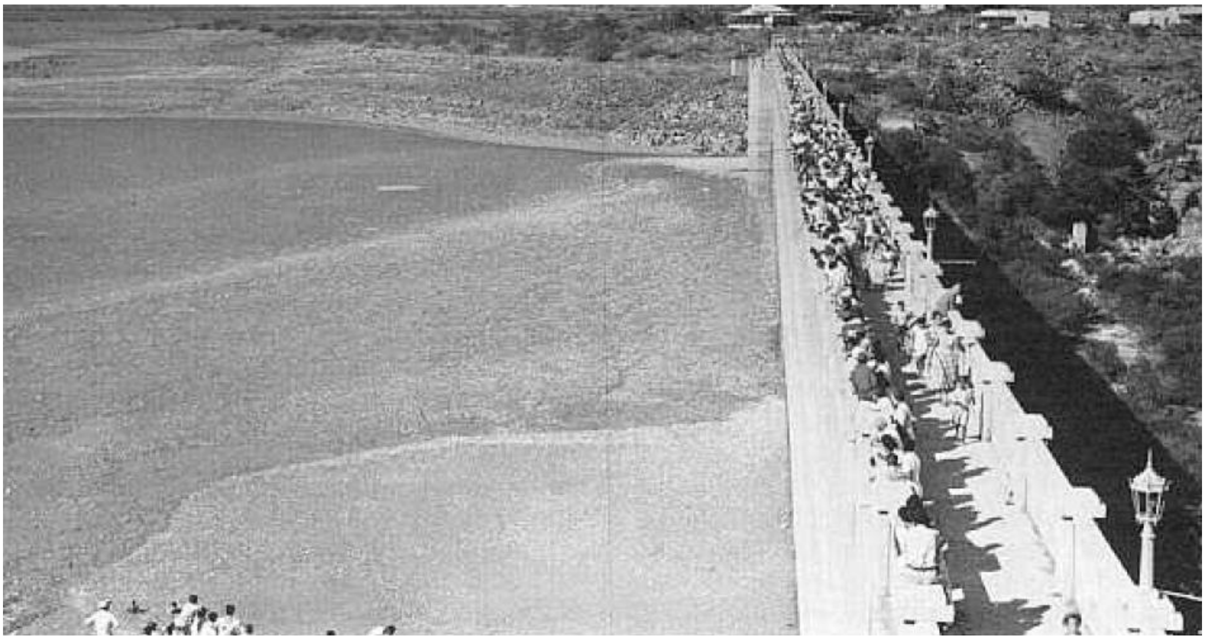


Figure 4.1 Nqweba Dam was empty for the first time on 26th November 1957 (Source: Minaar, 1987).

Figure 4.2 Ganora Dam, a much smaller farm dam in the region, has been so impacted by siltation that it is empty at regular intervals (Source: Kate Rowntree).

Two small catchments have been identified for this study. Their long term sediment yield and change in sediment sources have been studied by Foster et al. (2007; 2008, 2012), Foster & Rowntree (2012) and Rowntree & Foster (2012). There are detailed descriptions and hypotheses available for the sediment dynamics of each catchment. The Cranemere catchment (32°31'47"S; 24°59'37"E) has one of the first farm dams built in the Karoo and is 20 km from Pearston, whilst the Ganora catchment (31°50'42"S; 24°37'27"E) has a smaller farm dam built in 1910 and is about 10 km from Nieu Bethesda (Figure 4.3). The Ganora catchment occurs within the catchment for the above described Nqweba dam (32°12'41"S; 24°31'28"E). This dam occurs in Graaf-Reinet and the catchment size is 3667.7km^2 (Figure 4.4). The Ganora catchment is much smaller than the Cranemere catchment, at 2.7km^2, but it represents a different physiographic setting as it occurs at a higher altitude (1428 –1741 meters above sea level (masl)) and has clearly defined gullies and extensive badlands occupying around 15% of the total catchment area (Figure 4.5) (Foster et al., 2012). In contrast the Cranemere catchment is 57km^2 and only a small area is occupied by mountains in the north. The catchment has a complex drainage system with clearly defined gullies in some areas being disconnected from the main channel and the main channel itself becoming indistinct, with several alluvial fans appearing to act as temporary sediment storage (Figure 4.6) (Foster et al*.,* 2012). Rowntree & Foster (2012) and Foster & Rowntree (2012) reconstructed the historical changes in sediment source, transfer and yield for the Ganora and Cranemere catchments, respectively.

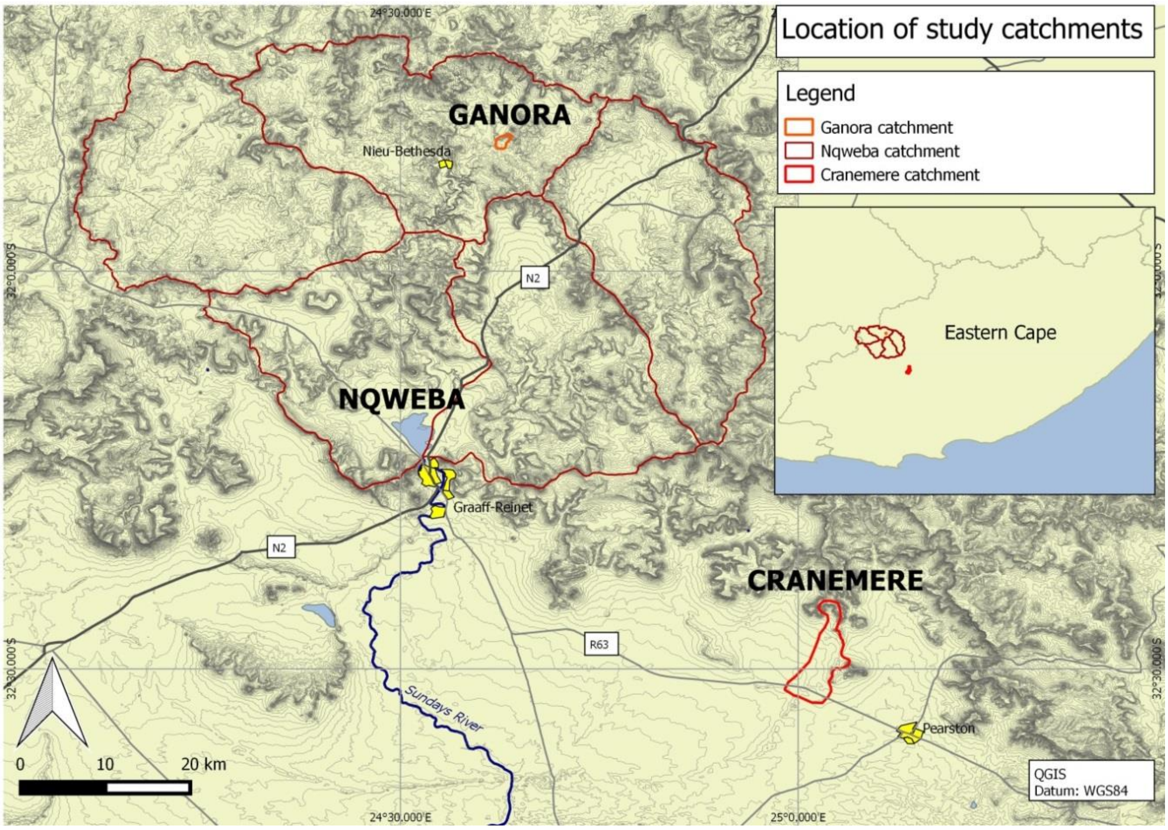


Figure 4.3 The location of the study area in the eastern Karoo, South Africa.

Figure 4.4 Nqweba dam at full capacity (source: DWS)

a. b.

Figure 4.5 The 2.7km^2 Ganora dam (a) with extensive badlands and gullies within the catchment (b).

a. b.

Figure 4.6 The 57km^2 Cranemere dam (a) with alluvial fans and floodouts acting as storage zones (b) and gullies being disconnected from the main channel.

4.2 Catchment characteristics

All three catchments are within the Sundays River catchment. The Ganora and Nqweba catchments occur in the uplands of the catchment, whilst the Cranemere catchment occurs in the following secondary catchment (Figure 4.7). Emergent properties for semi-arid catchments will be described for the entire study area, with a detailed review being presented for the Cranemere and Ganora catchments.

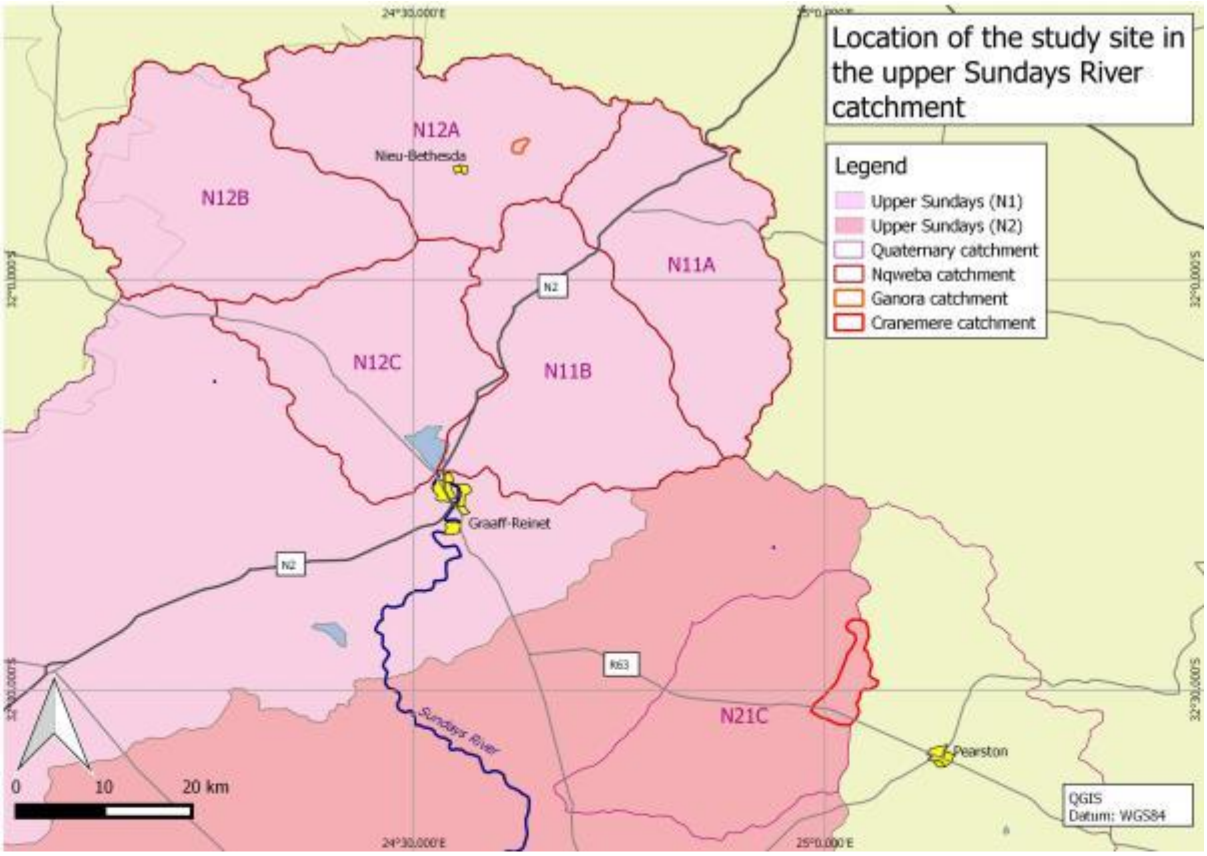


Figure 4.7 The location of Nqweba and Ganora catchment within N1 secondary catchment and Cranemere catchment within N2 secondary catchment.

4.3 Climatic drivers

The Sneeuberg region of the Karoo has a temperate climate with regards to temperature and rain. The uplands are wetter than the lowland areas of the Karoo because of its altitude which gives rise to orographically forced rainfall, providing moist conditions and mechanical weathering generally absent in the rest of the Karoo (Badenhost, 1970). Convectional thunderstorms are common in summer and snowfall, associated with the west to east passage of cold fronts, occurs in the upper mountainous areas and valley headwaters during winter (Boardman et al*.,* 2003). Long term rainfall data from Graaff Reinet indicate near decadal alternating wet and dry spells (Boardman et al., 2003).

4.3.1.1 Hydrology

Although annual precipitation is highly variable, characteristically low annual precipitation and high evaporative losses result in low annual runoff totals in the area. Flow is also considered to be “flashy”, which may be analysed via daily rainfall. A study in a catchment near Ganora by Grenfell et al. (2014) indicated that extreme rainfall events accounted for significant proportions of the mean annual rainfall. An event in 1973 accounted for 22% of the annual precipitation, with similar events in 1909, 1931, 1939 and 1987, accounting for more than a third of annual precipitation.

Rainfall records for the area were also collated by Hoffman et al. (2009) from around 100 years of daily rainfall. These records indicated that there are no significant long term trends in annual amount irrespective of altitude. Inter-annual variability was evident as changes in the magnitude of extreme daily rainfall at an upland station in Middleberg and a station at Cranemere (Foster et al., 2012). Foster & Rowntree (2012) provide a detailed description of the rainfall trends for Cranemere catchment. Field observations indicated that 10 mm of rainfall was sufficient to cause local runoff and storms of 20 mm or greater could be considered to give rise to widespread runoff, effectively connecting the hillslopes and channels. It was concluded that a significant proportion of the rainfall at Cranemere falls as high-energy storms that will have potential to erode and transport sediment. The most notable trend was that there had been a significant change in the magnitude of extreme daily rainfall. The trend for maximum rainfall indicated that extreme daily rainfalls increased after 1950. The erosivity or high-energy of storms, with the potential to erode and transport sediment in an otherwise dry landscape, had also increased since 1950. Using field observations for runoff may be representative for smaller catchments but for larger catchments the spatial variability may be an issue. Due to data limitations assumptions will have to be made for the spatial variability of each catchments hydrology.

4.3.1.2 Vegetation

In the Nqweba and Ganora catchments vegetation types range from the Upper Karoo Hardeveld to the Eastern Upper Karoo (Figure 4.8 and Figure 4.9). According to Mucina & Rutherford (2006) the Upper Karoo Hardeveld usually occurs on steep slopes and parts of the Great Escarpment covered with large boulders and stones supporting sparse Karoo scrub with *Aristida Eragrostis* and *Stipagrostis* grasses. Eastern Upper Karoo vegetation types occur on gently sloping plains dominated by microphyllous scrubs with similar such grasses. The Eastern Lower Karoo vegetation type of the Nama-Karoo biome occurs on Cranemere catchment where plains are interrupted by dolerite dykes and the dominating vegetation is low to moderate height microphyllous scrubland with similar grasses becoming abundant on sandy bottomlands (Figure 4.10). A larger proportion of the catchment consists of Camdeboo Escarpment Thicket of the Albany Thicket Biome. This vegetation type is considered to be a dense growth of trees and occurs on the steeply sloping mountain slope of the escarpment where it can be 2-3 m high. Smaller portions of the catchments consist of Karoo Escarpment Grassland and Southern Karoo Riviere. Karoo Escarpment Grassland occurs on mountain summits and is usually dominated by *Merxmuellera disticha*. Southern Karoo Riviere occurs in narrow riverine flats supporting a complex of *Acacia Karoo* or *Tamarix usneoides* thickets up to 5m tall, and fringed by *Salsola*-dominated shrubland. At a local level sheetwash on the foot slopes may have stripped much of the topsoil and

Lycium cinerum and *Eriocephalus spinescens* frequently dominates (Boardman et al*.,* 2003). On the degraded surfaces opportunistic *Asteraceae* as well as short lived grasses, are typical pioneers (Boardman et al., 2003).

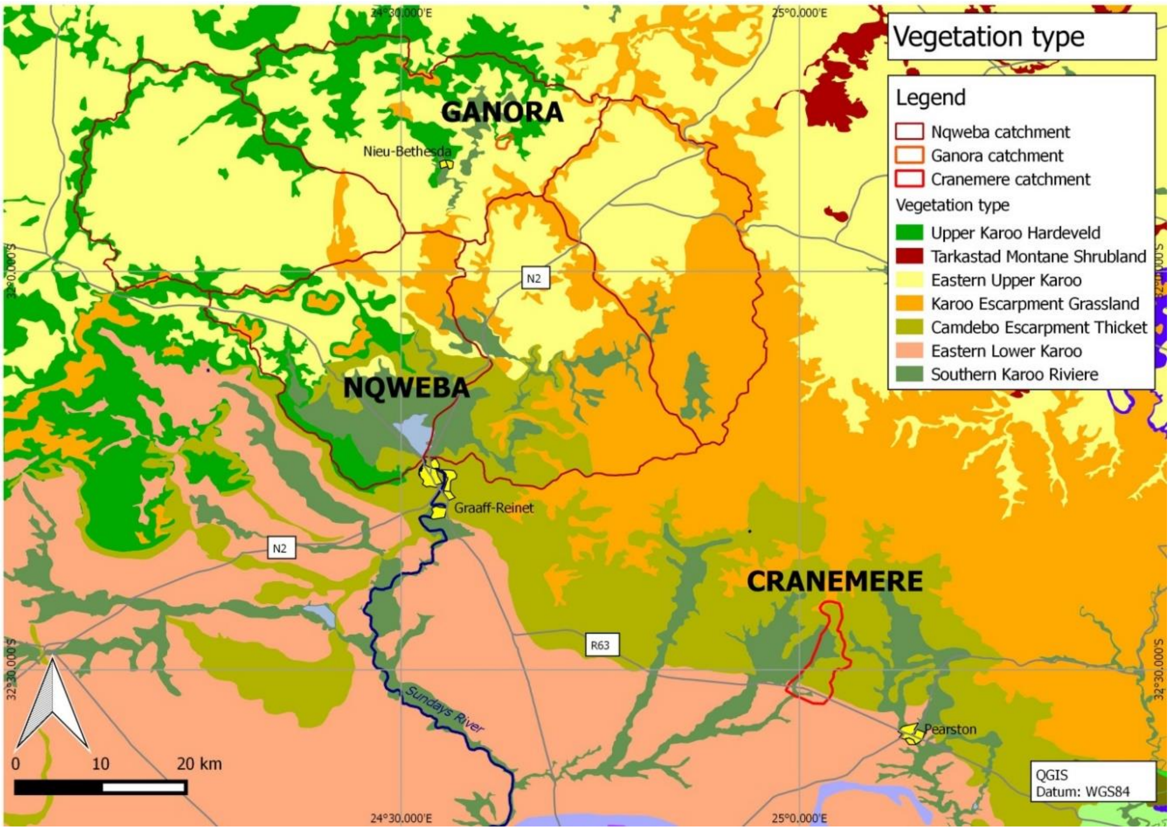


Figure 4.8 The vegetation type for the surrounding area of the study catchments (Source: BGIS, 2007).

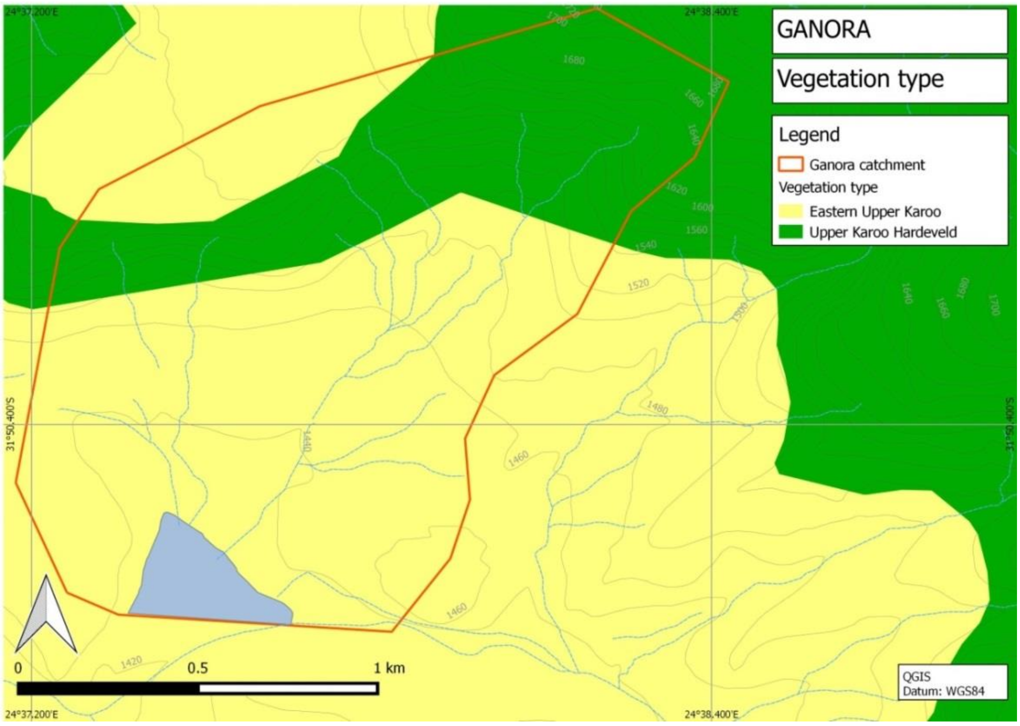


Figure 4.9 The vegetation type for Ganora catchment (Source: BGIS, 2007).

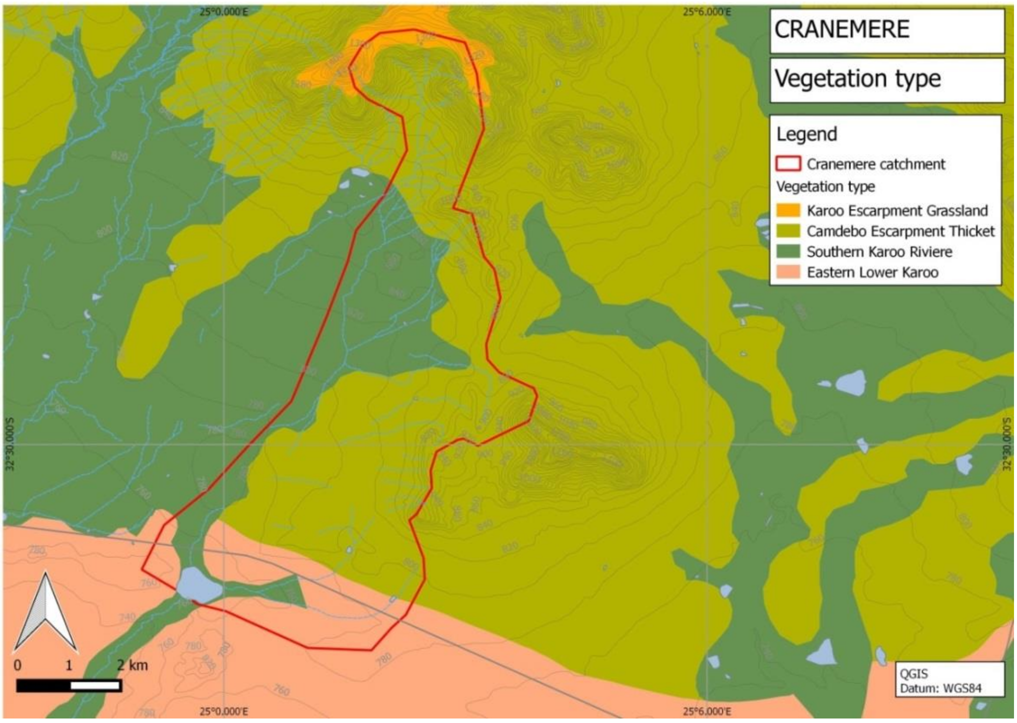


Figure 4.10 The vegetation type for Cranemere catchment (Source: BGIS, 2007).

Vegetation is directly correlated to runoff and erosion as it promotes infiltration and reduces raindrop impact. Boardman et al. (2003) conducted rainfall simulation experiments on vegetated plots which imitated that which would be expected in the eastern Karoo. These experiments indicated that fine particles led to large sediment production, whilst stones and vegetation were associated with lower sediment production. The authors also identified some geomorphic effects of vegetation change. Footslope areas with less stony soils, considered to be more susceptible to degradation as a result of vegetation change, were found to have the most significant relationship with runoff and erosion rates. These areas coincided with areas of badland development. Ganora catchment has significant badland erosion and the vegetation cover was considered by Rowntree & Foster (2012) to be highly dependent on recent rainfall, but on eroded badland areas it provides scanty cover even after good rain.

Vegetation disturbance and loss of grass species was assumed to be the result of overgrazing exacerbated by excessive drought (Boardman et al., 2003). The Karoo has a history of stock farming and cultivation. The sourveld grass of the upper slopes are usually utilised for grazing cattle, while the Karroid vegetation of the footslopes are more suited to smaller stock (Boardman et al., 2003). The valley bottom lands were largely used to grow dryland wheat on a small scale (Keay-Bright & Boardman, 2007). The Ganora catchment had not been cultivated but the Cranemere catchment had lower parts with limited areas of cultivation. In the Karoo during the early 1920s and early 1930s there was widespread overgrazing, but in the 1950s conservation efforts were implemented to improve water retention on the hillslopes and reduce soil erosion (Rowntree & Foster, 2012). In the Cranemere catchment livestock numbers were reduced and eroded areas were planted with *Agave americana*, which seemed to have been quite successful, and it was mentioned that there was a decrease in the amount of runoff that reached the dam (Rowntree & Foster, 2012). Both the Ganora and Cranemere catchments have poor vegetation cover as a result of overgrazing (Figure 4.11).

a. **b.**

Figure 4.11 There is moderate to poor vegetation cover in both the Ganora (a) and Cranemere (b) catchments.

4.3.2 Topographic drivers

The Karoo is a landscape of arid plains interspersed with flat topped hills. The Sneeuberg Mountains in the east are associated with the Great Escarpment that rises from the Camdeboo plain, at an altitude below 800 meters between Graaff-Reinet and Pearston, to a height of over 2000 meters. The area is underlain by near-horizontal sedimentary rocks of the Beaufort Group which consists of sediments laid down about 300 million years ago by wide rivers that deposited sand and silt over vast floodplains, giving rise to horizontal bands of alternating sandstones, mudstones and shales (McCarthy & Rubidge, 2005). Karoo sedimentation ended abruptly 182 million years ago when basaltic lavas intruded existing rocks and covered much of southern Africa, but which are no longer evident over the Karoo region (McCarthy & Rubidge, 2005). There was a single erosion cycle that lasted from the break-up of Gondwanaland to the early Miocene 24 million years ago, which gave rise to a vast undulating surface about 500 to 700 m above sea level. Resistant doleritic caps allowed mountains to stand above this surface. About 20 million years ago the southern African subcontinent experienced an uplift event that raised the eastern part of the country about 300 m and the western part about 150 meters. Following this, a second uplift occurred about

5 million years ago that raised the eastern part of the country by 900 meters, but less in the interior and the west. Uplift rejuvenated rivers, which, during periods of stability that followed, resulted in the removal of a large amount of the Karoo Supergroup sedimentary rocks and led to widespread river superimposition onto underlying resistant doleritic dykes and sills (Grenfell et al., 2009). This rejuvenation of river networks and associated incision of the subcontinent since these periods of uplift have resulted in almost all rivers in the region being predestined to erosion (Grenfell et al., 2009).

The Ganora catchment occurs in the upper elevated reaches of the Nqweba catchment (Figure 4.12). It is a small, steep catchment with extensive badland erosion (Figure 4.13). The steep upper region of the catchment has limited channels with narrow, stony channels developing as the slopes gradient decreases (Figure 4.14). Hillslopes have significant badland erosion with sediments either accumulating at fans beneath the badlands or being connected to the drainage line (Figure 4.15). Nearer the dam the channels are much wider, with large deposition of finer sediments.

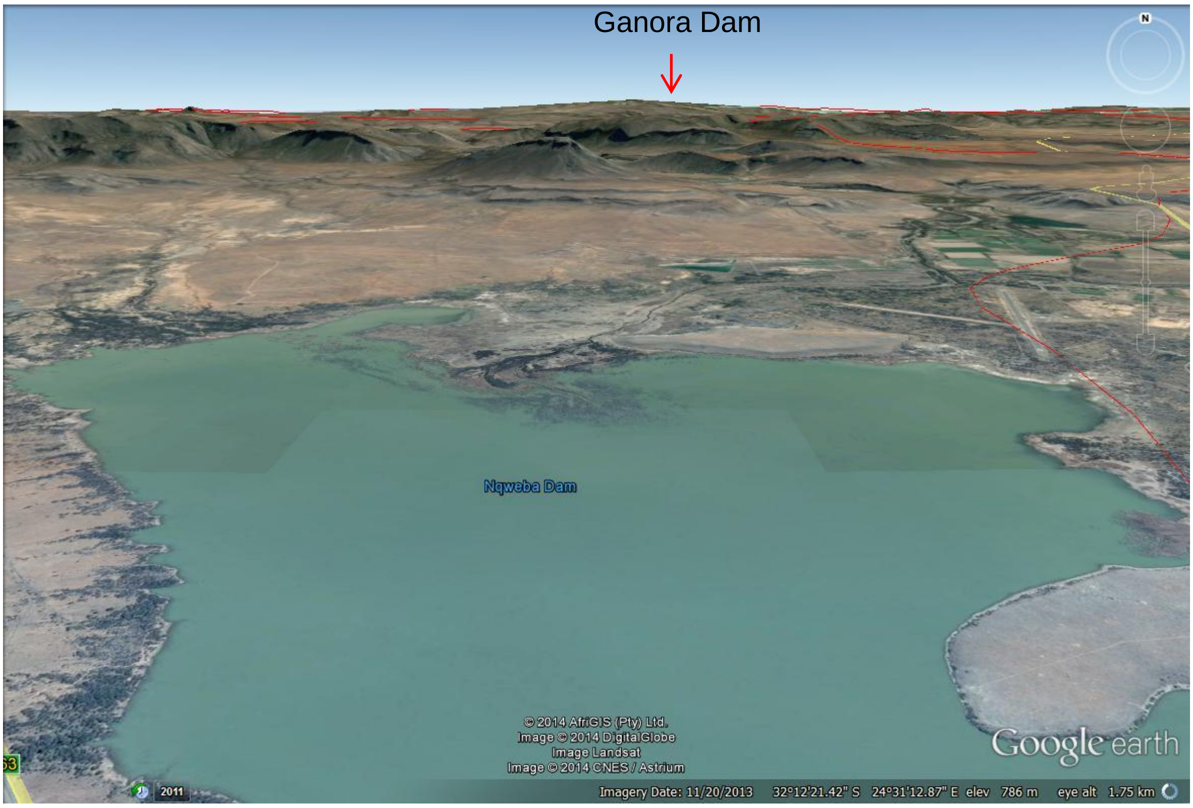


Figure 4.12 The topography surrounding Nqweba dam with Ganora dam occurring in the higher elevations of the catchment (Source: Google Earth).

Figure 4.13 The Ganora catchment from the vantage point of the steep upper reaches of the catchment.

Figure 4.14 The upper part of the Ganora catchment has steep slopes and limited rocky channels.

Figure 4.15 Hillslopes in the Ganora catchment have significant badlands that terminate in fans or that reconnect with the main wider channel.

The upper, elevated regions of the Cranemere catchment do not provide a large capacity for sediment storage (Figure 4.16) but the gentle gradient of the middle and lower parts provides a large capacity for temporary sediment storage (Figure 4.17). Storage zones are in the form of alluvial fans from the hillslopes and floodouts (Figure 4.18). Gullies may form effective sediment conduits on the hillslopes. The R63 road traverses the bottom of the catchment, near the main dam, with the bottom part of the catchment having gentle relief (Figure 4.19).

Figure 4.16 The uplands of the Cranemere catchment has elevated slopes (Source: Google Earth).

Figure 4.17 The mid-zone of the Cranemere catchment has wide channels with eroded banks.

Figure 4.18 Flow becomes dissipated at areas of low elevation and in the presence of dolerite dykes in the lower zones of the Cranemere catchment.

Figure 4.19 The lower part of the Cranemere catchment has a relatively gentle gradient.

4.3.3 Catchment connectivity drivers

Rooseboom et al. (1992) and Msadala et al. (2010) provide details on the amount of sediments stored in large dams in South Africa. The Nqweba Dam estimates showed that in 1978 the remaining storage capacity was about 47 million m^3, with 31 million m^3 of the dam being filled with sediments. Boardman et al. (2009) indicated that given an average deposition rate of 584 906 m^3 per year, by 2009 there would be about 49.1 million m^3 of sediment in the dam and a remaining capacity of 29 million m^3. This suggests that the dam has a storage life of about 50 years. Sediment accumulation for a number of storage reservoirs in South Africa has been recorded by the Department of Water Affairs and Sanitation (DWS) over a number of years. The Nqweba Dam has a record that extends from 1925 to 1998. Analysis of these measurements involves the conversion of recorded sediment volumes to annual sediment yields per unit area of effective catchment area (Figure 4.24). The mean proposed sediment yield was considered to be 260 t km^{-2} yr^{-1}.

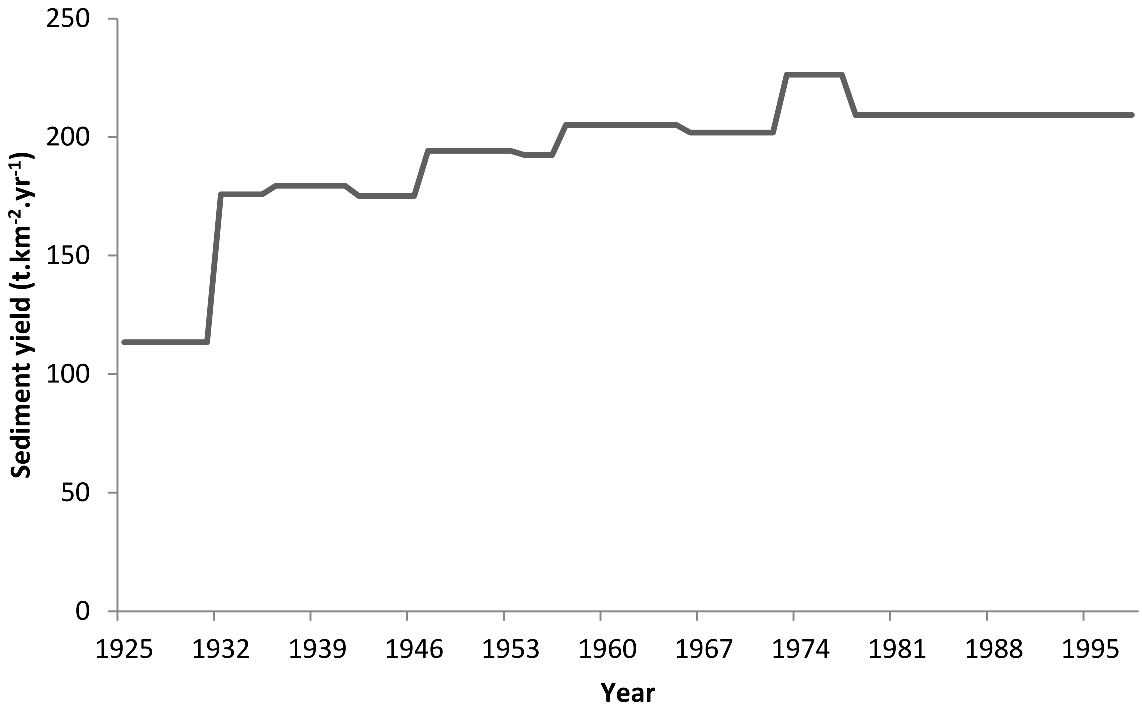


Figure 4.20 The sediment accumulation of the Nqweba dam from 1925 to 1998 (Source: DWS)

The absence of long term data for small catchments in the Karoo has been addressed by palaeoenvironmental reconstruction for catchments with dams at the downstream end (Foster et al., 2012). Regional processes of soil erosion and sediment yield were reconstructed through this study. Studying sediments trapped in these small farm dams may also provide insight into changing catchment sediment yield and sediment sources (Foster et al. 2005; 2007; 2008; Foster & Rowntree, 2012; Rowntree & Foster, 2013). Landscape degradation in this region is typified by intensely dissected colluvial footslopes (termed badlands) and by incised channels or gullies located in valley bottoms (Boardman et al., 2003; Keay-Bright & Boardman, 2006). The development of these landforms was studied by Boardman et al. (2003) in the upper catchments of the Klein Seeikooi River, a tributary of the Seekooi River which joins the Orange River, in the Karoo. The study indicated that it was unlikely that badland and gully systems were a long term feature of the landscape, and that both appear to be quite recently formed. Badland systems seem to actively erode during low magnitude, high-frequency events, whilst gully systems were considered active during the 1930s to 1960s due to land management changes. Keay-Bright & Boardman (2007) suggest that pre-rotational grazing systems and high stock numbers are the most likely causal factor behind the badlands and gullies observed in this region. An average loss of 5.6 mm of soil per year over an 8 year period from badlands in the area has been observed by Keay-Bright & Boardman (2009), although in certain cases in the Karoo, badlands are not often directly connected to the main valley channel network as eroded sediments form fans at the foot of badland areas.

Rowntree & Foster (2012) analysed aerial photography to determine the temporal and spatial variability of connectivity for Ganora catchment. It was evident that badlands existed in 1945, with a similar spatial distribution as the present day. There was a clear channel network draining the eastern half of the catchment, with limited channel development in the western half of the catchment (Figure 4.25). By 1966 the channel had extended down through the footslope area where badland sediments had been accumulating. This connected the badland area to the main channel network.

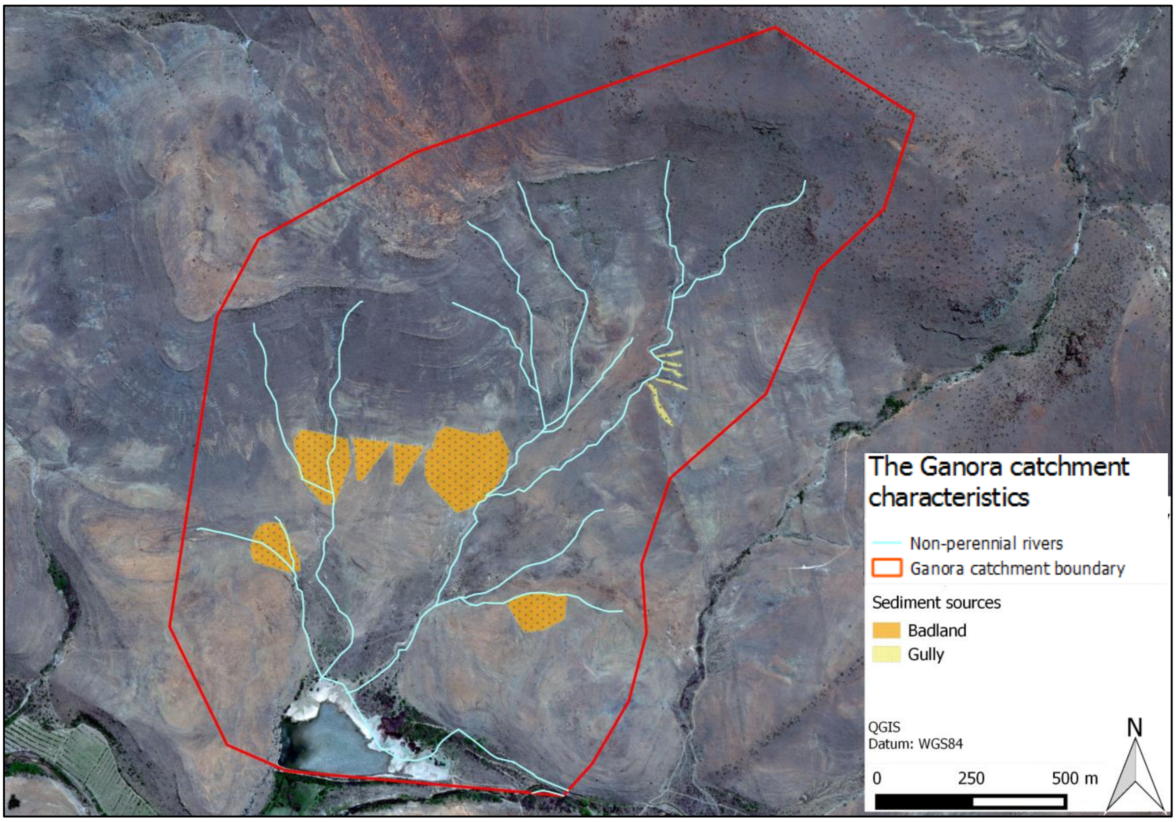


Figure 4.21 The sediment sources and stores in the Ganora catchment.

Palaeoenvironmental reconstruction of sedimentation rates for Ganora catchment support this argument for change in connectivity in the catchment. Rowntree & Foster (2012) relate the concept defined above to the sedimentation yield in the dam (Figure 4.26). It is clear that badland erosion was initiated prior to 1945, but there was only a significant contribution to catchment sediment yield in the 1960s. Prior to the 1960s dam sediment was dominated by channel bank erosion and or hillslope erosion from the eastern catchment. Once connectivity was established in the 1960s there was a rapid increase in catchment sediment yields.

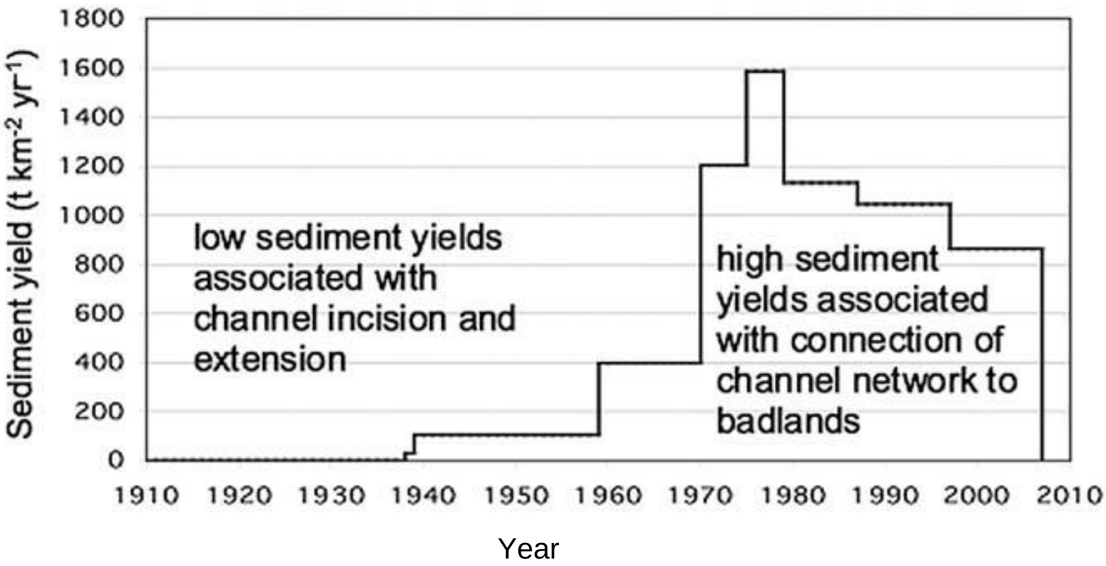


Figure 4.22 The proposed sequence of events in the Ganora catchment relating to changing sediment yield and sources, 1910 – 2007 (Rowntree & Foster, 2012).

Studies in the Cranemere (Foster & Rowntree, 2012) and Ganora catchments (Rowntree and Foster, 2012) provide a “history book” of landscape change. Cranemere catchments reconstructed sediment yield show significant temporal variability, with low yields (less than 25 t km-^{2} yr^{-1}) dominating the period from the 1840s to 1930s (Figure 4.23). From the 1930s onwards sediment yields increased to a peak of just under 250 t k^{-2} yr^{-1} in the late 1960s, followed by a decline to around 150 t km^{-2} yr^{-1} up until 2011. Most of the sediment was fine grained therefore considered to be transported as suspended sediment. The pattern of sediment yield was explained by the authors as a combination of a lag effect both for grazing pressure to increased erosion and conservation practices to recovery; increased sediment yields relating to increased rainfall intensity, erosivity and flooding; and due to changes in connectivity between sediment sources and the dam.

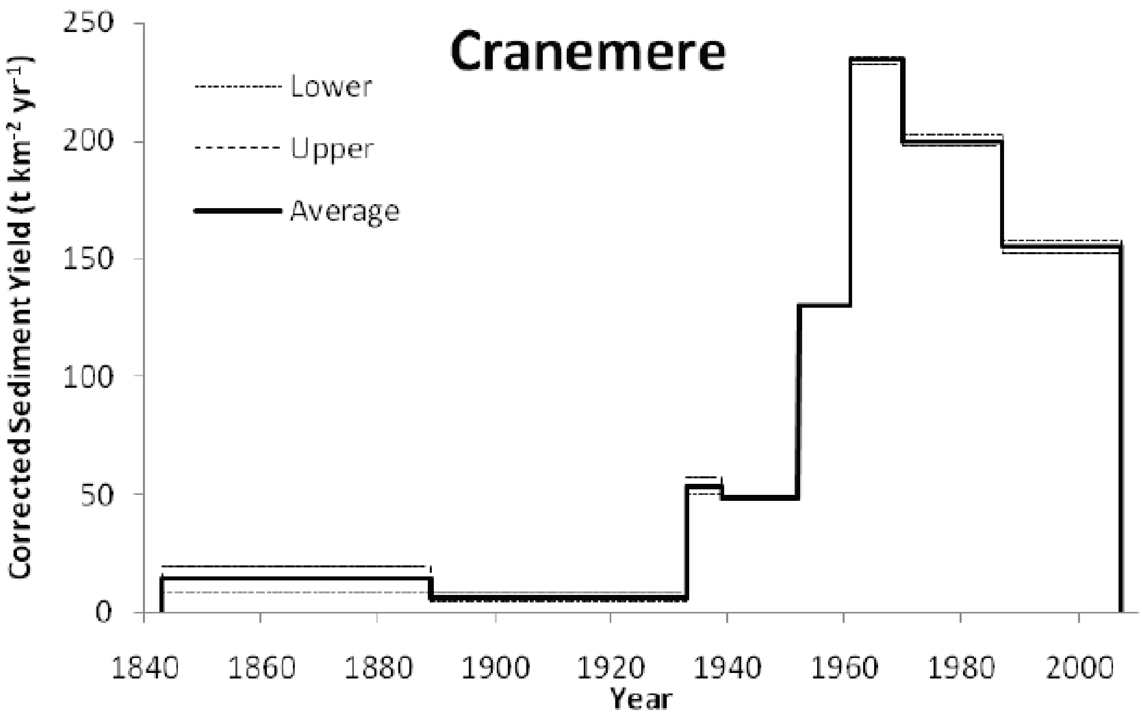


Figure 4.23 Reconstructed sediment yields for Cranemere catchment from 1843 (Foster & Rowntree, 2012; Foster *et al.,* 2008).

According to Foster et al*.* (2012) the low relief of the middle and lower catchment provides a large capacity for temporary sediment storage in Cranemere (Figure 4.24). Sediment is stored in fans and valley floor floodouts, causing discontinuities in the channel network. Soils eroded from source zones on the hillslopes can be stored for a long time in valley floor storage zones. These storage zones may disconnect the channel system, but they can also be reactivated into the system by the headward erosion of channels. The reworking of temporary sediment storages within the catchment following increased connectivity means that a more realistic calculation for sediment yield should be around 145 t km^{-2} yr^{-1} for the past 70 years (Foster & Rowntree, 2012).

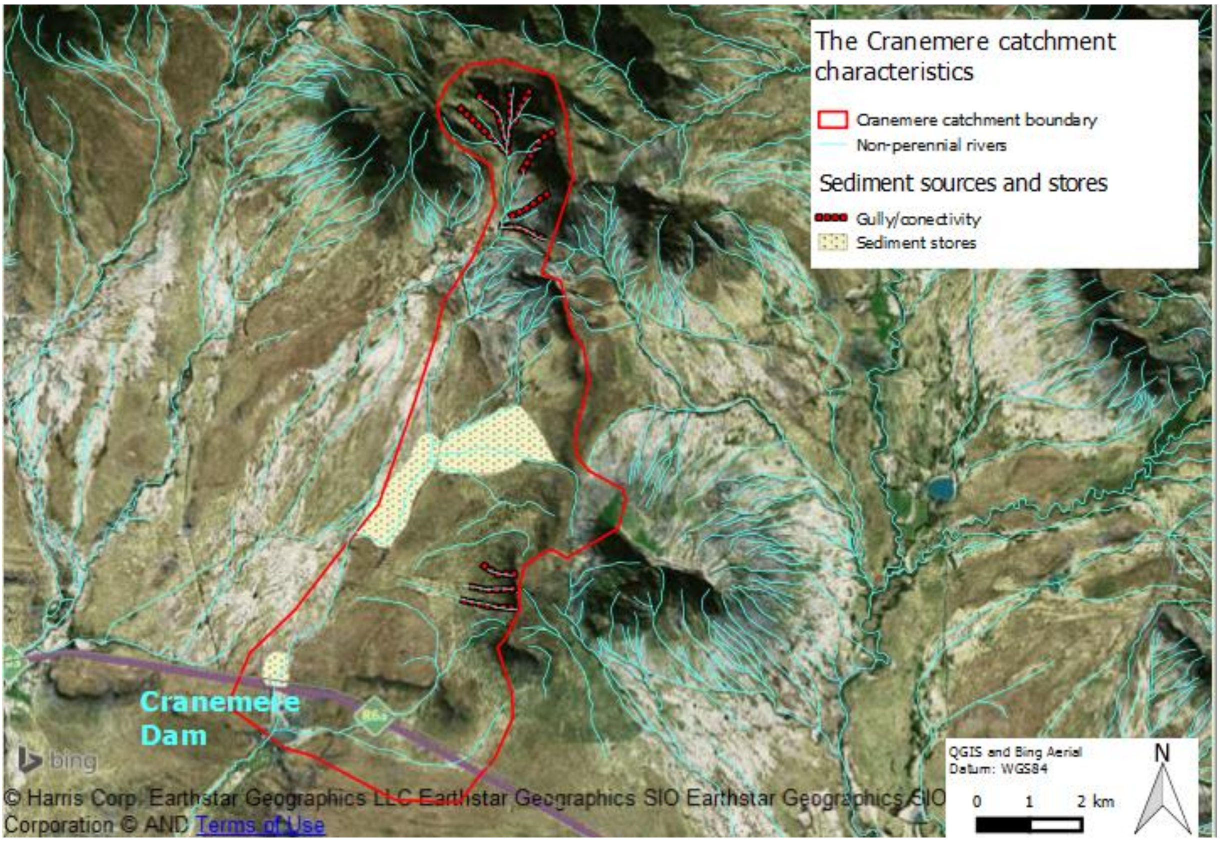


Figure 4.24 The sediment sources and stores in the Cranemere catchment.

4.4 Concluding remarks

The defining or emergent properties for each catchment were summarised in order to provide a conceptualisation for calibration of the model (Table 4.1). This summary would be referred to when developing an understanding of the realistic conditions that the model needs to represent. There are climatic, topographic and catchment connectivity trends which can be attributed to semi-arid catchments. These trends may be related to emergent properties, which vary over temporal and spatial scale.

Table 4.1 The characteristics of the study catchments for the erosion and sediment delivery model.

Driver of emergent properties		Ganora	Cranemere	Nqweba
General	**Area (km^2)**	2.7	57	3667.7
Climatic drivers	**MAP (mm)**	350	318	350
	Trends	– *Near decadal wet and dry spells* – *Low annual runoff totals* – *Extreme rainfall events account for large proportions of mean annual precipitation* – *Increased rainfall intensity and storm erosivity after 1950* – *Poor vegetation cover linked to overgrazing in the 1930s* – *Badland areas dependent on rainfall but limited vegetation cover on eroded areas.*		
Topographic drivers	**Elevation (masl)**	1440 to 1740	760 to 1540	1600 to 2080
	High elevation	Steep, limited channels.	Steep, limited channels.	Steep, limited channels.
	Moderate elevation	Narrow, stony channels, badlands.	Narrow channels, gullies.	Narrow, stony channels, badlands.
	Low elevation	Alluvial fans with sediment accumulation from badlands.	Alluvial fans and floodouts, disconnected channels.	Alluvial fans with sediment accumulation from badlands.
	Channel	Wider, fine sediments.	Wide, fine sediments, eroding banks and discontinuous drainage lines.	Wider, fine sediments.
	Badlands/gullies	Badlands initiated in the 1930s and connected to the main channel network in 1960s.	Increased sediment yield post-1930s; Discontinuous gullies on hillslopes	Badlands and gullies present.
	Floodouts/fans	Limited fans and storage.	Large temporary storage capacity in fans and floodouts.	Large temporary storage capacity.
	Trends	– *Rivers superimposed on resistant dolerite;* – *Rivers predestined to erosion;* – *Ganora in high elevations of the Nqweba catchment;* – *Predominantly sandy to loamy sand soil textures.*		

<table>
<tr><th colspan="2">Driver of emergent properties</th><th>Ganora</th><th>Cranemere</th><th>Nqweba</th></tr>
<tr><td rowspan="2">Catchment connectivity drivers</td><td>Observed Mean Annual Sediment Yield (SY) ($tkm^{-2}yr^{-1}$)</td><td>1096</td><td>175</td><td>207</td></tr>
<tr><td>Trends</td><td colspan="3">– High sediment yields; infrequent bursts each time floodplain channel rejuvenated by a switch at the floodplain head on a floodout;
– Infrequent flow means that sediment stays in temporary storage within the floodplain for long periods.</td></tr>
</table>

5 MODEL DEVELOPMENT

The approach to model development involved translating the conceptual framework into an appropriate structure for the erosion and sediment delivery model that includes the equations, the linkages between them and the parameter values. The structure was inevitably constrained by the likely availability of data with which to force the model and to quantify (or calibrate) the parameter values.

5.1 Model description

Sediment will be carried downslope depending on the transport capacity of overland flow and the total detachability of soil. Using a sediment transport model to control the movement of sediment when deposition conditions exist follows the approach of Meyer & Wischmeier (1969) by first determining the sediment available for delivery via an erosion model and adding a function to depict deposition if sediment exceeds the transport capacity of flow (Kinnel, 2004). It is important to incorporate an effective hydrological model as a good estimation of flow is vital for an accurate description of both erosion and sediment delivery. The stochastic nature of erosion and sediment delivery will be represented by using distribution function theory by relating important processes to the probability distribution of conceptual stores without needing to account for the full spatial variability of the physical characteristics that control the processes at the catchment scale. This conceptualisation of an erosion and sediment delivery model will provide a distributed description of catchment processes in a much simpler way.

The erosion and sediment delivery model is separated into the following components:

- Surface flow estimation;
- Erosion estimation; and
- Sediment storage and sediment delivery estimation.

The components of the distributed erosion and sediment delivery model are constrained by data availability as this would force the parameters used in the model development. The explanation for how parameters were derived for the study catchments is detailed in chapter six.

5.1.1 Surface flow estimation

In chapter three it was determined that the Pitman rainfall-runoff model would be a useful hydrological model for linking with an erosion and sediment delivery model. Using existing hydrological models increases the likelihood of use by water resource managers and ensures that already established model routines would not need to be re-developed (Slaughter et al., 2014). Established hydrological models, such as the Pitman rainfall-runoff model, act on a monthly time step, yet rainfall in semi-arid areas is generally in the form of high intensity, short duration storms. The Pitman model therefore needs to be disaggregated into a daily time step in order to effectively represent surface runoff in semi-arid catchments. This process has already been developed as part of an emerging water quality model that has been linked to existing and commonly used water resources estimation methods (Slaughter et al., 2014). The disaggregation method is based on daily rainfall data following the principles established by Smakhtin & Masse (2000). Parameters used in the method are linked to catchment characteristics, indicating that there is potential for the regionalisation of model parameters for un-gauged catchments. Some initial model assessments have shown that daily simulated flows are an acceptable match to daily observed flows, where they are available (Slaughter et al., 2014). The method also includes an approach that separates the total daily flow into surface, interflow and groundwater components. These are important for the overall water quality model and are also highly relevant for the sediment model, where it is important to distinguish between surface flow that could generate slope sediment delivery and other flows that might be more important for within-channel sediment transport.

The data available to force the erosion and sediment delivery model were therefore time series of rainfall depth (mm d^{-1}), surface runoff (m^3 d^{-1}) and baseflow runoff (m^3 d^{-1}) (combined interflow and groundwater from the method of Slaughter et al., 2014). The daily rainfall depth data over a long time period (up to 100 years) was used in the daily disaggregation of the Pitman model. The modelled sediment delivery results were partly dependent upon the accuracy (or representativeness) of the flow simulations generated by the Pitman model and the daily disaggregation model. It was necessary to estimate the daily peak flow volume (in m^3 hr^{-1}) based on some assumptions about the time distribution of the total daily volumes, as this variable is required for the MUSLE model runoff factor. Although it has been mentioned that uncertainties are related to flow, it is considered beyond the scope of this study to perform any stochastic sensitivity analysis.

The basis of the distribution system used in the model is the assumption that the catchment can be divided into areas of relatively high, moderate and low runoff. The first is further assumed to be steeply sloping areas around the catchment boundary, the second less steep foothill areas and the third the flatter valley bottom areas (Figure 5.1). Model parameters are therefore required to specify the proportion of the total catchment area occupied by these three zones.

Runoff depth refers to the vertical distance between the water surface and some point on the streambed, with discharge referring to the volume of water passing a stream cross-section per unit time. It was assumed the high runoff zone had a threshold flow that was 75% higher than the moderate runoff zone and this zone was in accordance 75% higher than the low runoff zone. This meant that the high runoff zone had the highest threshold flow and the low runoff zone had the lowest threshold flow.

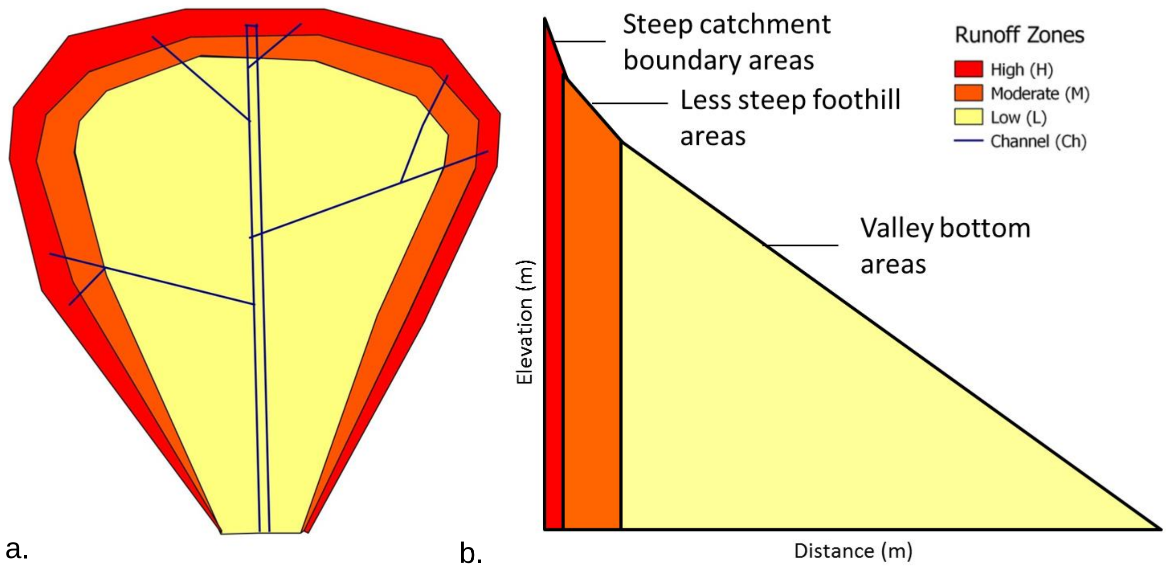


Figure 5.1 The conceptualisation of the runoff zones in a catchment (a) and as a cross section through a catchment (b). The runoff zones for a catchment are dependent on slope gradient as the high runoff zone occurs in the steep catchment boundary areas, the moderate runoff zones occurs in the less steep foothill areas and the low runoff zone occurs in the least steep valley bottom areas. The main channel may occur in all three runoff zones.

5.1.2 Erosion estimation

Daily sediment availability was calculated with the MUSLE model (Williams, 1975):

$$SA = RLSKCP$$ **Equation 5.1**

Where *SA* is the daily sediment availability (in $t.ha^{-1}$), *R* is the runoff factor, *C* is the cover factor, *LS* is the topography factor, *K* is the soil erodibility factor and *P* is the practice factor.

As previously stated, the stochastic nature of erosion and sediment delivery was accounted for by using distribution function theory. In the model, estimates of *SA* are made according to the inputs to Equation 5.1 for 100 sub-grids within the total catchment distributed according to the proportion of the catchment assumed to lie within the three runoff zones as identified in Figure 5.1. Thus, if the proportions for the high, moderate and low runoff zones are 0.1, 0.4 and 0.5 respectively, 10, 40 and 50 sub-grids will be used for the three zones (Figure 5.2). The way in which the *R*, *LS*, *K*, *C* and *P* inputs are estimated for the three zones are explained in the following sub-sections (refer to .

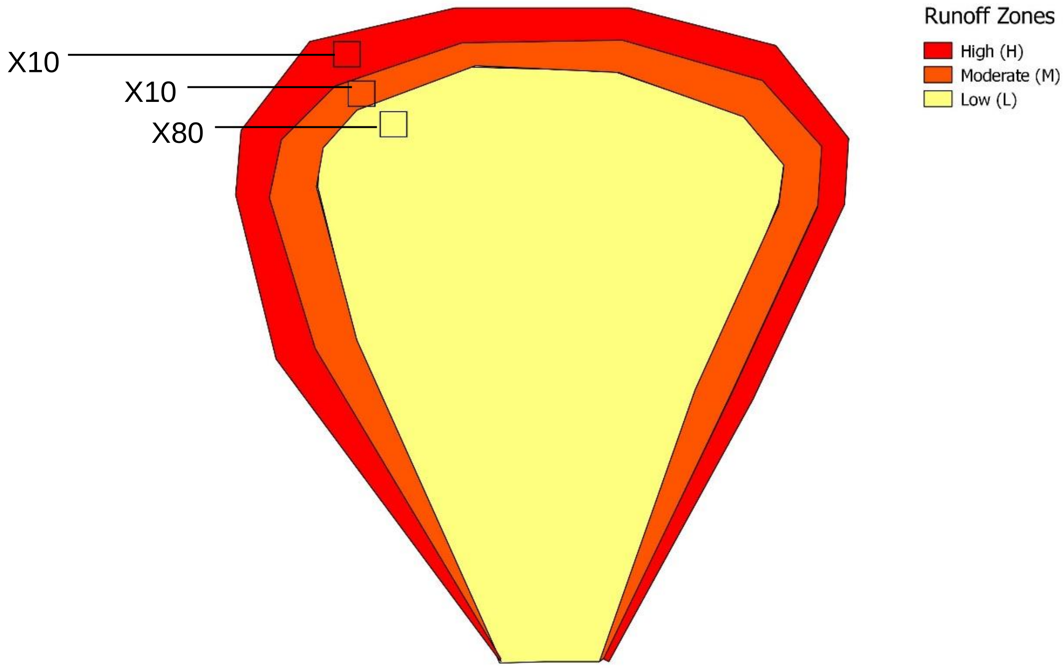


Figure 5.2 The conceptualisation of the way sub-grids will be determined for the runoff zones in a catchment, depending on the proportion of the catchment in each zone. For example 10 subgrids within the high runoff zone, 10 subgrids within the moderate runoff zone and 80 subgrids within the low runoff zone. One hundred sub-grids will be used.

5.1.2.1 Runoff factor

The runoff factor incorporates peak flow and the volume of runoff. These values were derived following surface flow estimation as described above. This represents the energy component of the model.

The governing equation to determine the runoff factor was defined using the recommendations of (Williams, 1995) as given in Equation 5.2:

$$\boldsymbol{R = 1.586(Q.q_p)^{0.56}A^{0.12}}$$ **Equation 5.2**

Where Q is the daily depth of runoff (in mm), q_p is the daily peak flow (in mm.h^{-1}) and A is the drainage area (in km^2). The values for Q and q_p were calculated for each sub-grid based on some assumptions about how the total runoff volume is distributed amongst the three runoff zones depth. The model assumes that the high runoff zone generates 75% more runoff than the moderate runoff zone, which in turn is assumed to generate 75% more than the low runoff zone. The depth of runoff in the high runoff zone can therefore be estimated by Equation 5.3:

$$\boldsymbol{Q_H = \frac{Q_{sf}}{H+\frac{M}{1.75}+\frac{L}{3.0625}}}$$ **Equation 5.3**

Where Q_H is the depth of surface runoff for the high runoff zone, *Qsf* is the depth of surface flow (input from the hydrological model), *H* is the fraction of the catchment in the high runoff zone, *M* is the fraction in the moderate runoff zone and *L* the fraction in the low runoff zone. Q_M and Q_L (depth of surface flow in the other two zones) are then calculated as Q_H/1.75 and Q_H/3.0625, respectively.

Equation 5.2 also requires an estimate of the peak flow (q_p)during each day of the model run and this was based on an assumed non-linear relationship between runoff volume and duration using fixed scale, power and constant parameters (D_{scale}, D_p and D_{con}) as shown in Equation 5.4:

$$\boldsymbol{D = D_{scale}(Vsf)^{Dp} + D_{con}}$$ **Equation 5.4**

Where *D* is the duration (in hours) and *Vsf* is the catchment surface runoff volume (in m^3). All three runoff zones therefore are assumed to have the same duration of runoff. The peak discharge for each runoff zone is calculated assuming a double triangle shaped hydrograph using a form of Equation 5.4:

$$\boldsymbol{q_{Hp} = \frac{2.VH}{0.75.D.3600}}$$ **Equation 5.5**

Where q_{Hp} is the peak runoff (in m^3 s^{-1}), V_H is the volume of surface runoff (in m^3) and *D* the duration (in hours). Equivalent equations are used to estimate q_{Mp} and q_{Lp} from V_M and V_L for the moderate and low runoff zones.

The important variables and parameters for estimation of the surface flow for the three runoff zones in a catchment are therefore:

- Catchment Area (km^2).
- Proportions of the catchment lying in the high, moderate and low runoff zones (H, M and L).
- Daily surface runoff depth (Q_{sf}) from the hydrological model simulations (including the daily disaggregation and baseflow separation procedures).
- Storm duration-volume relationship scaling factor (D_{scale}), power (D_p) and constant (D_{con}) parameters

The other inputs to Equation 5.1 (*LS*, *K*, *C, P*) for each sub-grid are randomly sampled from uniform probability distributions defined by the mean and range (LS_{MN} and LS_{RAN}, for example) for the total catchment. The sampling process is constrained where it is assumed that there is likely to be a relationship between the range of expected values for the input variable and the runoff zone (Figure 5.3). These constraints relate to the relationship of runoff with slope and the relationship of runoff with vegetation cover (Figure 5.4).

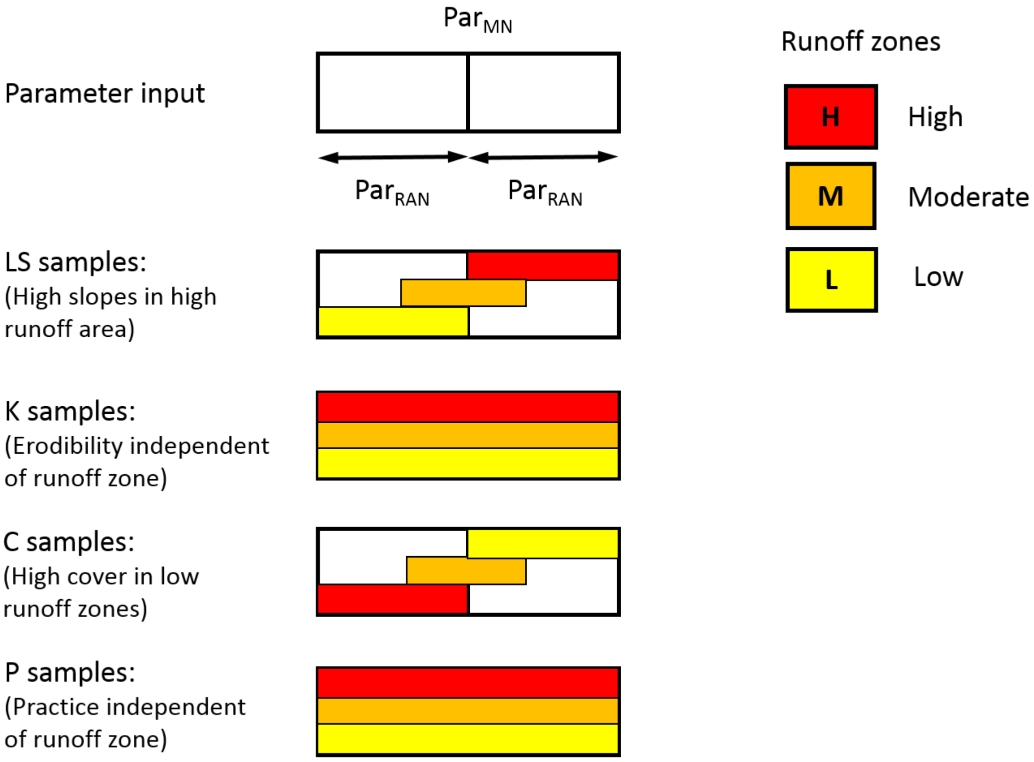


Figure 5.3 The sampling process for erosion parameters is constrained where there is a relationship between the range of expected values for the input variable and the runoff zone. The topography and vegetation cover factors are assumed to be related to the runoff zone.

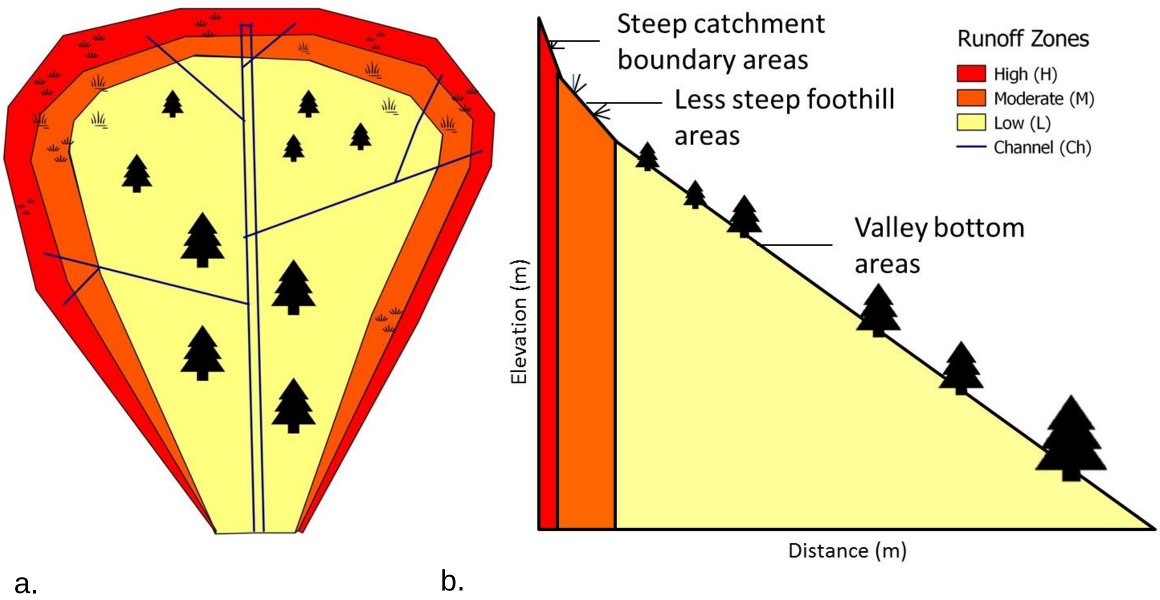


Figure 5.4 The conceptualisation of the relationship of vegetation with the runoff zones in a catchment (a) and as a cross section through a catchment (b). Where limited vegetation cover is expected to be in the high runoff zone and dense vegetation cover is expected in the low runoff zone.

5.1.2.2 Topography factor

Sadeghi et al. (2014) identified that the use of GIS to determine the topography factor improved the performance of model estimates. Commonly available data to create a Digital Elevation Model (DEM) of a study site are 1:50 000 point elevation and contour vector data. Flow accumulation and slope, are calculated by using this data and the mean and variance of the topography factor is determined from the resulting topography factor raster file.

The topography factor represents the effect of topography on soil erosion. *L* represents the effect of slope length and *S* the effect of slope gradient on erosion. *LS* is determined using the equations as given by Moore & Burch (1986). The combined slope gradient and slope length factor was defined as follows:

$$\boldsymbol{LS} = \left(\frac{A}{22.13}\right)^{0.4}\left(\frac{\sin\theta}{0.0896}\right)^{1.3} \qquad \textbf{Equation 5.6}$$

Where *LS* is the topography factor, *A* is the product of flow accumulation and cell size, θ is the slope angle in degrees.

Both *A* and θ are derived from the DEM directly. The mean (LS_{MN}) and range (LS_{RAN}) of the *LS* factor for the catchment are determined using this approach. The topography factor is assumed to be related to the runoff zone and therefore the sub-grid *LS* factors for the high runoff zone are randomly sampled from the range LS_{MN} to $LS_{MN} + LS_{RAN}$ (higher slopes), the moderate runoff zone from $LS_{MN} – LS_{RAN}/2$ to $LS_{MN} + LS_{RAN}/2$ (moderate slopes) and the low runoff zone from $LS_{MN} – LS_{RAN}$ to LS_{MN} (low slopes) (Figure 5.3).

The physical meaning of the topography parameter is related to the combined effects of slope gradient and length. Slope length is defined by Wischmeier & Smith, 1978) as the distance from the point of origin of surface flow to the point where either the slope gradient decreases enough for deposition, or the surface flow enters a well-defined channel of the drainage network. Surface flow generally increases with slope gradient. As has been discussed in chapter two, topography is an important property of semi-arid catchments as it exerts a control on sediment erosion and deposition. The factor is closely linked with the runoff factor due to the control it exerts on runoff.

5.1.2.3 Soil Erodibility factor

Sadeghi et al. (2014) also identified that using limited site specific information, with the help of the Wischmeier & Smith (1978) soil erodibility diagram, did not affect the accuracy of results when calculating the soil erodibility factor. Wischmeier & Smith (1978) developed this diagram with the knowledge that certain soils erode more readily than others even when all other factors in the USLE equation are the same. This difference is caused by the inherent physical characteristics of the soil. This diagram was used to develop a table of general soil texture classes and related soil erodibility (Mitchell & Bubenzer, 1980).

The land type distribution for South Africa is obtained from the Agricultural Research Council- Institute for Soil, Climate and Water (ARC-ISCW). The land type distribution for the study catchments is determined and the surface soil type defined as part of the land type classification is used to determine soil erodibility factors using Table 5.1. Once each land type and its corresponding soil erodibility factor has been identified it is then possible to create a raster map of the distribution of soil erodibility over the catchment from which the mean (K_{MN}) and range (K_{RAN}) parameters could be determined. The sub-grid K factors are based on random sampling from the range K_{MN} - K_{RAN} to K_{MN} + K_{RAN}, with no differences between different runoff zones (Figure 5.3).

Certain soils are more erodible and the response to erosive forces depends on the interaction of chemical and physical properties such as soil texture, structure and organic matter content. Soil texture refers to the distribution of primary particle sizes making up the soil and influences the ability of a soil to absorb and hold water for plant use. Particle size groups are classified according to the basis of particle diameter as sand, silt or clay (according to the United States Department of Agriculture system). Soils high in clay restrict the entry of water into the soil, whilst soils high in sands allow more water to flow through the soil. Medium-textured soils, such as silt-loams, provide the best moisture conditions for plants (Toy et al., 2002). Organic matter content is also an important component of soils as it provides surfaces for water storage and binds mineral soil particles into larger aggregates that resist water erosion. Some soils are inherently more erodible than others, relating to the above mentioned soil properties.

Differences in soil susceptibility to erosion are difficult to quantify from field observations. Complications may be in the case of a highly erodible soil under gentle rainfall on short and gentle slopes will not show signs of erosion, as opposed to a soil with a relatively low erodiblity factor on long or steep slopes under intensive storms showing signs of erosion. The soil erodibility factor would therefore need to be analysed separately from the effects of other factors (Wischmeier & Smith 1978).

Representative values of *K* for most soil types and texture classes may be obtained from tables such as Table 5.1, as certain relationships between soil texture and organic matter content may be inferred. Soils resistant to detachment, such as clayey soils and coarse textured soils with low runoff, such as sandy soils, both have low K values, Medium textured soils, such as the silt loam soils, have a moderate *K* value. Soils with high silt content are most erodible of all soils. Interpreting these relationships is necessary when calibrating the *K* factor in the erosion model.

Table 5.1 Soil Erodibility (Mitchell & Bubenzer, 1980)

Texture class	Organic matter content		
	<0.5%	**2%**	**4%**
	K	***K***	***K***
Sand	0.05	0.03	0.02
Fine sand	0.16	0.14	0.1
very fine sand	0.42	0.36	0.28
Loamy sand	0.12	0.1	0.08
Loamy fine sand	0.24	0.2	0.16
Loamy very fine sand	0.44	0.38	0.3
Sandy loam	0.27	0.24	0.19
Fine sandy loam	0.35	0.3	0.24
Very fine sandy loam	0.47	0.41	0.33
Loam	0.38	0.34	0.29
Silt loam	0.48	0.42	0.33
Silt	0.6	0.52	0.42
Sandy clay loam	0.27	0.25	0.21
Clay loam	0.28	0.25	0.21
Silty clay loam	0.37	0.32	0.26
Sandy clay loam	0.14	0.13	0.12
Silty clay	0.25	0.23	0.19
Clay		.13-.29	

5.1.2.4 Cover factor

The temporal variation of vegetation cover has been identified as an important property to consider when determining the cover factor for the MUSLE model (Sadeghi et al., 2014). The cover factor is a value between 0 and 0.5 that is associated with the extent of vegetation cover that protects the soil surface from rainwater impact or runoff detachment. Cover factor values are based on vegetation cover GIS data and the guidelines provided by Wischmeier & Smith (1978).

The data available to determine the vegetation type distribution for South Africa is obtained from the South African National Biodiversity Institutes (SANBI) GIS resource (BGIS). This provides spatial data for the vegetation types as described by Mucina & Rutherford (2006) and represents a coarse description of South African vegetation characteristics. Further interpretation of these data is supported by field visits to determine the validity of the vegetation descriptions. The mean (C_{MN}) and range (C_{RAN}) of the cover factor are determined using the GIS data, satellite imagery and field visits to determine the vegetation cover characteristics which are translated into C values using Table 5.2.

The cover factor is assumed to be related to the runoff zone and therefore the sub-grid C factors for the high runoff zone are randomly sampled from the range C_{MN} – C_{RAN} to C_{MN} (limited cover), the moderate runoff zone from C_{MN} – $C_{RAN}/2$ to C_{MN} + $C_{RAN}/2$ (moderate cover) and the low runoff zone from C_{MN} to C_{MN} + C_{RAN} (dense cover) (Figure 5.3).

As has been mentioned in chapter two, climate has an impact on both hydrology and vegetation. Water availability acts as important control over vegetation growth and vegetation cover may act as a protective covering for soil from the impacts of rainfall and be a dominant control on runoff generation in semi-arid areas. Erosion is closely correlated with the cover factor due to the linked correlation of the cover computation with runoff. Poor vegetation cover would provide a high *C* factor, resulting in more available sediment for removal or storage. Good vegetation cover would provide a low C factor and result in less available sediment for removal or storage.

5.1.2.5 Practice factor

The Practice factor table (Table 5.3) from Wischmeier & Smith's (1978) study can be used effectively. Satellite imagery was also used to determine the management practices present in the catchment. Table 5.3 was used to determine the practice factor, taking into account the extent of topographic modification through contouring or terracing. In the absence of any such management practices, *P* is assumed to be 1. The sub-grid *P* factors were based on random sampling from the range P_{MN} - P_{RAN} to P_{MN} + P_{RAN}, with no differences between different runoff zones (Figure 5.3). The erosion mitigation techniques applied to land will slow runoff and reduce erosion therefore a practice factor is an important feature of the MUSLE model. As *P* is assumed to be 1 in the absence of any management practices it can be assumed that calibration of this parameter is not necessary.

Table 5.2 The estimation of the cover factor (C) for permanent pasture, range, and idle land (Wischmeier & Smith, 1978)

Vegetative canopy	Cover that contacts the soil surface							
Type and height[1]	**Percent cover**[2]		**Percent ground cover**					
		Type[3]	**0**	**20**	**40**	**60**	**80**	**95+**
No appreciable canopy		G	0.45	0.2	0.1	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.091	0.043	0.011
Tall weeds or short bush with average drop fall height of 50 cm	25	G	0.36	0.17	0.9	0.038	0.013	0.003
		W	0.36	0.2	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.4	0.18	0.22	0.04	0.013	0.003
		W	0.4	0.22	0.14	0.087	0.042	0.011
Appreciable bushes, with average drop fall height of 2 m	25	G	0.4	0.18	0.09	0.04	0.013	0.003
		W	0.4	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.033
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.04	0.011
Trees, but no appreciable low bush. Average drop fall height of 4 m	25	G	0.42	0.19	0.1	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.04	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.2	0.13	0.084	0.041	0.011

[1] Canopy height is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to drop fail height and is negligible if fall height exceeds 10 m.

[2] Portion of total-area surface that would be hidden from view by canopy in a vertical projection (a bird's-eye view).

[3] G: cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 5 cm deep
W: cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral root network near the surface or undecayed residues or both).

Table 5.3 Practice factor (Wischmeier & Smith, 1978)

Land slope (%)	Contouring	Contour strip cropping and irrigated furrows	Terracing
1 to 2	0.60	0.30	0.12
3 to 8	0.50	0.25	0.10
9 to 12	0.60	0.30	0.12
13 to 16	0.70	0.55	0.14
17 to 20	0.80	0.40	0.16
21 to 25	0.90	0.45	0.18

5.1.3 Sediment storage and delivery estimation

Fryirs (2013) suggests that a method of dealing with the issue of scale in sediment delivery modelling is by focusing on the sediment cascade. This involves analysis of the (dis)connectivity and the strength of linkages of a catchment. Semi-arid catchments in South Africa, within the Karoo in particular, have characteristic sediment source and sink landforms. Sediment sources may be badlands, gully systems and general slope erosion; whilst sediment sinks may be floodouts and alluvial fans. Downstream reservoirs also act as significant sediment sinks in most cases and catchment connectivity is enhanced by the presence of gully systems, which act as runoff and sediment conduits. In some cases landscape units may act to buffer or absorb the sediment flux within a catchment, resulting in the effects of upstream change not manifesting at the catchment outlet. Sediment flux may primarily be reflected in the reorganisation of temporary sediment stores within the catchment rather than as a direct change in the catchment sediment yield (De Vente & Poessen, 2005; Fryirs et al., 2007). A lumped model is not able to reflect this behaviour therefore a distributed modelling approach is more appropriate.

The available sediment, produced by the erosion model, goes into storage within the catchment or is removed from the catchment at the catchment outlet (Figure 5.5). The subdivision of the catchment into runoff zones incorporates both the spatial distribution of the landscape units and runoff. Each runoff zone is assumed to have two storage components, one representing slopes and one representing channel features (gullies or channels). The sediment availability calculated from the erosion model for each runoff zone is assumed to first be added to the slope storage within the runoff zone. The slope storage can then contribute to the channel storage within that zone, as well as to slope storage in a lower zone (i.e. high runoff zone to moderate runoff zone and moderate to low runoff zones). The channel storage in each zone can also contribute to the channel storage in a lower zone, while a main channel storage is included that receives sediment from the slope and channel storage of the low runoff zone and any outputs from the main channel storage represent the total catchment sediment delivery.

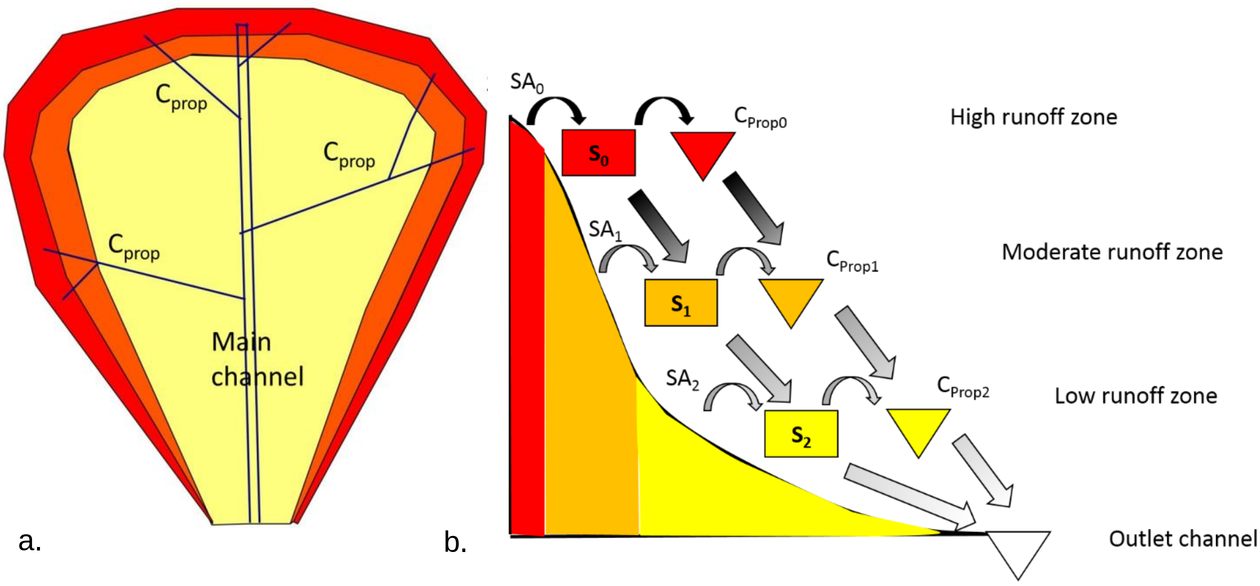


Figure 5.5 The sediment storage and delivery component of the model is driven by runoff, with inputs from the erosion component of the model. Each runoff zone has an input from the erosion model (*SA_0*, *SA_1*, *SA_2*), which provides available sediment. Sediment is placed in storage zones (*S_0*, *S_1*, *S_2*) with a proportion being removed through the gully or channel storages ($C_{prop\ 0}$, $C_{prop\ 1}$ $C_{prop\ 2}$) and, depending on the size of the runoff event, sediment is also removed to the next storage zone. Following the runoff zones sediment moves to the channel zone before being removed at the catchment outlet as sediment yield.

The maximum storage capacity for each runoff zone as well as for the main channel is calculated in the model using Equation 5.7:

$$S_{max} = A \times \rho \times d \qquad \textbf{Equation 5.7}$$

Where S_{max} is the maximum sediment storage capacity (kg) of the runoff zones or main channel, *A* is the area (m^2) of the runoff zone or channel, *ρ* is the bulk density (kg m^2) and *d* is the maximum depth (m) of sediment stored. The proportion of gully or channel storage in each runoff zone is calculated from Equation 5.8:

$$C_{prop} = \ln DD \qquad (0.1 \leq C_{prop} \leq 0.8) \qquad \textbf{Equation 5.8}$$

Where C_{prop} is the proportion of the total storage in a runoff zone that is assumed to be represented by gully or channel storage and *DD* is the drainage density (km km^2) of the channel features in that zone. C_{prop} is constrained to lie between 0.1 and 0.8.

The proportion of gully or channel distributions in the runoff zones, and therefore the drainage density can be determined by field or literature based studies.

Sediment is added to the three slope storage zones in each time interval of the model using Equation 5.9:

$$\boldsymbol{SS(t) = SS(t-1) + S_{input}}$$ **Equation 5.9**

Where *SS(t-1)* is the sediment storage at the end of the previous time interval, *SS(t)* is the new storage (before any transport to other storages) and S_{input} is the sediment generated from the soil loss soil loss estimation procedure described in 5.3.2.

The output from each storage component is calculated using the peak surface runoff (q_{sed} mm h^{-1}) for that runoff zone relative to the maximum mean daily total flow depth (q_{max} mm h^{-1}) for the whole catchment (over the whole time series) and a threshold flow depth (q_t mm h^{-1}), as well as a power function of the amount of sediment currently in storage relative to the maximum possible storage. For the main channel storage the peak runoff value is based on the total flow (not only surface runoff) depth during the day for the whole catchment. The maximum mean daily total flow depth is pre-calculated from the full time series of flow data input from the hydrological model. This approach represents a pragmatic approach to estimating sediment delivery from storage that assumes that the rate of delivery will be partly based on the amount of accumulated storage and partly on the size of the runoff event that will move sediment.

If $q_{sed} > q_t$ then:

(i.e. if the peak discharge is greater than the threshold discharge)

$$\mathbf{S_{out}} = \frac{\mathbf{(q\_sed - q\_t}}{\mathbf{(q_{max} - q_t)}} \times \mathbf{SS} \times \frac{\mathbf{SS}}{\mathbf{S_{max}}}^{\mathbf{pow}}$$ **Equation 5.10**

(i.e. if the total output from the storage zone is greater than the sediment storage than total output equals the sediment storage).

For the three slope sediment storage components the C_{prop} value (i.e. the proportion of total sediment storage for the runoff zone that is considered to be in channel features) is used to determine the destination of the sediment delivery. $S_{out} \times C_{prop}$ is added to the channel storage within the same runoff zone, while $S_{out} \times (1 - C_{prop})$ is added to the slope storage of the next runoff zone in the cascade. The outputs from the channel storages are directed to the next channel storage in the cascade, while all of the outputs from the lower runoff zone are directed to the main channel. The outputs from the main channel become the final sediment delivery for the total catchment.

In summary, the sediment delivery during any day of the time series is determined partly by the relative amount of sediment in storage and partly by the relative size of any days runoff event compared to the maximum size of a runoff event expected in the specific catchment. The same sediment delivery equation is used for all of the sediment storage components shown in Figure 5.5. The same runoff threshold parameter (q_t in mm h^{-1}) and relative storage power parameter (*pow*) values are used for all sediment storage components. Differences in sediment delivery rates between runoff zones and between slope and channel storage components therefore depend upon:

- Variations in sediment input from the erosion model for each runoff zone.
- Variations in the peak runoff rates between runoff zones.
- Variations in the proportion of storage assigned to slope and channel storage for each runoff zone.
- The proportion of total daily flow from the hydrological model that is assumed to be surface runoff, rather than baseflow. The surface runoff component is used for the erosion and sediment delivery modelling in all three runoff zones, but total runoff is used for the sediment delivery calculations in the main channel storage.

The parameters involved in the sediment delivery and storage component of the model are as follows:

- Maximum storages
- Proportion of storage in gully store

As described above these parameters are dependent on the erosion component to provide sediment for storage and the runoff parameters to provide energy for removal from stores. This indicates that the most important parameters relate to runoff and erosion parameters. As runoff is a time series variable it is not considered in calibration.

5.2 Using the erosion and sediment delivery model

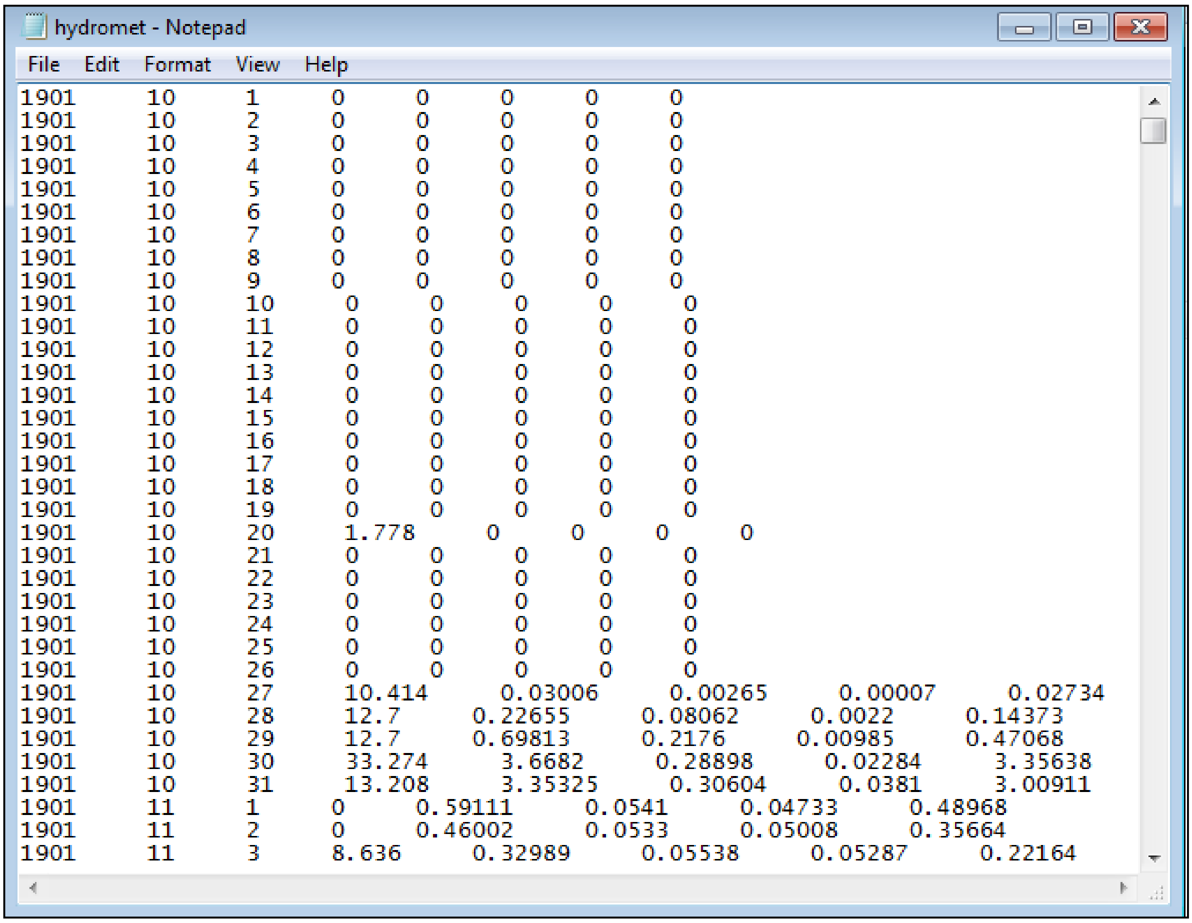
The erosion and sediment delivery model relies on text file inputs and provides text file outputs, which can be incorporated into Microsoft Excel for detailed analyses of the time variations of stored sediment. A Microsoft Excel worksheet (Appendix A; represented in Table 5.4) was developed for parameter preparation and model output interpretation. The parameter worksheet (Worksheet 2) relies on the estimation of surface flow, erosion and sediment storage and delivery parameters (Worksheet 2.1; 2.2; 2.3) as well as incorporation of catchment specific parameters (Parameters 1-5; 16-17). The time series and parameter text file are model inputs (Worksheet 1; 2). The model output, in the form of a text file of sediment outputs, may be loaded to the sediment output worksheet for model interpretation (Worksheets 3.1; 3.2; 3.3; 3.4).

Table 5.4 Using the model with an Excel spreadsheet for model interpretation

Worksheet	Description
1. Time series	*Output from Pitman model*
2. Parameters	
2.1. Surface flow estimation	*Parameters 13-15*
2.2. Erosion estimation	*Parameters 5-12*
2.3. Sediment storage and delivery estimation	*Parameters 18-25*
3. Sediment output	
3.1. Interpret the addition of a "switch" in catchment connectivity	*Represent the "switch" in the time series*
3.2. Compare observed vs modelled annual cumulative sediment yields	*Correlation of cumulative results*
3.3. Compare daily erosion vs sediment delivery estimates	*Correlation of estimated results*
3.4. Compare study catchment outputs	

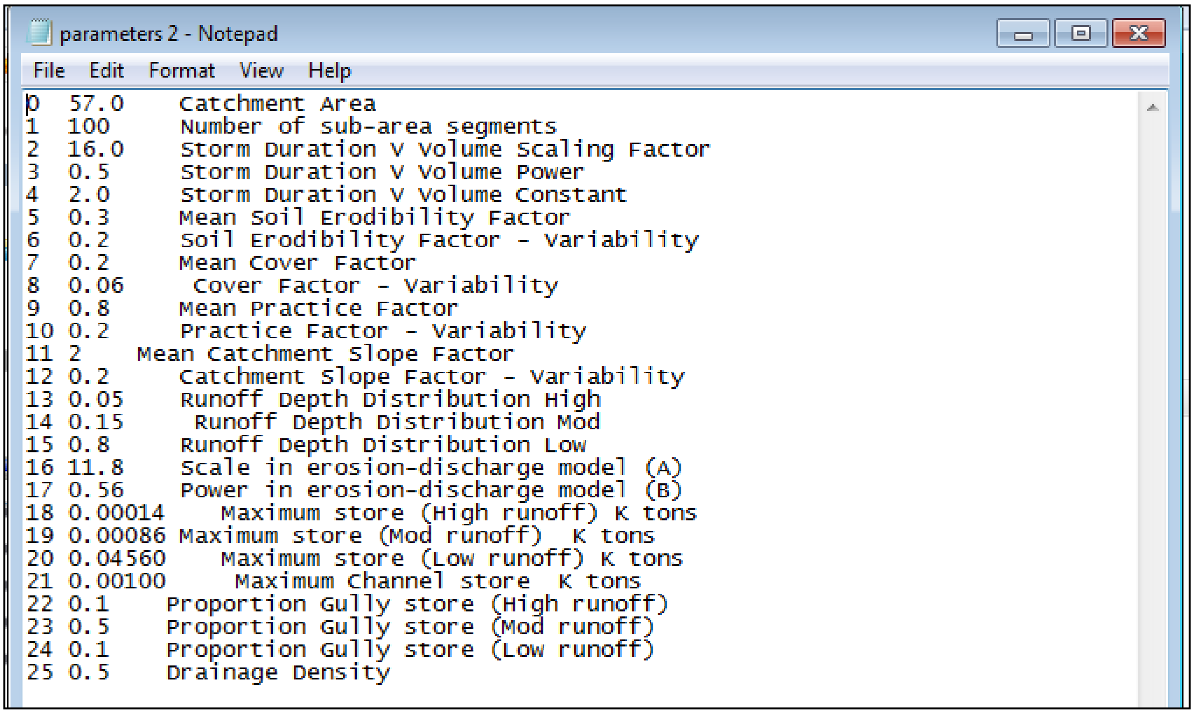
5.2.1 Model Inputs

The first input to the model is a text file from the disaggregated Pitman model which provides daily surface runoff estimations (Figure 5.6). Derivation of this input is detailed in section 5.2.1. The second input to the model is a text file for the model parameters (Figure 5.7). The model user would be able to adjust these parameters according to specific catchment characteristics. The Microsoft Excel Worksheet (Appendix A) will help with determination of the parameters. There are 25 parameters which relate to runoff, erosion and sediment storage components of the model.



```
hydromet - Notepad
File  Edit  Format  View  Help
1901    10    1    0    0    0    0    0
1901    10    2    0    0    0    0    0
1901    10    3    0    0    0    0    0
1901    10    4    0    0    0    0    0
1901    10    5    0    0    0    0    0
1901    10    6    0    0    0    0    0
1901    10    7    0    0    0    0    0
1901    10    8    0    0    0    0    0
1901    10    9    0    0    0    0    0
1901    10    10    0    0    0    0    0
1901    10    11    0    0    0    0    0
1901    10    12    0    0    0    0    0
1901    10    13    0    0    0    0    0
1901    10    14    0    0    0    0    0
1901    10    15    0    0    0    0    0
1901    10    16    0    0    0    0    0
1901    10    17    0    0    0    0    0
1901    10    18    0    0    0    0    0
1901    10    19    0    0    0    0    0
1901    10    20    1.778    0    0    0    0
1901    10    21    0    0    0    0    0
1901    10    22    0    0    0    0    0
1901    10    23    0    0    0    0    0
1901    10    24    0    0    0    0    0
1901    10    25    0    0    0    0    0
1901    10    26    0    0    0    0    0
1901    10    27    10.414    0.03006    0.00265    0.00007    0.02734
1901    10    28    12.7    0.22655    0.08062    0.0022    0.14373
1901    10    29    12.7    0.69813    0.2176    0.00985    0.47068
1901    10    30    33.274    3.6682    0.28898    0.02284    3.35638
1901    10    31    13.208    3.35325    0.30604    0.0381    3.00911
1901    11    1    0    0.59111    0.0541    0.04733    0.48968
1901    11    2    0    0.46002    0.0533    0.05008    0.35664
1901    11    3    8.636    0.32989    0.05538    0.05287    0.22164
```

Figure 5.6 The hydrological input to the model as a text file (output of Pitman model).



```
parameters 2 - Notepad
File  Edit  Format  View  Help
0  57.0     Catchment Area
1  100      Number of sub-area segments
2  16.0     Storm Duration v Volume Scaling Factor
3  0.5      Storm Duration v Volume Power
4  2.0      Storm Duration v Volume Constant
5  0.3      Mean Soil Erodibility Factor
6  0.2      Soil Erodibility Factor - Variability
7  0.2      Mean Cover Factor
8  0.06      Cover Factor - Variability
9  0.8      Mean Practice Factor
10 0.2      Practice Factor - Variability
11 2     Mean Catchment Slope Factor
12 0.2      Catchment Slope Factor - Variability
13 0.05     Runoff Depth Distribution High
14 0.15      Runoff Depth Distribution Mod
15 0.8      Runoff Depth Distribution Low
16 11.8     Scale in erosion-discharge model (A)
17 0.56     Power in erosion-discharge model (B)
18 0.00014     Maximum store (High runoff) K tons
19 0.00086 Maximum store (Mod runoff)  K tons
20 0.04560     Maximum store (Low runoff) K tons
21 0.00100      Maximum Channel store  K tons
22 0.1     Proportion Gully store (High runoff)
23 0.5     Proportion Gully store (Mod runoff)
24 0.1     Proportion Gully store (Low runoff)
25 0.5     Drainage Density
```

Figure 5.7 The parameter input to the model as a text file (adjusted by user).

5.2.2 Running the model

The computer interface allows the user to input the above mentioned text files in a step wise manner (Figure 5.8). First the hydrological data is uploaded (Step 1), followed by the parameter data (Step 2). The output from the model is stored in a text file, which needs to be uploaded to allow data to be directed to it when run (Step 3).

Running the “Uncertain Sediment Erosion Model” (Step 4) will run the distributed erosion and sediment delivery model to produce the top graph with daily erosion and sediment on the primary axis being represented as a red and black line, and mean daily discharge on the secondary axis as a blue line. Summary data would be incorporated in the “parameter” box as the distributed total and delivery total in Kilo tons. This represents the total erosion and sediment delivery for the time series.

Running the “Lumped Sediment Erosion Model” (Step 5) will run the MUSLE model for the whole catchment to produce the bottom graph with daily erosion on the primary axis being represented as a red line, and mean daily discharge on the secondary axis as a blue line. Summary data would be incorporated in the “parameter” box as the lumped total in Kilo tons, representing the total erosion for the time series. This model is used as a comparison to represent the application of an erosion model lumped over the entire catchment, with no account for sediment storage.

5.2.3 Detailed analysis of stored sediment

As the output data for the distributed model is stored as a text file (Figure 5.9), it is possible to upload the data as a Microsoft Excel spreadsheet (Appendix A) for a detailed analysis of the time series. The data is presented with discharge, erosion and sediment delivery in the first three columns and the storages with associated gully storages in the remaining columns (Table 5.5). Each runoff event may be related to a particular date via consultation with the hydrological dataset. With limited observed data it would be necessary to use a degree of subjectivity to interpret erosion and sediment yield values. Being able to refine the model outputs by detailed analysis of the output file allows for a more refined interpretability. The erosion and sediment delivery outputs will be compared with limited observed data in this way.

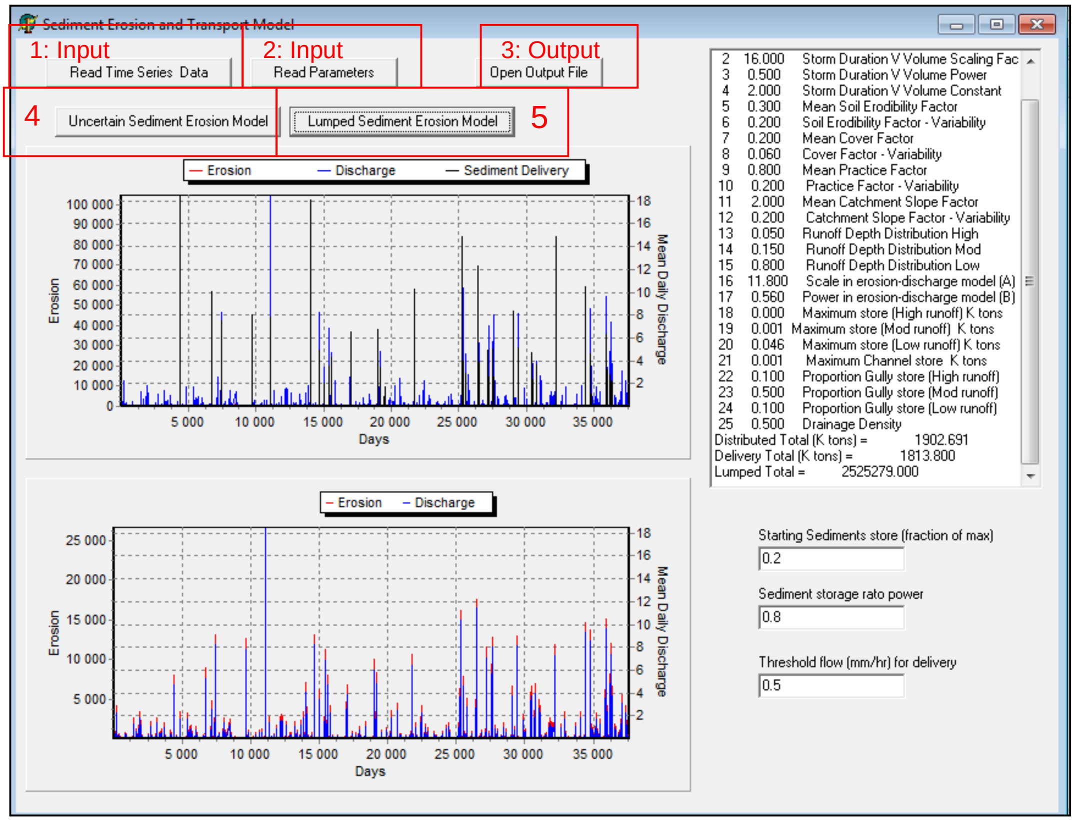
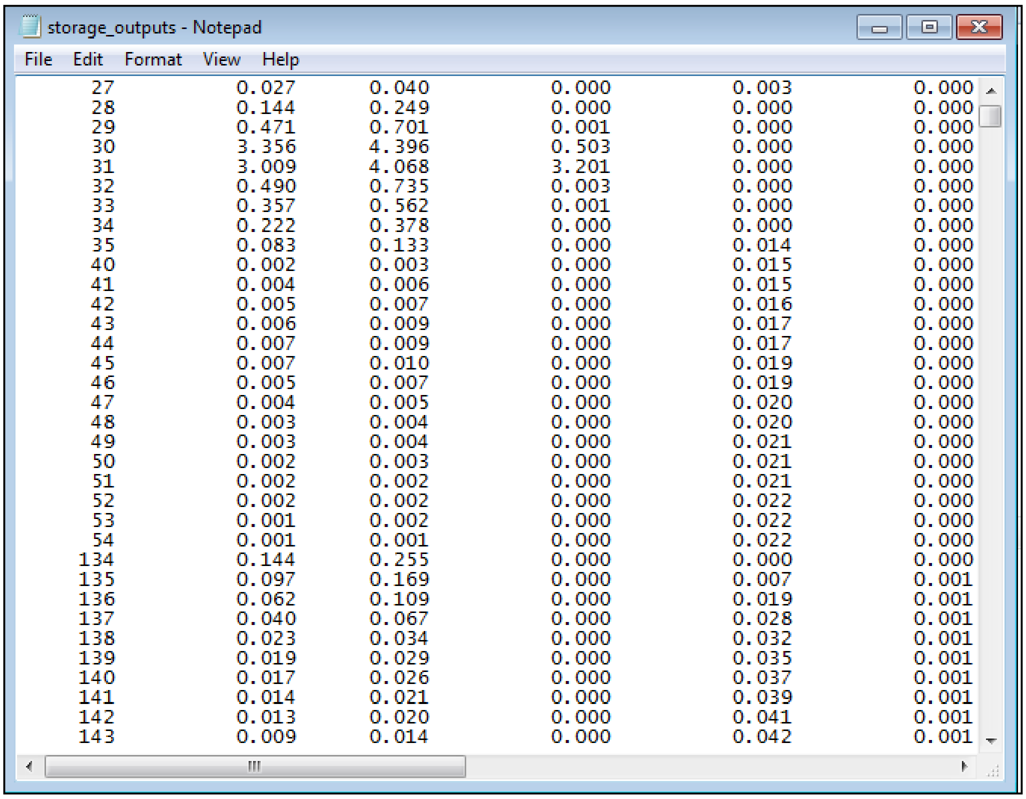


Figure 5.8 The erosion and sediment model computer interface.


storage_outputs - Notepad

File Edit Format View Help

27	0.027	0.040	0.000	0.003	0.000
28	0.144	0.249	0.000	0.000	0.000
29	0.471	0.701	0.001	0.000	0.000
30	3.356	4.396	0.503	0.000	0.000
31	3.009	4.068	3.201	0.000	0.000
32	0.490	0.735	0.003	0.000	0.000
33	0.357	0.562	0.001	0.000	0.000
34	0.222	0.378	0.000	0.000	0.000
35	0.083	0.133	0.000	0.014	0.000
40	0.002	0.003	0.000	0.015	0.000
41	0.004	0.006	0.000	0.015	0.000
42	0.005	0.007	0.000	0.016	0.000
43	0.006	0.009	0.000	0.017	0.000
44	0.007	0.009	0.000	0.017	0.000
45	0.007	0.010	0.000	0.019	0.000
46	0.005	0.007	0.000	0.019	0.000
47	0.004	0.005	0.000	0.020	0.000
48	0.003	0.004	0.000	0.020	0.000
49	0.003	0.004	0.000	0.021	0.000
50	0.002	0.003	0.000	0.021	0.000
51	0.002	0.002	0.000	0.021	0.000
52	0.002	0.002	0.000	0.022	0.000
53	0.001	0.002	0.000	0.022	0.000
54	0.001	0.001	0.000	0.022	0.000
134	0.144	0.255	0.000	0.000	0.000
135	0.097	0.169	0.000	0.007	0.001
136	0.062	0.109	0.000	0.019	0.001
137	0.040	0.067	0.000	0.028	0.001
138	0.023	0.034	0.000	0.032	0.001
139	0.019	0.029	0.000	0.035	0.001
140	0.017	0.026	0.000	0.037	0.001
141	0.014	0.021	0.000	0.039	0.001
142	0.013	0.020	0.000	0.041	0.001
143	0.009	0.014	0.000	0.042	0.001

Figure 5.9 The output from the model (Including daily rainfall, erosion, sediment delivery and storages).

Table 5.5 An example of the data that may be inferred from the sediment model output.

Year	Dis (mm)	Er (Kt)	SD (Kt)	Storage (Kt)						
				H	GH	M	GM	L	GL	Ch
1901	0.027	0.045	0	0.005	0	0.01	0	0.052	0.002	0.001
1901	0.14	0.242	0	0.025	0	0.061	0	0.22	0.002	0.001
1901	0.47	0.787	0	0	0	0.31	0.005	0.77	0.009	0
1901	3.37	4.57	0.2	0	0	0.40	0	5.07	0	0
1901	3.01	4.36	0.18	0	0	0.51	0	9.15	0	0
1901	0.49	0.75	0	0	0	0.70	0.004	9.69	0.003	0
1901	0.36	0.59	0	0	0	0.90	0.008	10.07	0.004	0
1901	0.22	0.36	0	0	0	1.01	0.012	10.32	0.004	0
1901	0.083	0.15	0	0.013	0	1.04	0.012	10.42	0.004	0
1901	0.002	0.003	0	0.014	0	1.04	0.012	10.42	0.004	0

5.3 Concluding remarks

The model is conceptualised as three components: surface flow estimation, erosion estimation and sediment storage and sediment delivery estimation (Figure 5.10). These components require certain inputs in the form of daily surface flow (output from the Pitman rainfall runoff model) and model parameters for a specified catchment. Once inputs are loaded into the model the distributed model runs daily iterations to provide total daily erosion and total daily sediment delivery for the time series. The model outputs may be analysed in more detail in Microsoft Excel.

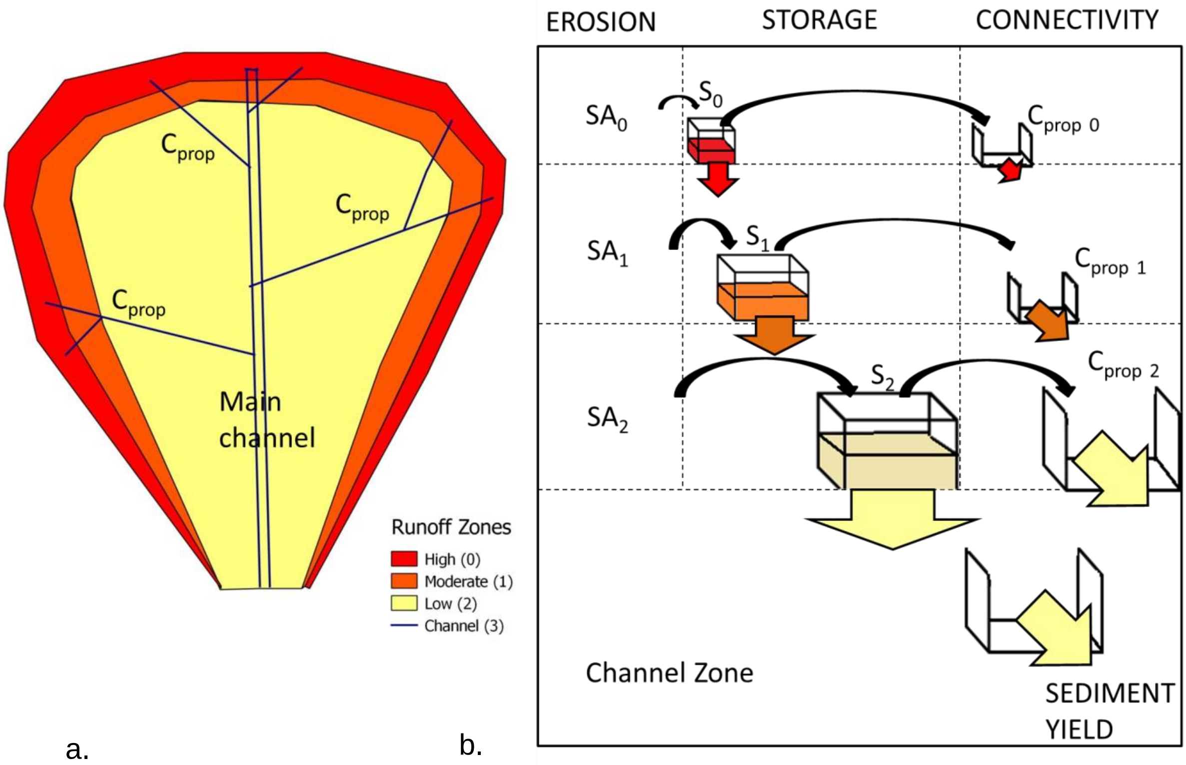


Figure 5.10 A conceptualisation of the erosion and sediment delivery model. First the daily surface flow is calculated, followed by sediment availability (equations 5.1 to 5.6). Next sediment storage and delivery is calculated for each runoff zone, channel zone and the catchment outlet (equations 5.7 to 5.10). Surface flow acts as the driving force behind both erosion and sediment delivery.

6 MODEL TESTING AND RESULTS

The erosion and sediment model was calibrated and tested for two small catchments using available long-term sediment yield data from farm dams. A limitation to using the observed data in model calibration is that the data provides only average annual sediment yields. This is a significant consideration when calibrating the model. Once the model was calibrated it was applied to a larger catchment for which long-term sediment accumulation data are available. These data are also limited in that they are available as average annual data.

6.1 Introduction

Parameters of an environmental model are typically calibrated on the basis of very limited measurements, by extrapolation from other sites or by inference by comparing observed responses with model outputs (Beven, 2009). In South Africa, optimisation is difficult due to the issue of finding consistency in parameter values in a region where the reliability and accuracy of input data is questionable (Hughes, 2004). Optimization processes tend to generate parameter values that account for errors in the data rather than the real signal. An understanding of the model and sediment system is vital in the calibration exercise to reduce these errors.

6.2 Calibration

Calibration is the process of determining whether the equations, parameters and logic give expected results (Toy et al., 2003). The first step in model testing should be running the model with default parameters using the first independent data set. Parameters should be adjusted to obtain a good fit between the model output and this first data set (Chapra, 2003). The model will be considered 'calibrated' once the simulated data are favourably compared to observed data. The model can be considered validated by using an independent data set that was not used in calibration, for instance a different time series, a different catchment or both. There are many different ways in which the similarity between the simulated and observed data can be measured or assessed. The choice of which method, and which objective functions to use to quantify the similarity will often depend on the type and availability of the observed data. As the only observed data are available as annual yield (in t km^{-2} yr^{-1}) the model results will need to be assessed against these limited data. South Africa has very limited observed sediment yield data therefore the only option available is to use the annual data available. Prediction of sediment yields in South Africa has mainly focused on sediment yield maps due to the limitations of available sediment yield data (Msadala et al., 2010). This approach has yielded a coarse prediction for sediment yield at a national scale.

A conceptual calibration procedure was followed for all three study catchments in order to determine whether the model provides logical results according to an understanding of the catchments properties as defined in Chapter 4. Table 6.1 presents the final calibrated parameters for surface flow, erosion and sediment storage and delivery estimation components for the study catchments. The determination of the parameters for these components will be described in the following sub-sections.

Table 6.1 The final calibrated parameters for the study catchments.

			Ganora	Cranemere	Nqweba
Surface flow estimation					
		Area (km^2)	2.7	57	3667.7
Runoff depth distribution[4]	**High (H)**		0.05 (5%)	0.05 (5%)	0.18 (18%)
	Moderate (M)		0.25 (25%)	0.15 (15%)	0.32 (32%)
	Low (L)		0.7 (70%)	0.8 (80%)	0.5 (50%)
Erosion estimation					
Runoff factor (R)	**D_{scale}**		16	16	4
	D_p		0.5	0.5	0.5
	D_{con}		2	2	2
Topography factor (LS)[5]	**LS_{MN}**		5	3.8	3.5
	LS_{RAN}		1	1	2
Soil erodibility factor (K)[6]	**K_{MN}**		0.3	0.3	0.3
	K_{RAN}		0.01	0.01	0.01
Cover factor (C)[7]	**C_{MN}**		0.05	0.03	0.1
	C_{RAN}		0.02	0.02	0.05
Practice factor (P)[8]	**P_{MN}**		0.8	0.8	0.8
	P_{RAN}		0.2	0.2	0.2
Sediment storage and delivery					
Maximum sediment storage (Kt)	**S_{max}**[9]	**H**	75	1500	219750
		M	1050	13500	176100
		L	5700	138000	660300

[4] The Topography factor calculation provided a LS distribution map over each catchment. This distribution was divided into three groups, and the proportional distribution of each group was calculated to provide the runoff depth distributions.
[5] Refer to LS raster map
[6] Refer to Tables 5.1 & 5.2
[7] Refer to Tables 5.3
[8] Refer to Table 5.4
[9] Refer to Table 6.5

			Ganora	Cranemere	Nqweba
		Channel	6	110	14700
Sediment connectivity	C_{prop}	**H**	0.1	0.1	0.1
		M	0.5	0.5	0.5
		L	0.5	0.5	0.5
DD[10]			0.29	0.13	0.27
Starting sediment store			0.015	0.01	0.02
Storage ratio			0.8	0.8	0.8
Threshold flow (mm.hr^{-1}) for delivery			0.5	0.6	0.5

6.2.1 Surface flow estimation

The disaggregated Pitman model monthly flows provided mean daily flow estimates which were further separated into surface, interflow and groundwater components based on regionalised separation parameters that are used within the month to daily disaggregation model (Slaughter et al., 2014) (Table 6.2). No attempts were made to calibrate the Pitman model or the disaggregation model parameters in this study as there are no observed flow data available to perform such a calibration. It was therefore necessary to assume that the simulated monthly and disaggregated daily flows (based on previous regional assessments such as Midgley et al., 1994) are acceptably representative of the stream flow conditions within the study catchments. Unfortunately, this assumption cannot be tested, a typical problem in data scarce areas.

Table 6.2 The mean daily rainfall input and mean daily flow output from the disaggregated Pitman model.

Catchment (area km^2)	Time series	Mean Annual Rainfall (mm.yr^{-1})	Mean flow (mm.yr^{-1})			
			Total	Interflow	Groundwater	Surface
Ganora (2.7)	1901-2003	327.4	15.5	2.6	1.2	11.7
Cranemere (57)	1901-2004	308.8	23.5	3.0	1.1	19.4
Nqweba (3 668)	1900-1999	329.6	9.4	1.7	1.1	6.6

[10] Refer to Table 6.5

Figure 6.1 provides the simulated daily stream flow duration curves (standardised by dividing by catchment area) indicating characteristics that are typical of semi-arid catchments; including relatively long periods of zero, or near zero flow, together with steep curves in the higher flow parts of the frequency distribution ("flashy" catchment responses).

The runoff depth distribution estimates (Table 6.1) were calculated by determining the distribution of steep areas around the catchment boundary, less steep foothill areas and the flatter valley bottom areas. As the topography factor is dependent on slope gradient and flow accumulation it was used to calculate the runoff depth distribution. The topography factor was distributed into high, moderate and low distributions which coincided with runoff depth distributions (Q_H: High runoff zone; Q_M: Moderate runoff zone; Q_L: Low runoff zone). All catchments had the highest proportion of runoff depth distribution occurring in the low runoff zone, or flatter valley bottom areas (Figure 6.2). These distributions act as inputs to the runoff factor part of the erosion model (Equation 5.3) along with surface flow (Q_{sf}) which is an input from the hydrological model. The final calibrated parameters for the surface flow component in the model are presented in Table 6.1.

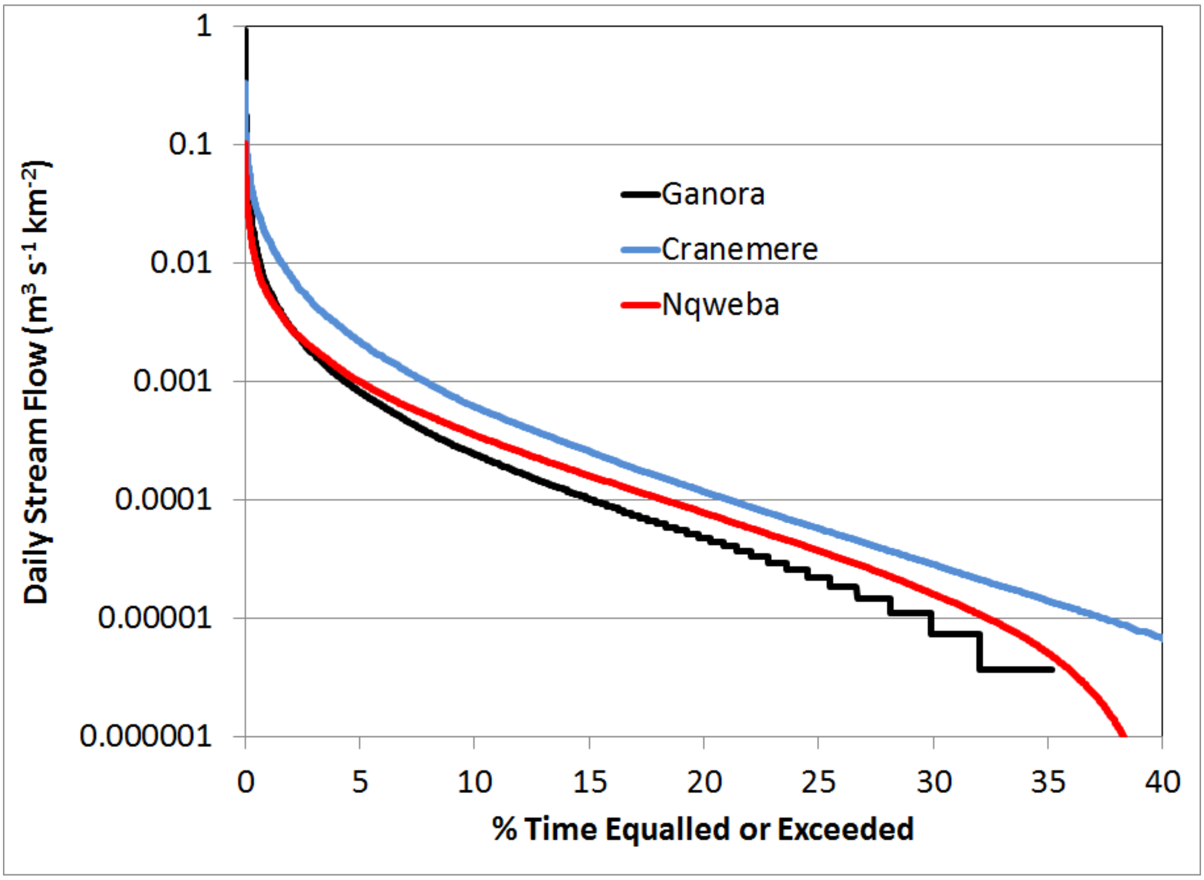
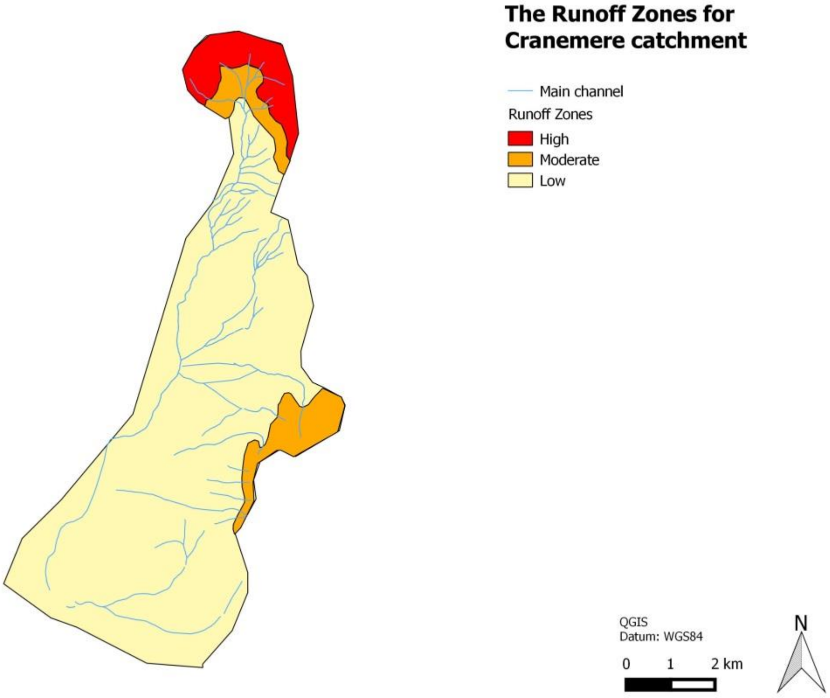
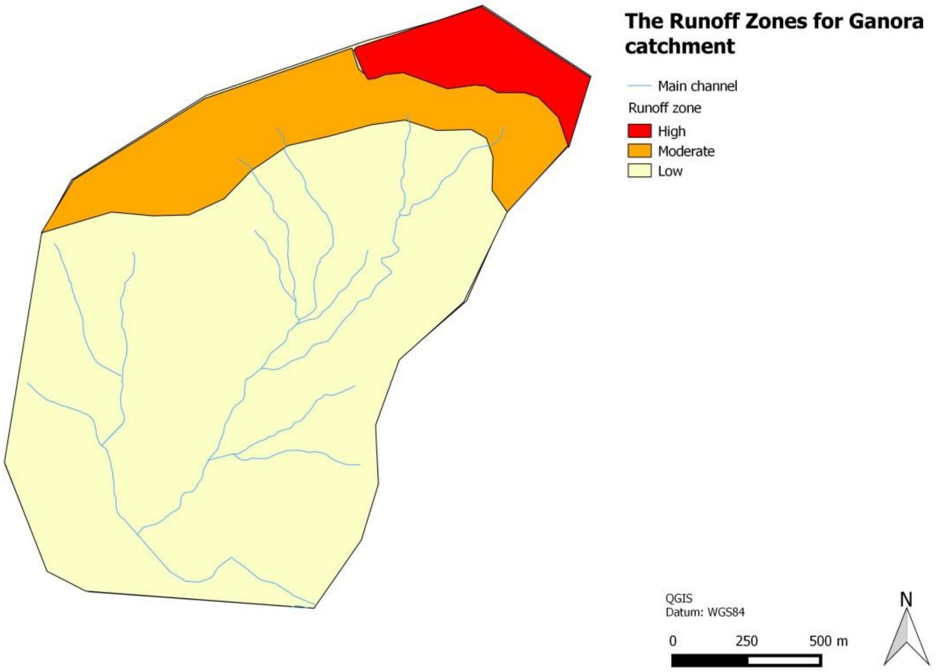


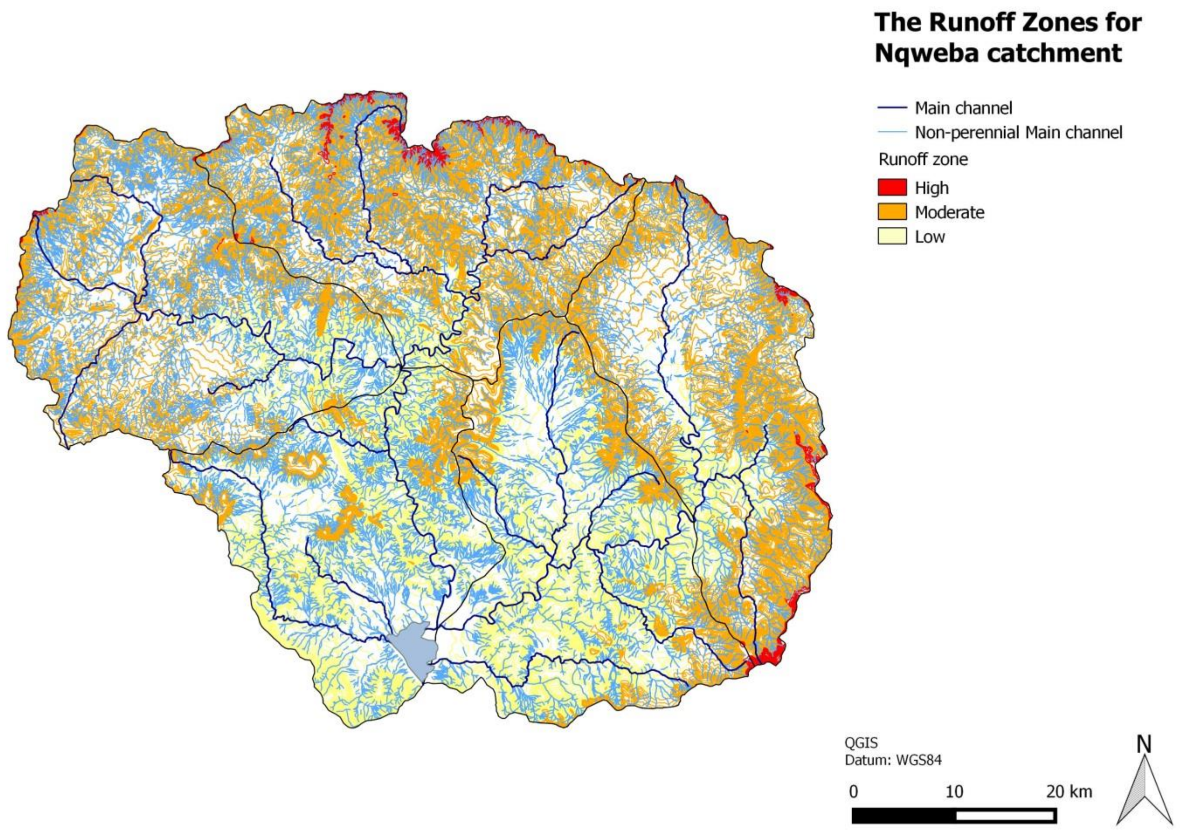
Figure 6.1 Standardised (by catchment area) daily stream flow duration curves for the three study catchments.


The Runoff Zones for Cranemere catchment
Main channel
Runoff Zones
High
Moderate
Low
QGIS
Datum: WGS84
0 1 2 km
N

a.


The Runoff Zones for Ganora catchment
Main channel
Runoff zone
High
Moderate
Low
QGIS
Datum: WGS84
0 250 500 m
N

b.



c.

Figure 6.2 The runoff zones and main channels for Ganora (a) Cranemere (b) catchments and runoff zones for Nqweba (c) catchment.

6.2.2 Erosion estimation

Erosion parameters are the most important determinants of the model as they provide the daily estimates for the amount of sediment available to be transported or stored. The final calibrated parameters for the erosion component of the model are provided in Table 6.1.

6.2.2.1 Runoff factor

The runoff factor part of the erosion model (Equation 5.2) relies on the estimation of the daily depth of runoff (Equation 5.3) and peak flow (Equation 5.4 and 5.5); as well as the area of a catchment. The surface flow estimation provides the input to Equation 5.3 in the form of the fraction of the catchment in each runoff zone (High, Moderate, Low: Table 6.1); and the depth of surface flow (Q_{sf}: input from the hydrological model).

The D_{scale}, D_p and D_{con} parameters are used to estimate the storm duration from the surface runoff volume, which is then used to calculate the peak instantaneous flow during any single day, which is required by the erosion estimation model (Equation 5.4). The current format of the equation is scale dependent as it uses absolute values of the surface runoff volume. This accounts for the much smaller value used for the Nqweba catchment. The parameter values given in Table 6.1 result in short durations of less than 4 hours for all but the highest daily flows in the very small Ganora catchment. The durations for the other two catchments are quite similar ranging from over 20 hours for very high flows, but dropping to 4 hours and less for flows that are exceeded more than 5% of the time. In the absence of short-interval runoff observations, establishing appropriate values for these parameters becomes a very uncertain process that will affect the peak values used in the erosion model and therefore the simulated erosion values.

6.2.2.2 Topography factor

The topography factor distribution for a catchment can be estimated using inputs from flow accumulation and slope data from ArcGIS (Figure 6.3) as inputs to Equation 5.6. A Digital Elevation Model (DEM) is created from contour data by interpolation via the TopoToRaster tool in ArcGIS. This provides the input necessary for the hydrological toolset in ArcGIS to determine flow accumulation and slope for each catchment. This data is then opened as excel worksheets and the topography factor is calculated as a separate worksheet by using Equation 5.6. It is important to note that calculations in excel use radians instead of degrees so the slope worksheet needs to be transferred into radians before logical calculations can begin. The final topography factor worksheet is saved as a text file in order to be loaded back into ArcGIS as a new shape file. The mean and variance of the topography factor are determined from this file (Figure 6.4).

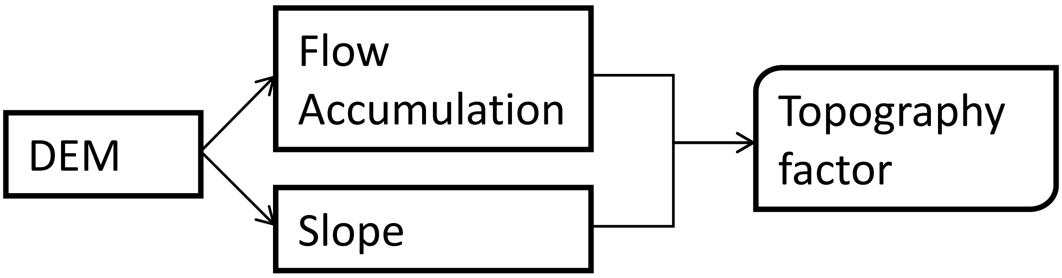
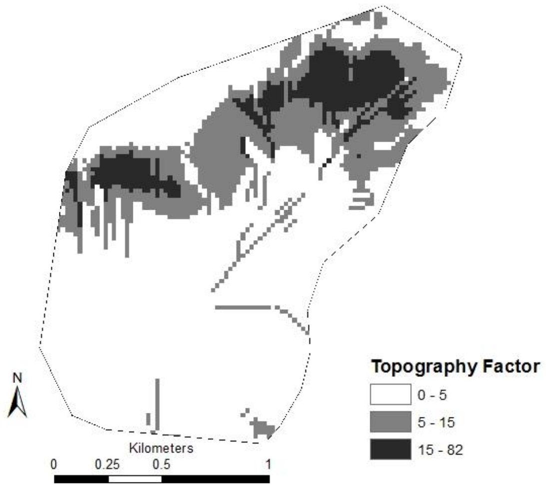
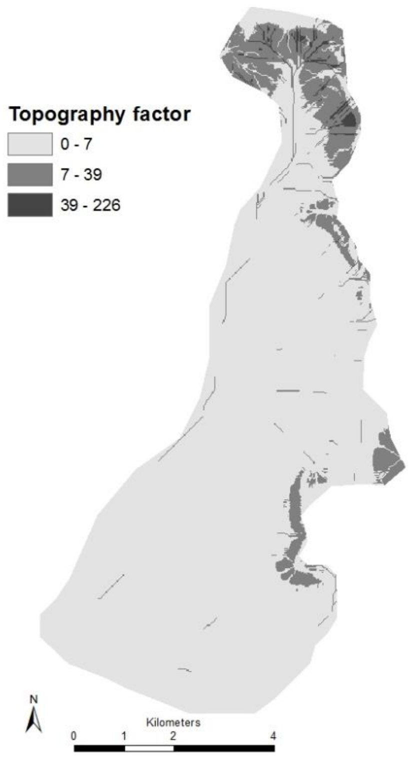


Figure 6.3 The determination of the inputs for Equation 5.6.

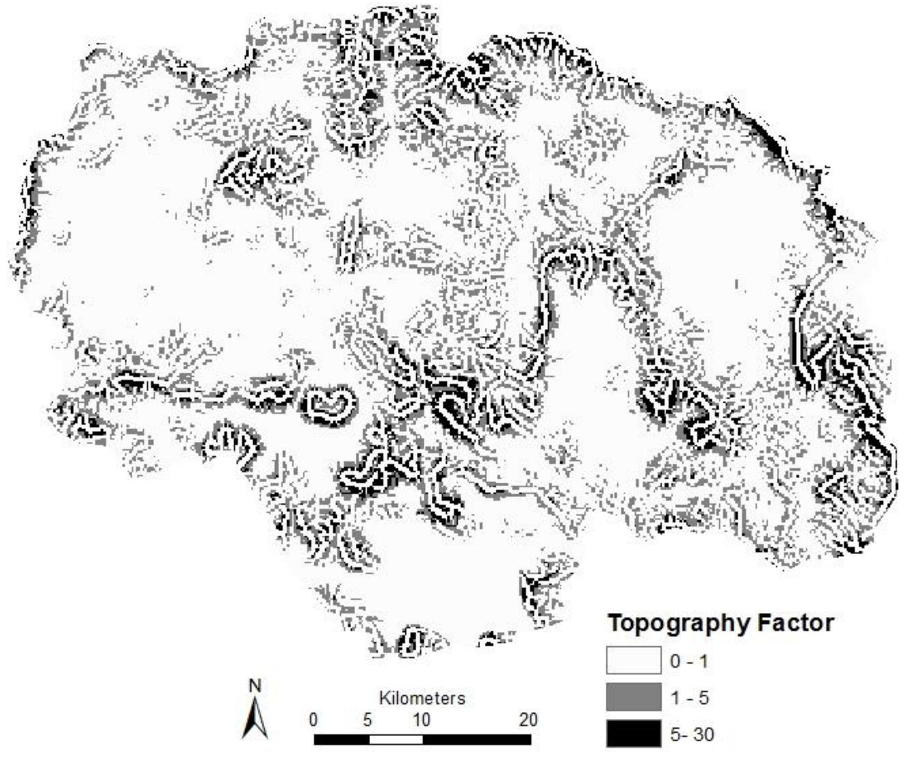
The topography factor is an important parameter as it is closely related to the runoff factor. A high topography factor is indicative of a high energy catchment, resulting in a higher sediment yield and lower storage capacity, all other factors being equal. As the Nqweba catchment is much larger there is more variation in the topography factor (Table 6.1).



a.



b.



c.

Figure 6.4 The topography factor for the Ganora (a); Cranemere (b) and Nqweba (c) catchments.

6.2.2.3 Soil erodibility factor

The land type distribution for South Africa was obtained from the Agricultural Research Council- Institute for Soil, Climate and Water (ARC-ISCW, 1972-2006). For a particular land type the top layer of soil is classified as a particle size which, when referring to Table 5.1 allows for the soil erodibility to be determined. Once each land type and its corresponding soil erodibility factor are identified it is then possible to determine the distribution of soil erodibility over the catchment. This allows for the mean and range of the soil erodibility factor in the catchment to be determined. For the study catchments there is limited variation in K, as the soil data for all of the catchments suggest soils with Sandy Loam to Fine Loamy Sand with limited organic content. This is indicative of a moderate soil erodibility factor for all study catchments (Table 6.1). The soil type is difficult to analyse via a desktop study and it is probable that there is much higher spatial variability of soil types in the catchments.

6.2.2.4 Cover factor

The vegetation type distribution for South Africa was obtained from the South African National Biotic Institutes Biodiversity GIS resource (SANBI, 2007). The SANBI vegetation types identify the types of vegetation to be expected within the catchments (as defined in section 4.2.1). As this is a coarse scale interpretation of vegetation cover, it is necessary to refer to a Google earth image to determine the actual vegetation characteristics. The interpreted vegetation cover with reference to Table 5.3 provides the mean cover factor. In general it was considered that the Karoo has poor to moderate vegetation cover, producing a cover factor estimate of around 1. During model calibration the Ganora and the Cranemere datasets produced much high erosion estimates than sediment delivery. This was considered unrealistic as it presented a very unstable model over the long term. The calibrated cover factors were therefore adjusted in order to reduce erosion estimates (Table 6.1).

6.2.2.5 Practice factor

There was assumed to be very small variations in the effects of land use practice on soil erosion as there is no evidence of erosion mitigation measures within the catchments (Table 6.1). A mean value of 0.8 with a variance of 0.2 was assumed for all catchments to allow for the impact of erosion mitigation practices to be present in the time series.

6.2.3 Sediment storage and delivery estimation

Sediment mass from the erosion model enters the “sediment cascade” and may either go into storage within the catchment or be removed from the catchment at the catchment outlet. The maximum storage capacity for each runoff zone as well as for the main channel (Equation 5.7) and the proportion of gully or channel storage (Equation 5.8) are components of the sediment cascade calculations. Sediment is added to the three slope storage zones in each time interval (Equation 5.9) and the sediment output from each storage component (both slope and channel) is calculated with Equation 5.10. The final calibrated parameters for sediment storage and delivery component of the model are provided in Table 6.1.

According to Equation 5.7, maximum sediment storage capacity was estimated by multiplying the area, bulk density and maximum assumed depth of sediment for each zone and the main channel (Table 6.3). These calculations were estimated as follows:

Area:

- The area of each runoff zone was calculated by multiplying the proportion of the total catchment area covered by each runoff zone (using the topography factor distribution) by the total catchment area.
- The area of the channel zone was calculated by multiplying the length of the main channel by the width of the main channel. The length of the main channel was calculated in ArcGIS by digitizing the channel through the use of satellite imagery. The channel length was then calculated with the use of a geometry tool in ArcGIS. Google Earth imagery was used for measuring the average width of the main channel. Google Earth represents a useful source of positional data that can be used for investigation and preliminary studies with suitable accuracy and low cost. Google Earth uses the WGS84 datum, the resolution of the 2014 imagery was 1256x730. The main channel width was compared to satellite imagery in ArcGIS.

Bulk density:

- The sediment present in all catchments was defined as sandy loam. According to the literature sandy loam has an average bulk density of 1.5 $g.cm^{-3}$ (Bulk Density: Saxton et al., 1986). Data from site visits confirmed this value as 1.4 $g.cm^{-3}$ at the Cranemere catchment (N=29; SD= 0.2421) and as 1.0 $g.cm^{-3}$ at the Ganora catchment (N= 84; SD= 0.1418).

Depth of sediment:

- The depth of sediment was calculated through field visits to Cranemere and Ganora catchments. These field visits, with reference to Foster and Rowntree (2012) for the Cranemere catchment and Rowntree and Foster (2012) for the Ganora catchment, provided estimates for expected depth of sediment in each zone and the main channel (as listed in Table 4.1).

On the basis of the assessment of the topography, all catchments have the highest maximum storage in the low runoff zone, with the high runoff zone and channel having the lowest maximum storage (Table 6.3).

Table 6.3 The components to calculate the maximum storage capacity for runoff zones and the main channel in the Ganora, Cranemere and Nqweba catchments.

		Ganora	Cranemere	Nqweba
Catchment area (km^2)		2.7	57	3667.7
Channel length (m)		0.00077	0.0073	0.984
Channel width (m)		5	10	10
Drainage density (channel length / catchment area)		0.29	0.13	0.27
Runoff zone area in km^2 (% of catchment)	**High (H)**	0.1 (5%)	2 (5%)	660(18%)
	Moderate (M)	0.7 (25%)	9 (15%)	1174 (32%)
	Low (L)	1.9 (70%)	46 (80%)	2201 (50%)
	Channel (Ch)	0.004 (0.15%)	0.073 (0.12%)	9.8 (0.27%)
Runoff zone area (m^2)	**H**	100000	2000000	660000000
	M	700000	9000000	1174000000
	L	1900000	46000000	2201000000
	Ch	4000	73000	9800000
Maximum depth of sediment (m)	**H**	0.5	0.5	0.5
	M	1	1	1
	L	2	2	2
	Ch	1	1	1
Bulk density (g.cm^{-3})		1.5	1.5	1.5
Maximum sediment storage (Kt)	**H**	75	1500	219750
	M	1050	13500	176100
	L	5700	138000	660300
	Ch	6	110	14700

According to Equation 5.8, the drainage density and proportion of each runoff zone with gully/connectors needed to be estimated. These calculations were estimated as follows:

Drainage density:

- The drainage density is the total length of all the channels in a catchment divided by the total area of the catchment. The drainage density for each catchment was determined by dividing the catchment length (as calculated for Equation 5.7) by the catchment area.

Gully/connectivity proportion:

- Each runoff zone is expected to have a proportion of smaller channels or gullies which increase the connectivity of each zone with the proceeding runoff zone and the main channel.
- The estimation of the connectivity of each runoff zone was determined through field visits to the Cranemere and the Ganora catchments as well as through consultation of the relevant literature (Foster and Rowntree (2012) and Rowntree and Foster (2012)).
- A "switch" in connectivity was afforded through manipulation of the gully/connectivity proportions according to relevant scenarios. This, as well as other possible scenarios for a change in connectivity, are described in more detail below:

According to Rowntree & Foster (2012), the Ganora catchment had a change in connectivity in 1967 when a badland area was connected to the main drainage network, thereby increasing sediment yield. Similarly in the Cranemere catchment there was a change in connectivity in 1950 when floodouts were reworked and connectivity to stored sediment was increased (Foster & Rowntree, 2012). Foster et al. (2012) noted that although the timing of major increases and the peak sediment yields for the Ganora and Cranemere catchments are different, there are identifiable trends in sedimentation. Four hypotheses were proposed to explain this pattern of sediment yield. These related to both anthropogenic land use change as well as natural factors of climatic change and intrinsic geomorphological change. The proposed hypotheses are outlined in Table 6.4).

Table 6.4 The proposed hypotheses by Foster et al. (2011) to explain the pattern of sediment yield in the Cranemere and Ganora catchments.

<table>
<tr><th colspan="2">Hypothesis:</th><th>Relates to:</th></tr>
<tr><td>1</td><td>High sediment yield is related to overstocking, but the temporal pattern of sediment yield reflects a lag effect as proposed by Archer (2000).</td><td rowspan="2">Change in vegetation cover</td></tr>
<tr><td>2</td><td>Increased sediment yield in the mid-20th Century was due to the introduction of cultivation.</td></tr>
<tr><td>3</td><td>Increased sediment yield from the mid-20th Century was due to changes in weather patterns that have resulted in increased rainfall energy, greater erosivity and flooding.</td><td>Inherent variation in sedimentation as a result of rainfall</td></tr>
</table>

4	Increased sediment yield from the mid-20th Century is due to changes in connectivity between sediment sources and the dam.	A change in connectivity between sediment sources and the catchment outlet

These conditions (Table 6.4) may be represented through three possible scenarios:

Scenario 1: No parameter changes representing hypothesis three.

Scenario 2: A decrease in vegetation cover after 1950 representing hypotheses one and two.

Scenario 3: An increase in catchment connectivity after 1950 representing hypothesis four.

In order to emulate the change in sediment yield of the 1950s it was necessary to adjust parameter values accordingly. Parameter adjustments impacted the erosion and/or sediment storage and delivery component of the model. These adjustments will be assessed for the Ganora and Cranemere catchments.

The Nqweba catchment posed a unique challenge owing to its much larger size in comparison to the Ganora and Cranemere catchments. The model was also tested for this catchment with adjusted parameters by relying on lessons learnt from the smaller catchments.

6.3 Model testing

During model interpretation the model outputs using the calibrated parameters were loaded into a Microsoft Excel Spreadsheet (Appendix A; represented in Table 5.6) in order to compare with observed annual sediment yields. It is important to note that the observed data were based on very infrequent observations, whilst the simulated results were based on continuous daily modelling. This is why the observed data are represented by points in comparison to simulated data. The daily simulation results were aggregated to annual totals to facilitate comparison with the observed data. The best model fit was determined by comparing observed annual sediment yield with cumulative modelled sediment delivery. The cumulative modelled erosion estimates were included in this comparison to check whether erosion was either over- or under-estimated. Similar erosion estimates to the observed sediment yield indicates an underestimation of erosion. The under- or over-estimation of erosion or sediment delivery indicates potential structural constraints within the model. By referring to the properties of semi-arid catchments identified in Chapter four (Table 4.1) it was possible to identify key features of the model.

The change in connectivity or “switch” conditions for each catchment were tested through the three scenarios as described in Section 6.2.3 as follows (Table 6.5):

Scenario 1: Fixed parameters, with the assumption that connectivity was low to represent no change.

Scenario 2: Decreasing the cover factor from 1967 to 2003 for the Ganora catchment and 1950 to 2004 for the Cranemere catchment

Scenario 3: Increasing the connectivity parameters from 1967 to 2003 for the Ganora catchment and 1950 to 2004 for the Cranemere catchment.

Scenarios 2 and 3 were incorporated into the model by running it twice, with different parameters for each model run. The two time series were then merged. This provided a time series with both model runs incorporated.

Table 6.5 The parameters used to test the Foster et al. (2011) hypotheses for increased sediment yield in the latter half of the century for the Ganora and Cranemere catchments.

Scenario	Parameter	Ganora		Cranemere	
		1901-2003	1901-1967	1901-1950	1901-1950
1	N/A	Refer to Table 6.1; assume low connectivity i.e. C_{prop}=0.1			
2	C_{MN}	0.5	0.8	0.3	0.5
	C_{Range}	0.02	0.02	0.02	0.02
3	C_{prop} (H)	0.1	0.1	0.1	0.1
	C_{prop} (M)	0.1	0.5	0.1	0.5
	C_{prop} (L)	0.1	0.5	0.1	0.5
	Threshold flow ($mm.hr^{-1}$) for delivery	0.8	0.5	0.8	0.6

Initial testing with a high cover factor (to be expected in Karoo catchments) achieved calibration of sediment yield but erosion estimation was considered too high. Having such extreme erosion would result in an unstable model as when extended over long periods the large stores of sediment would inevitably be released into the catchment outlet, causing an extreme peak in sediment yield. The cover factor was reduced in order to decrease erosion (a high cover factor relates to low cover density and a low cover factor relates to high cover density). This effectively reduced the erosion in both the Ganora and Cranemere datasets.

6.3.1 Ganora dataset

The hypotheses for a change in sediment yield after 1950 for the Ganora catchment were tested by following the methods described above in three different scenarios (Table 6.5). As described above, in model runs with a high cover factor the erosion model produced much higher sediment yield than sediment delivery at the catchment outlet (Figure 6.5). This was considered unrealistic therefore the cover factor was reduced in order to reduce erosion.

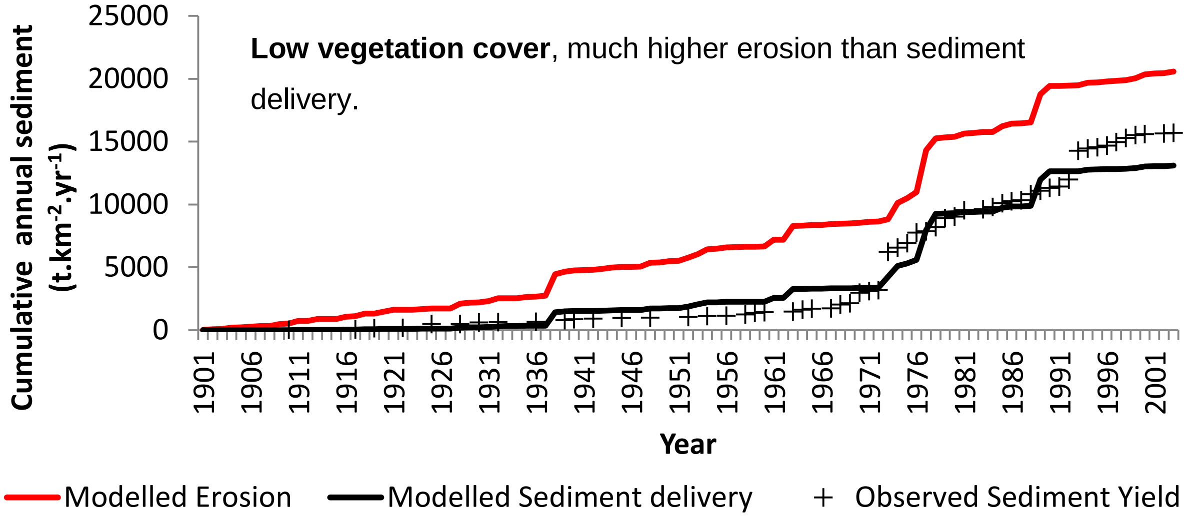


Figure 6.5 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Ganora dataset with low vegetation cover.

Scenario 1:

Running the model with "no change" to parameters throughout the time series provided cumulative annual modelled sediment delivery and erosion which were well correlated to cumulative annual observed sediment yield (Table 6.6 and Figure 6.7). Notable trends were seen in the stepped observed sediment yield, whereby the sediment yield increased significantly in the latter half of the time series after the 1970s. The erosion and sediment delivery estimates followed this trend, and included steps in the 1930s aswell. An increased sediment yield in the latter half of the century was evident in the cumulative annual observed sediment delivery, but the cumulative annual modelled sediment delivery was higher than cumulative annual observed sediment yield for most of the time series (Figure 6.6). This is indicative of rainfall being an important driver for the observed increase in sediment yield in the latter half of the century, but that other variables were also important in emphasising this increase.

Scenario 2:

The model was first run with the calibrated cover factor (Table 6.5 and Figure 6.8a) and then run with a low cover factor (Table 6.5 and Figure 6.8b). The outputs from 1967 to 2003 for the second model run were merged into the first model run to produce a new time series (Figure 6.8c). This new time series represented a "decreased vegetation cover" scenario in the latter half of the century. This resulted in cumulative annual sediment delivery estimates being better correlated to cumulative annual observed sediment yield than what it would have been had there been no change (Table 6.6 and Figure 6.9). Changing the vegetation cover had the largest impact on erosion as the adjusted parameters impacted directly on the erosion component of the model. The decrease in vegetation cover increased both erosion and sediment delivery as the sediment delivery component is dependent on the erosion component of the model to provide available sediment. The sediment delivery estimates seemed to follow a similar trend as the observed sediment yield, but from the 1990s the sediment delivery estimates are lower than observed sediment yield.

Scenario 3:

To represent a "change in connectivity" the model was first run with low connectivity and high threshold flow for delivery (Table 6.5 and Figure 6.10a) and then run with high connectivity and low threshold flow for delivery (Table 6.5 and Figure 6.10b). The change in threshold flow for delivery was incorporated due to the perceived influence of badlands. Badlands have a low threshold flow for delivery due to the land being heavily degraded. Given that post-1967 the badlands to the east of the Ganora catchment were connected to the main channel, it may be assumed that the threshold flow decreased too. The outputs from 1967 to 2003 from the second model run were merged into the first model run to produce a new time series (Figure 6.10c). This new time series represented an "increased connectivity" in the latter half of the century. Similarly to scenario 2, the sediment delivery estimates seemed to follow the observed sediment yield trend, missing the trend from the 1990s.

Cumulative annual sediment delivery estimates had a similar correlation to cumulative annual observed sediment yield as the other scenarios (Table 6.6 and Figure 6.11). Adjusting the connectivity of the catchment did not have an impact on erosion estimation. The modelled cumulative annual sediment delivery during 1967 to 2003 was better correlated to observed cumulative annual sediment yield. The increased connectivity meant that there were more sediment delivery events as the catchment became more active.

Table 6.6 The correlation of modelled outputs with observed sediment yield for the Ganora dataset.

	Correlation (R^2) of cumulative annual yields		Correlation (R^2) of annual yields
	Sediment delivery vs Observed sediment yield	Erosion vs Observed sediment yield	Sediment delivery vs erosion
No Change	0.955	0.932	0.900
Decreased vegetation	0.965	0.956	0.902
Increased connectivity	0.967	0.932	0.870
"disconnected" (1901-1967)	0.903	0.952	0.945
"connected" (1967-2003)	0.941	0.912	0.897

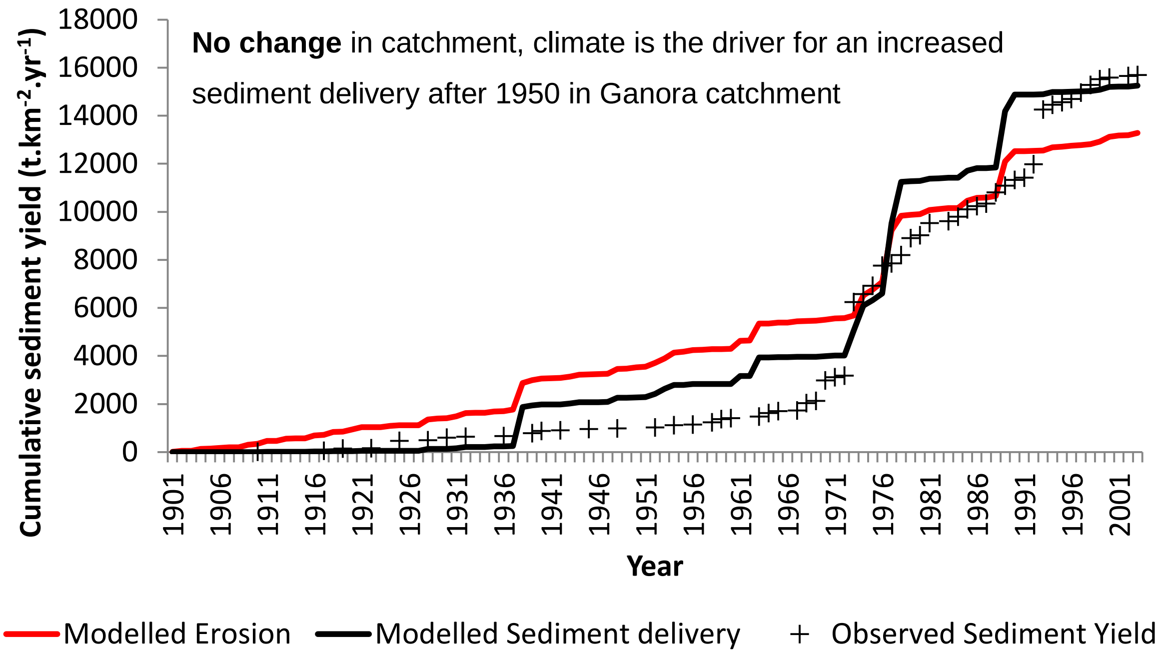
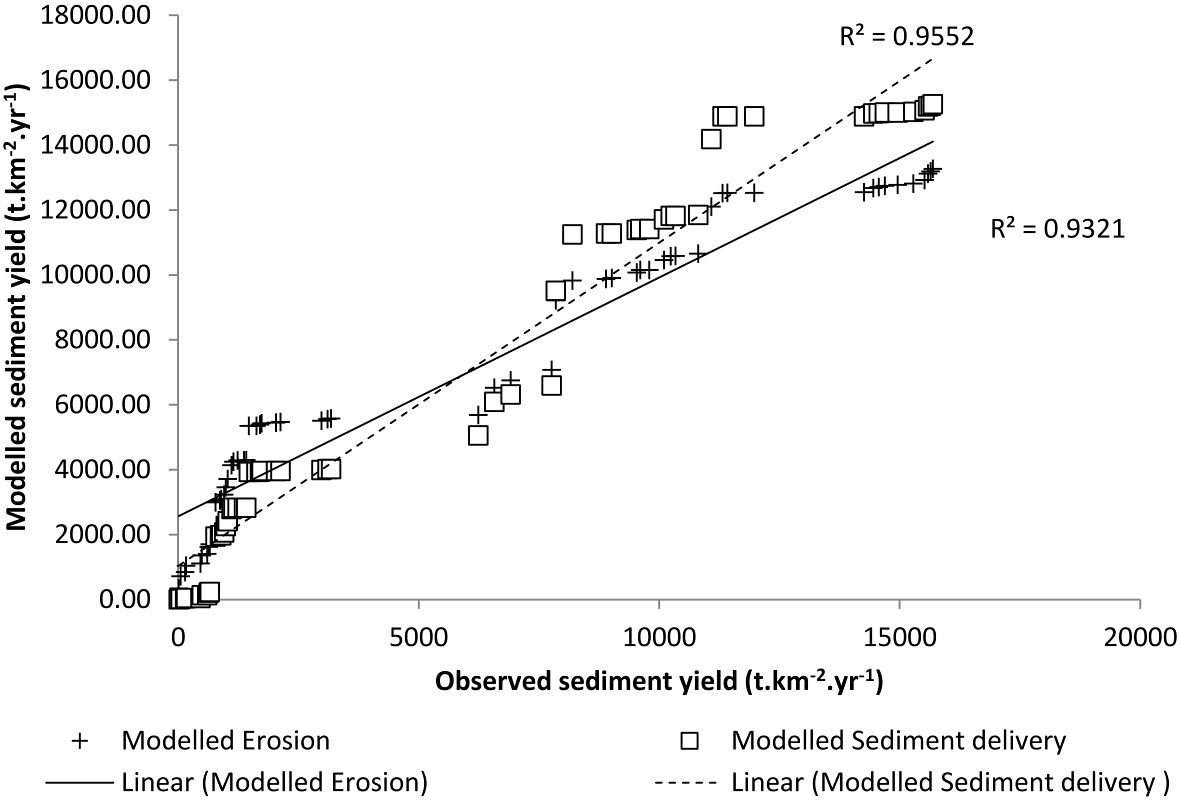
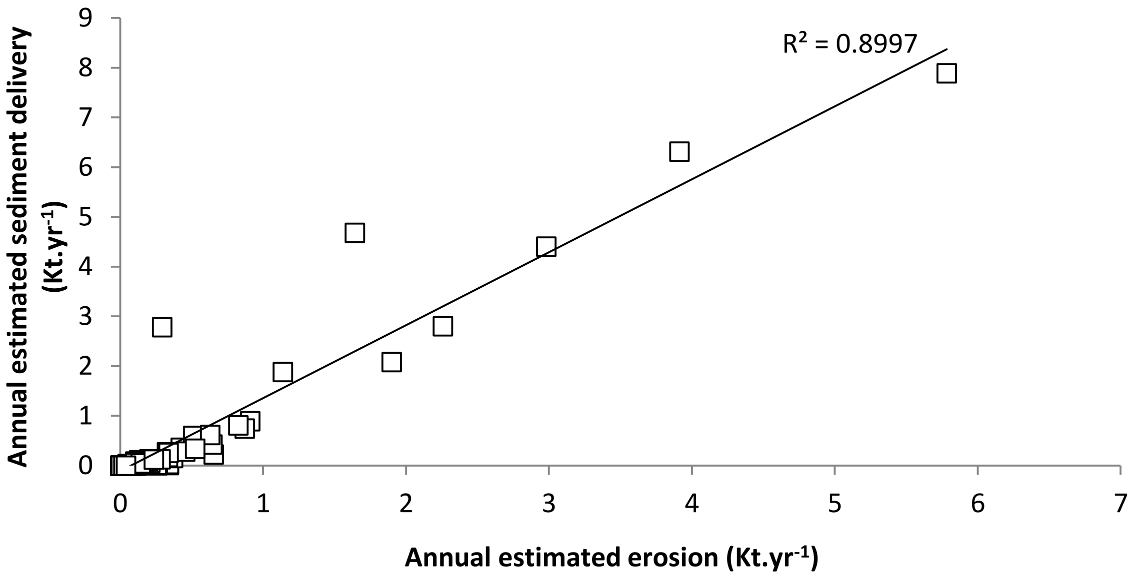


Figure 6.6 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Ganora dataset testing Scenario 1.



a.



b.

Figure 6.7 The correlation of annual modelled sediment delivery to annual modelled erosion (a) and the correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield (b) for the Ganora dataset testing Scenario 1.

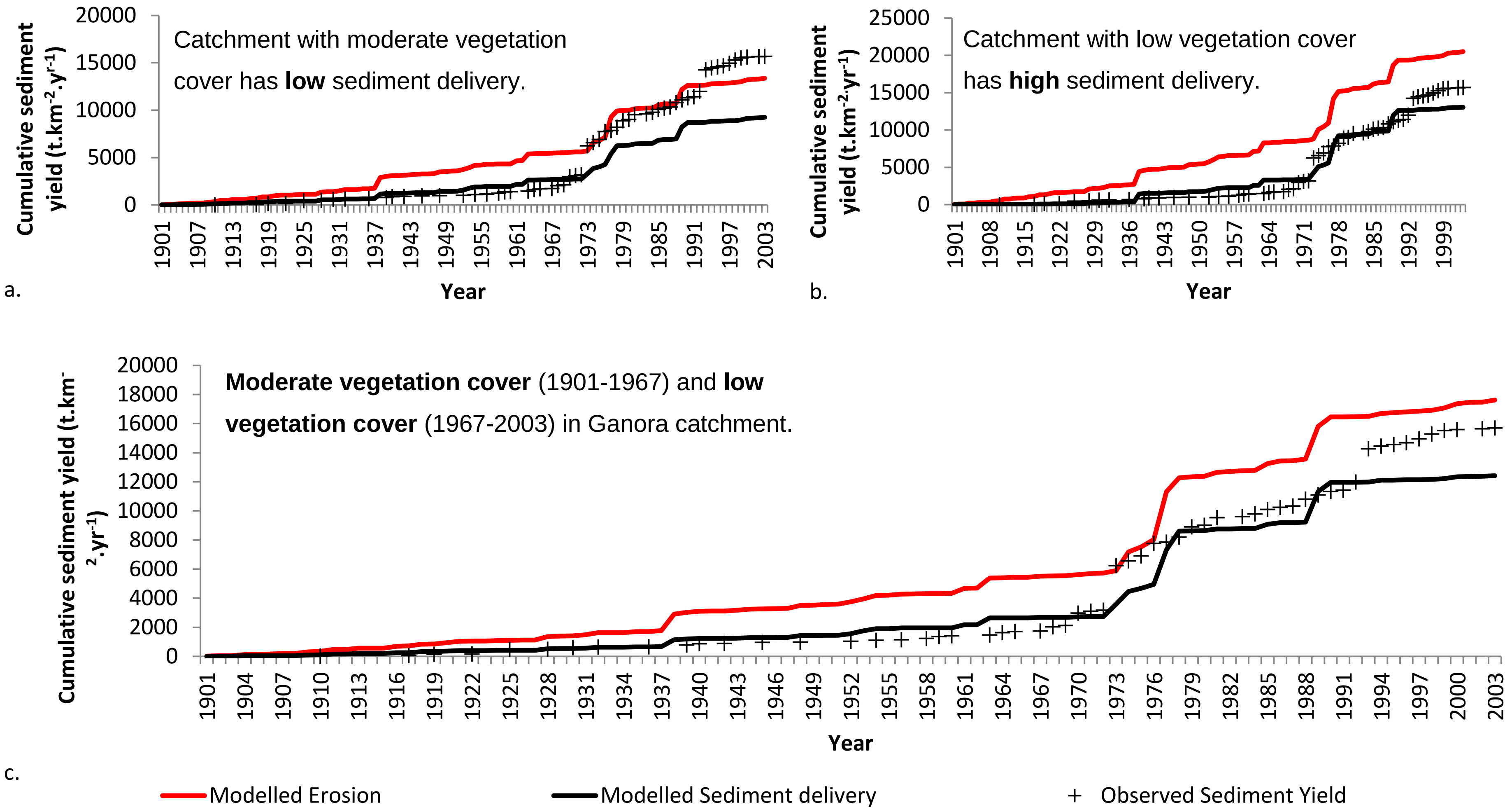


Figure 6.8 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Ganora dataset testing Scenario 2.The model was first run with the calibrated vegetation cover (C=0.05) (producing outputs for a) and then the model was run with a low cover factor (C=0.8) (producing outputs for b). The model outputs from (b) were merged with (a) to produce outputs for (c).

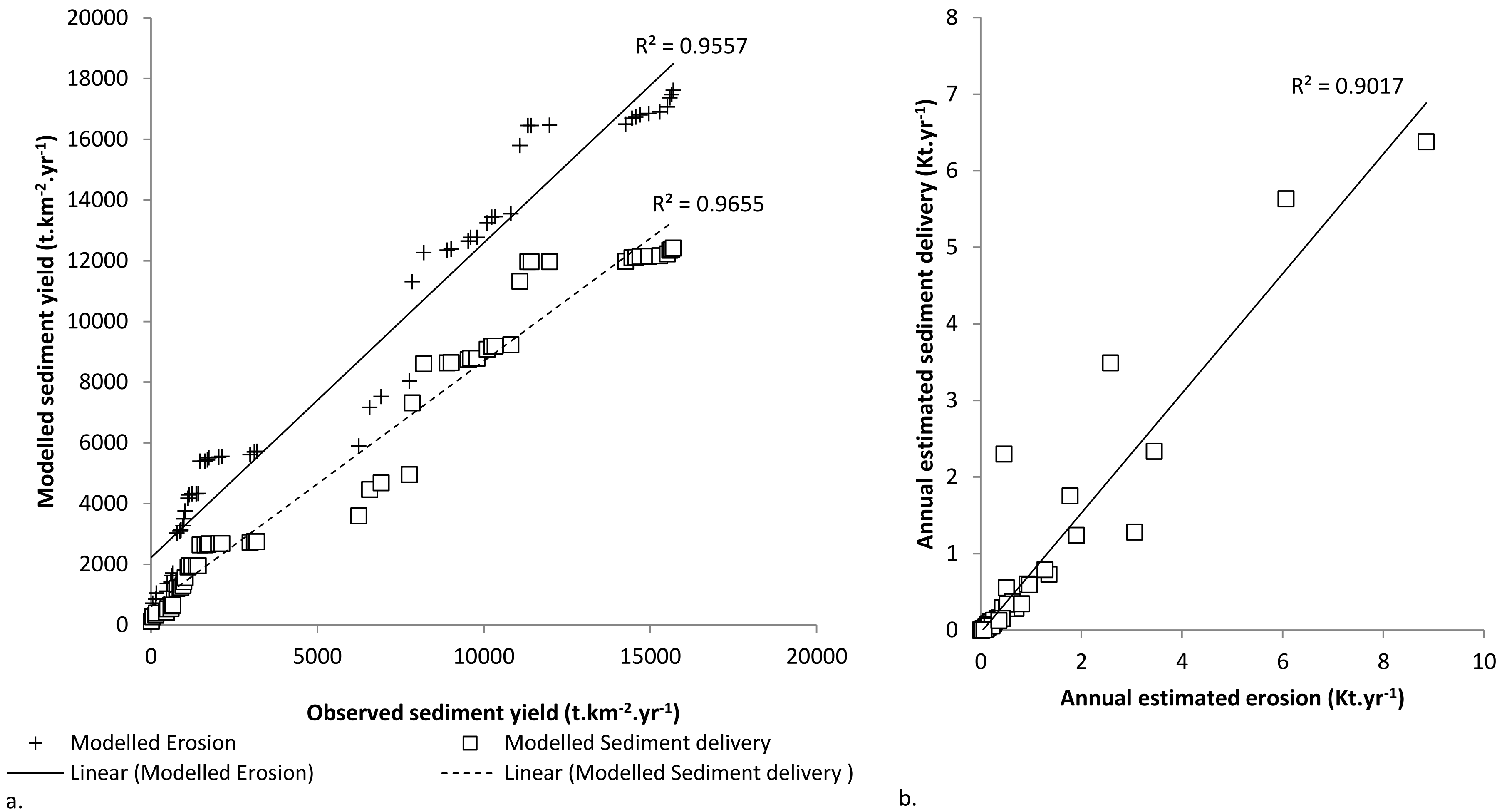


Figure 6.9 The correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield (a) and the correlation of annual modelled sediment delivery to annual modelled erosion (b) for the Ganora dataset testing Scenario 2.

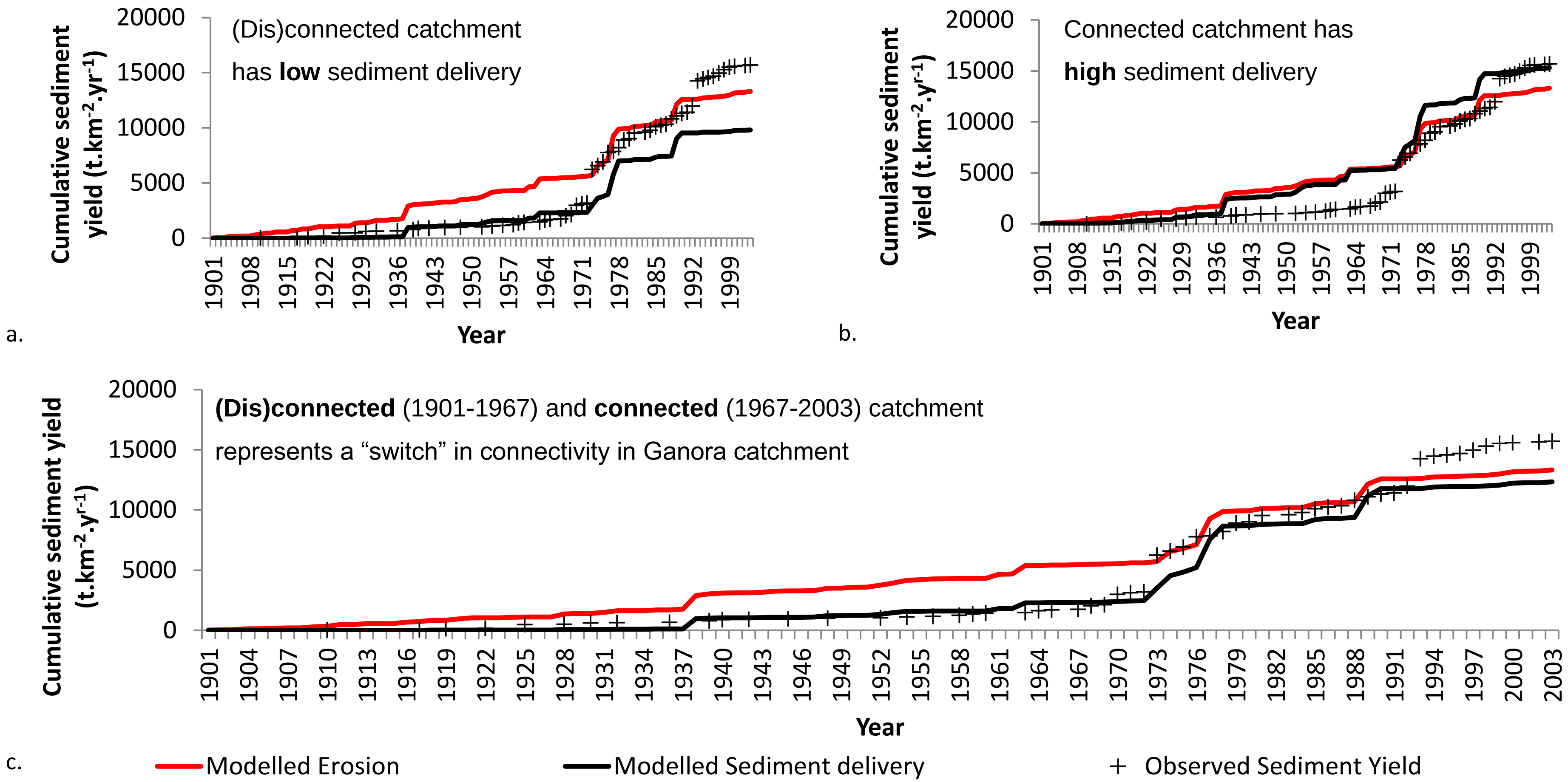


Figure 6.10 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Ganora dataset testing Scenario 3.The model was first run with low connectivity parameters (producing outputs for a) and then the model was run with increased connectivity parameters (producing outputs for b). The model outputs from (b) were merged with (a) to produce outputs for (c).

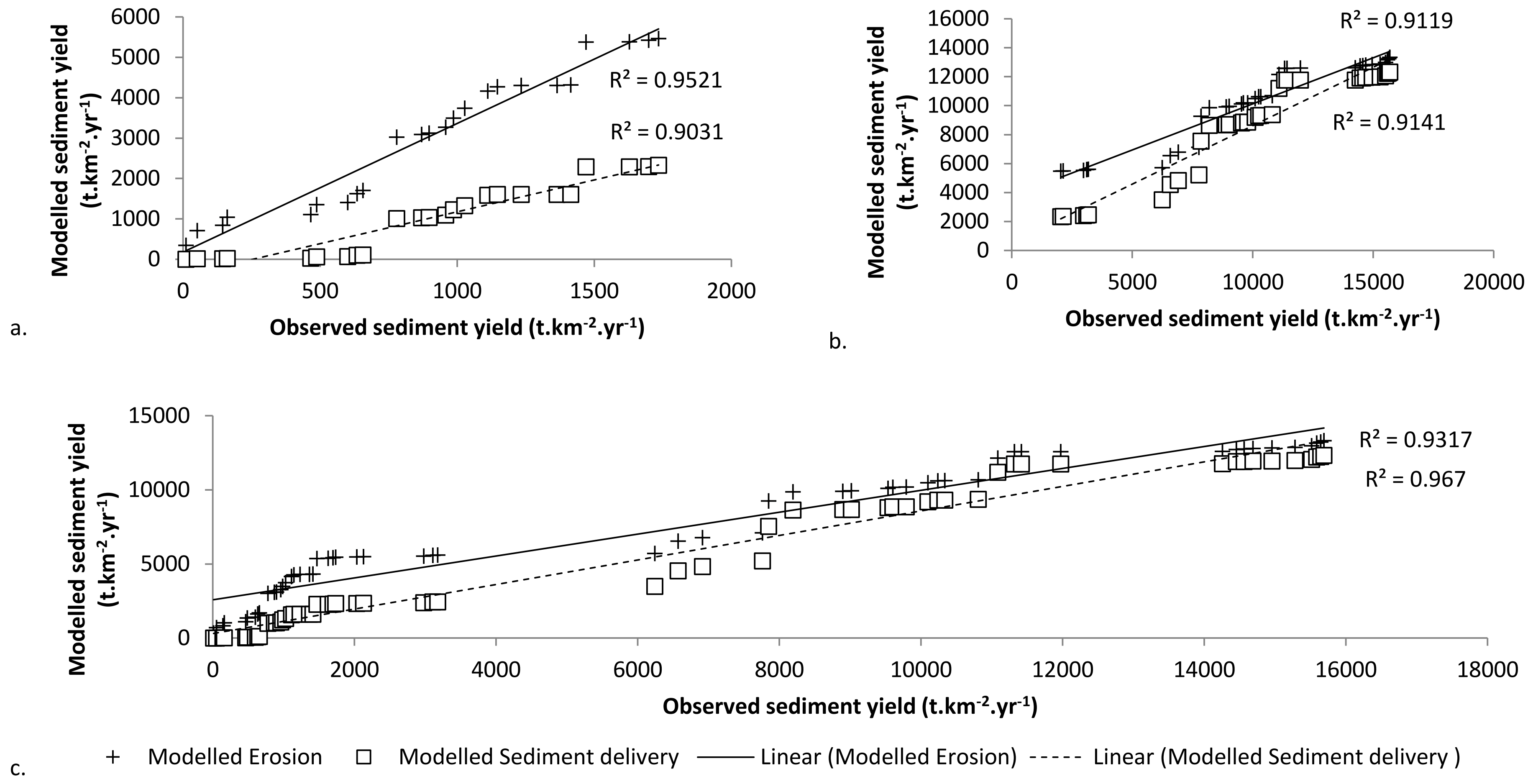


Figure 6.11 The correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield from 1901 to 1967 (a), from 1967 to 2003 and from 1901 to 2003 for the Ganora dataset testing Scenario 3. Modelled sediment delivery and erosion estimates are better correlated before the "switch" in connectivity.

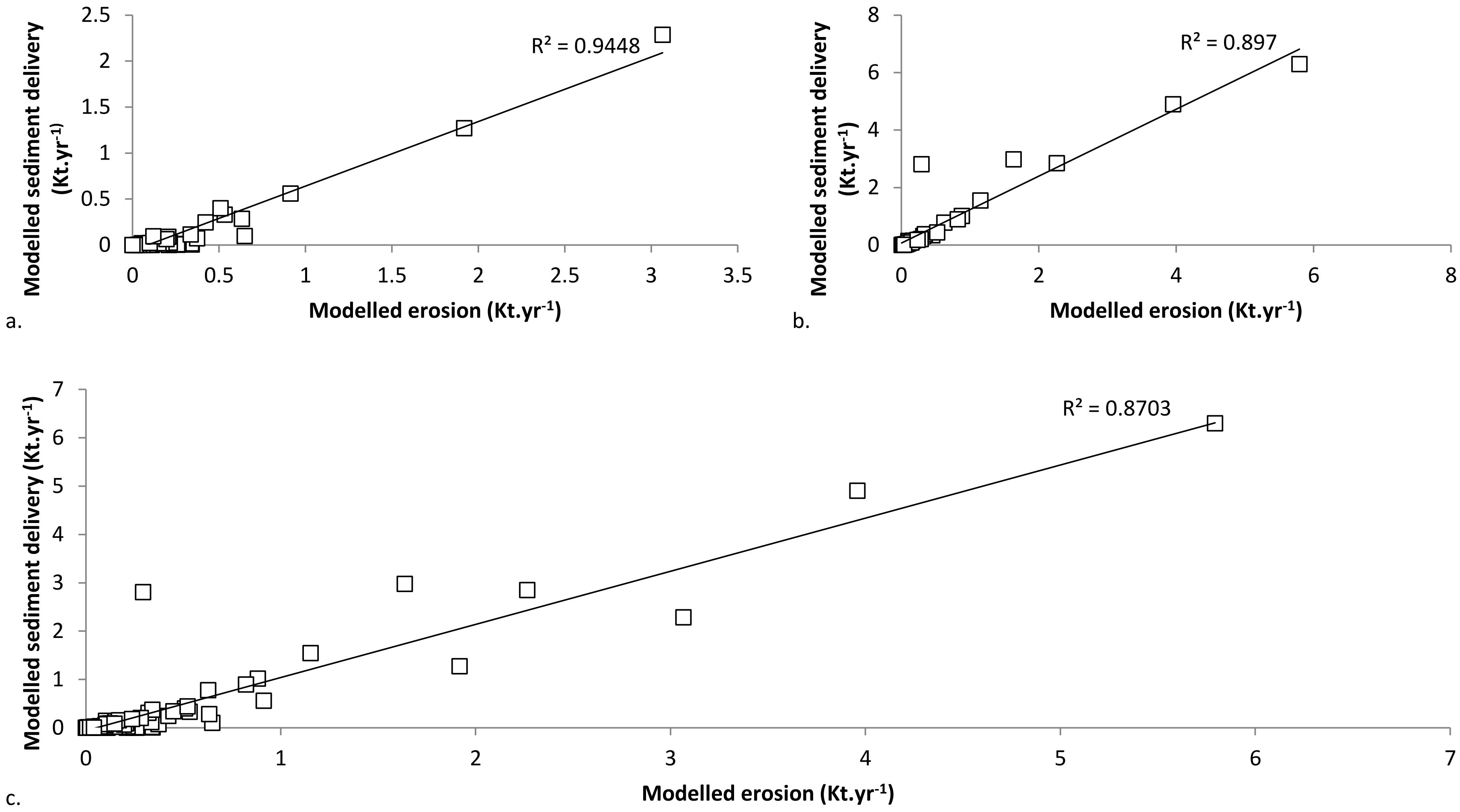


Figure 6.12 The correlation of annual modelled sediment delivery to annual modelled erosion from 1901 to 1967 (a), from 1967 to 2003 and from 1901 to 2003 for the Ganora dataset testing Scenario 3. Sediment delivery is better correlated to erosion before the "switch" in connectivity.

6.3.2 *Cranemere dataset*

The Cranemere dataset also produced much higher erosion estimates than sediment delivery estimates when the model was run with a high cover factor (Figure 6.13). This was considered unrealistic therefore the cover factor was reduced in order to reduce erosion.

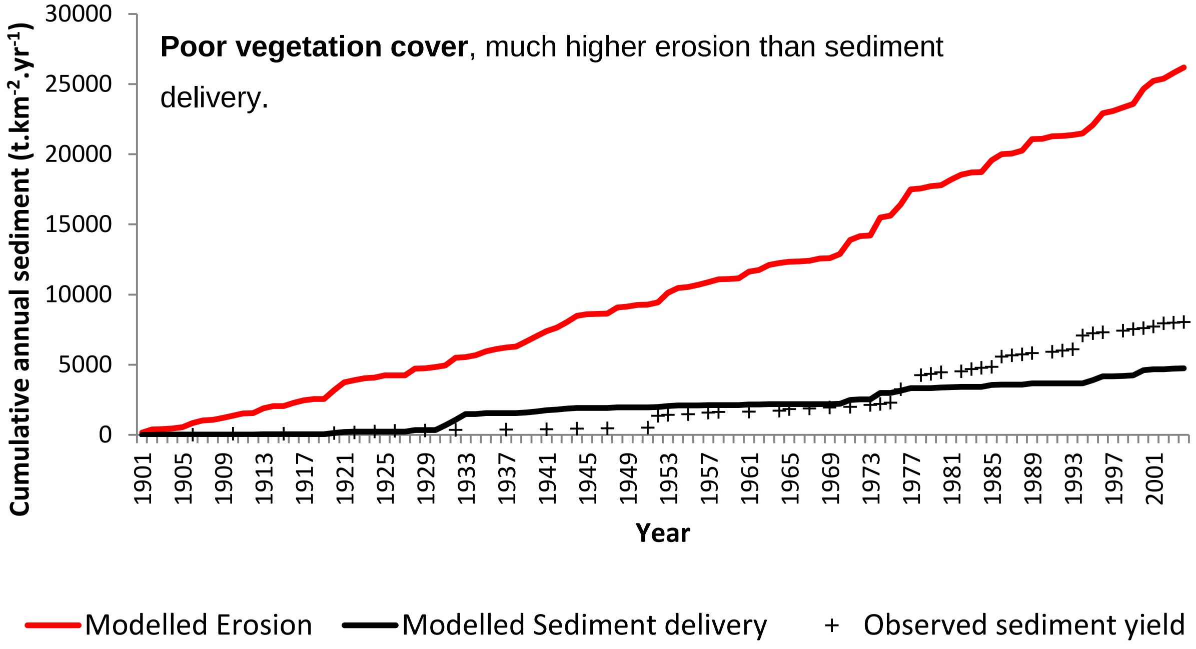


Figure 6.13 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Cranemere dataset with poor vegetation cover.

In all model runs the erosion model produced larger estimates than the sediment delivery model at the catchment outlet. In the Cranemere dataset this was more pronounced than the Ganora dataset as the Cranemere catchment had a greater capacity for sediment storage. The case may be that with increasing sediment storage capacity too much sediment is staying in storage and not being released effectively within the model. This may indicate a structural constraint in the sediment storage component of the model. In all scenarios the erosion estimation does not follow the stepped trend of observed sediment delivery in the 1930s and 1970s.

<u>Scenario 1:</u>

Running the model with “no change” to parameters throughout the time series provided cumulative annual modelled sediment delivery and erosion which were well correlated to cumulative annual observed sediment yield (Table 6.7 and Figure 6.15). An increase in sediment yield in the latter half of the century was not as evident in the cumulative annual modelled sediment delivery time series (Figure 6.14). This is indicative of rainfall not being an important driver for the observed increase in sediment yield in the latter half of the century. Other variables were important in emphasising this increase. This is in contrast to the Ganora catchment, where rainfall had a closer relationship with sediment delivery (Figure 6.6). The estimated sediment delivery did not follow the significant step evident in the observed sediment yield after the 1970s.

Scenario 2:

The model was first run with the calibrated cover factor (Table 6.5 and Figure 6.16a) and then run with a low cover factor (Table 6.5 and Figure 6.16b). The outputs from 1950 to 2004 from the second model run were merged with the first model run to produce a new time series (Figure 6.16c). This new time series represented a “decreased vegetation cover” in the latter half of the century. This resulted in a better correlation of cumulative annual modelled sediment delivery to cumulative annual observed sediment yield than when there was no parameter change (Table 6.7 and Figure 6.17). As in the Ganora dataset, changing the vegetation cover had the largest impact on erosion with only a slight change in sediment delivery. The decrease in vegetation cover increased both erosion and sediment delivery as the sediment delivery component is dependent on the erosion component of the model to provide available sediment. Similarly to scenario 1, sediment delivery did not follow the significant step in observed sediment yield after the 1970s.

Scenario 3:

To represent a “change in connectivity” the model was first run with low connectivity (Table 6.5 and Figure 6.18a) and then run with high connectivity (Table 6.5 and Figure 6.18b). A slight change of threshold flow for delivery was incorporated as the Cranemere catchment was not as impacted by badlands as the Ganora catchment. The outputs from 1950 to 2004 from the second model run were merged into the first model run to produce a new time series (Figure 6.18c). This new time series represented an “increased connectivity” in the latter half of the century. Cumulative annual modelled sediment delivery was better correlation to cumulative annual observed sediment yield than other scenarios (Table 6.7 and Figure 6.19). The erosion estimates were not affected by a change in connectivity but the cumulative annual sediment delivery and erosion estimates were much better correlated. Analysis of the correlation of cumulative annual modelled sediment delivery to cumulative annual observed sediment yield from 1901 to 1950 and from 1950 to 2004 indicated that after the “switch” in connectivity modelled results were better correlated (Table 6.7 and Figure 6.19). Annual modelled sediment delivery was also much better correlated to erosion

(Table 6.7 and Figure 6.20). This indicates that eroded sediment is transferred to the catchment outlet effectively after the "switch" in connectivity.

Table 6.7 The correlation of modelled outputs to observed sediment yield for the Cranemere dataset.

	Correlation (R^2) of cumulative annual yields		Correlation (R^2) of annual yields
	Sediment delivery vs Observed sediment yield	**Erosion vs Observed sediment yield**	**Sediment delivery vs erosion**
No Change	0.817	0.928	0.401
Decreased vegetation	0.817	0.928	0.400
Increased connectivity	0.930	0.928	0.715
"disconnected" (1901-1950)	0.794	0.958	0.435
"connected" (1950-2004)	0.944	0.966	0.889

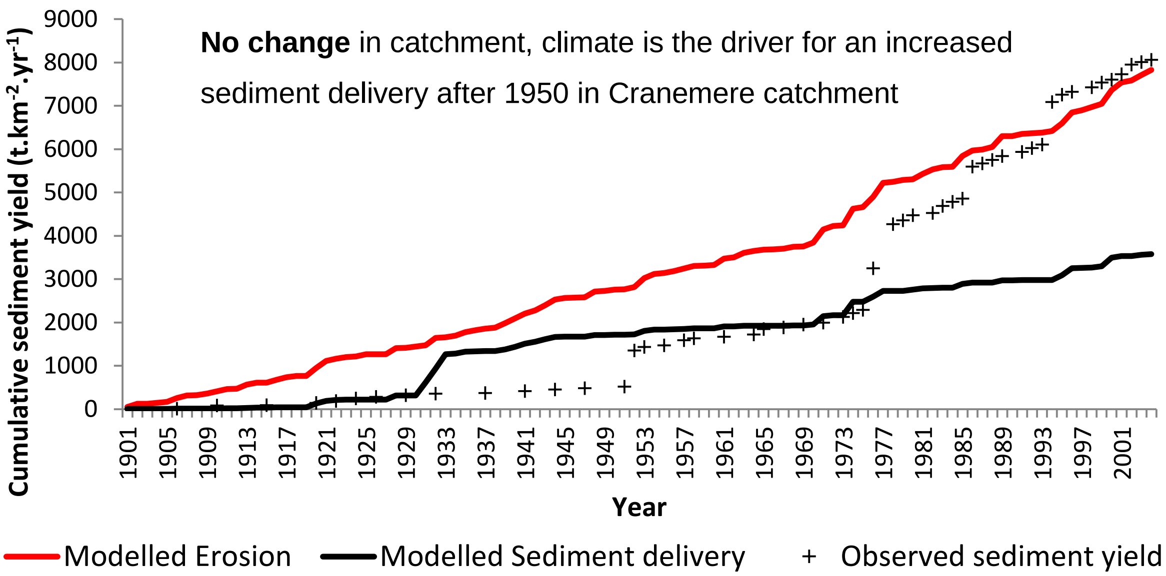


Figure 6.14 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Cranemere dataset testing Scenario 1.

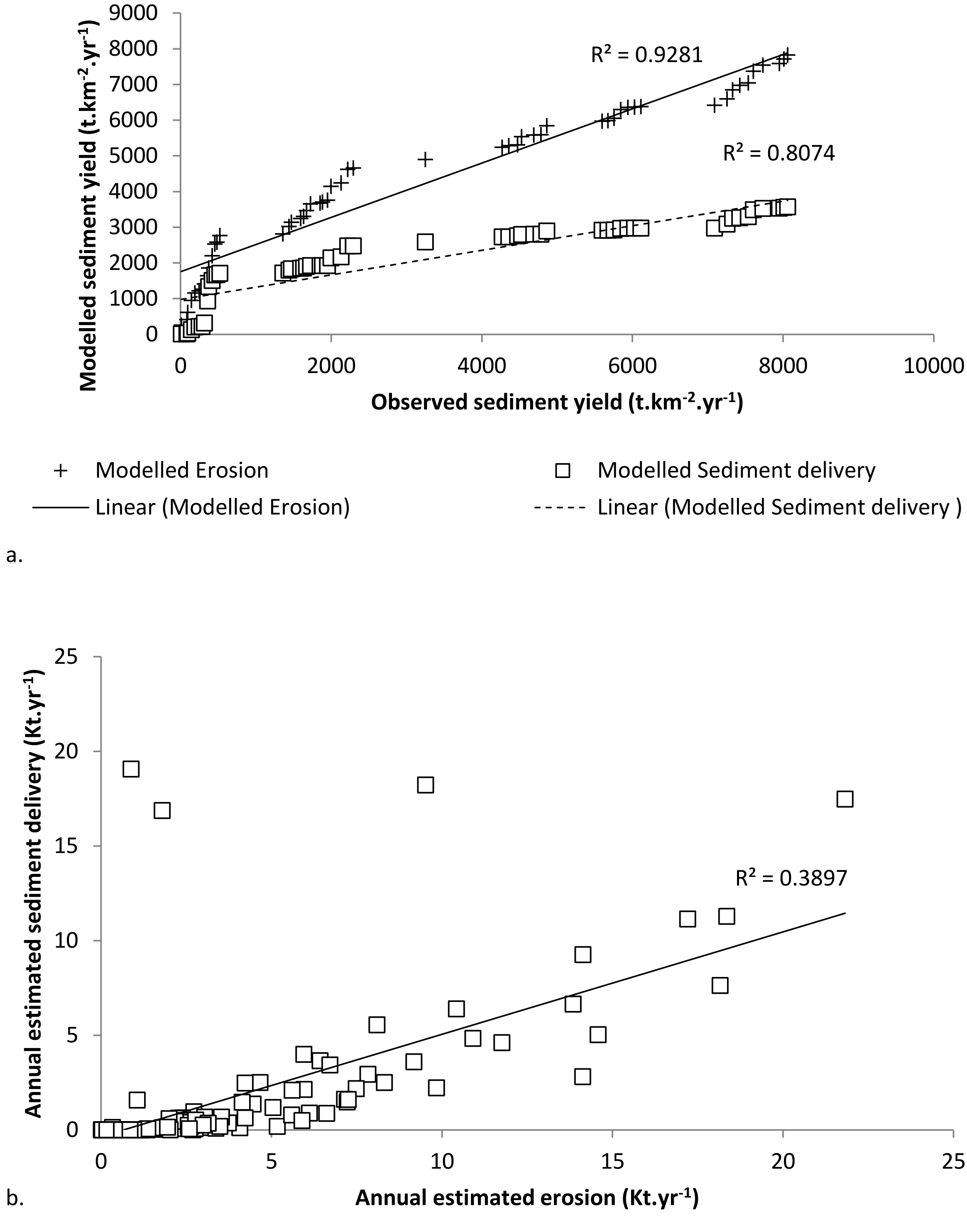


Figure 6.15 The correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield (a) and the correlation of annual modelled sediment delivery to annual modelled erosion (b) for the Cranemere dataset testing Scenario 1.

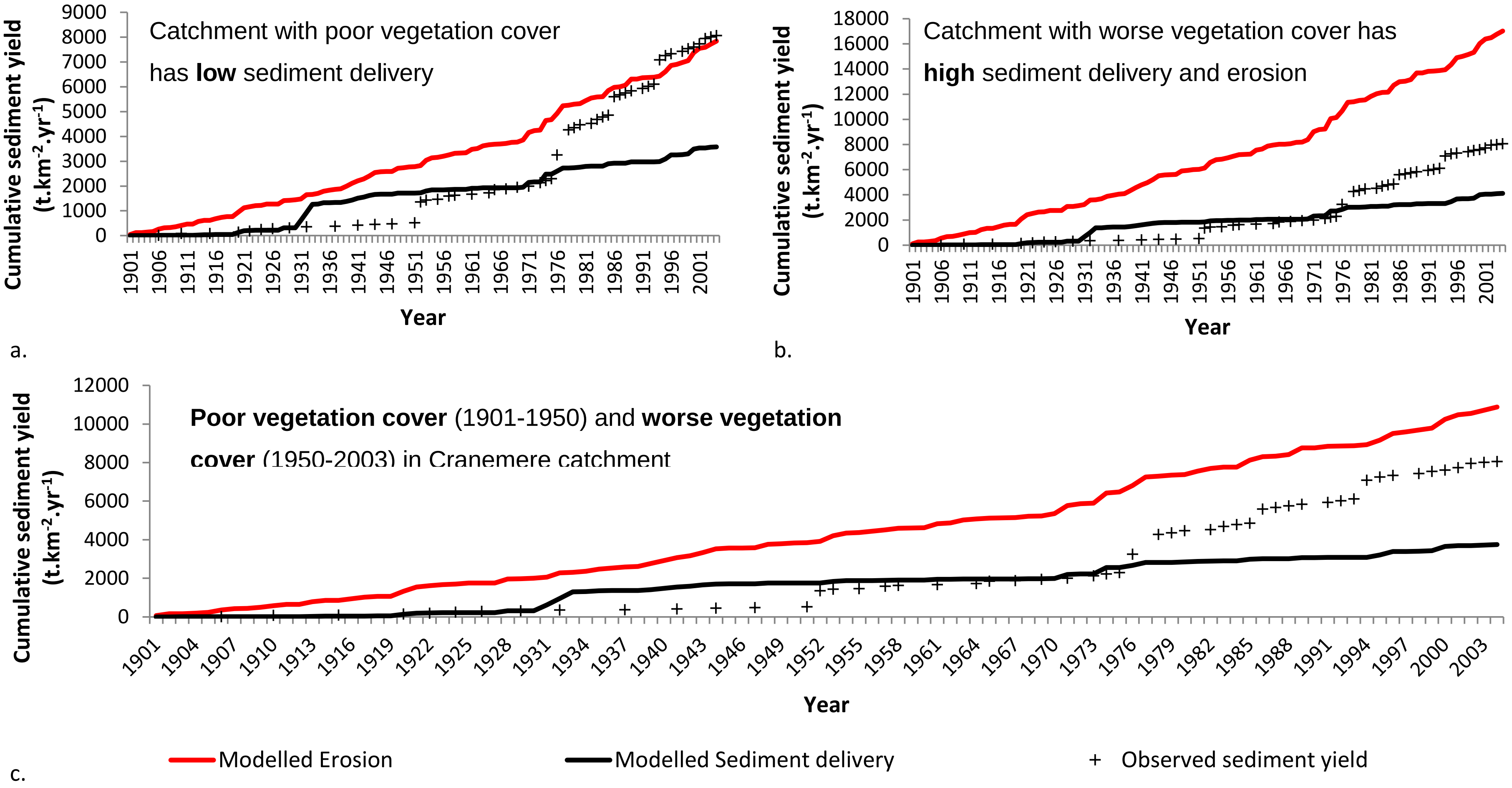


Figure 6.16 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Cranemere dataset testing Scenario 2. The model was first run with the calibrated vegetation cover (C=0.02) (producing outputs for a) and then the model was run with a low cover factor (C=0.5) (producing outputs for b). The model outputs from (b) were merged with (a) to produce outputs for (c).

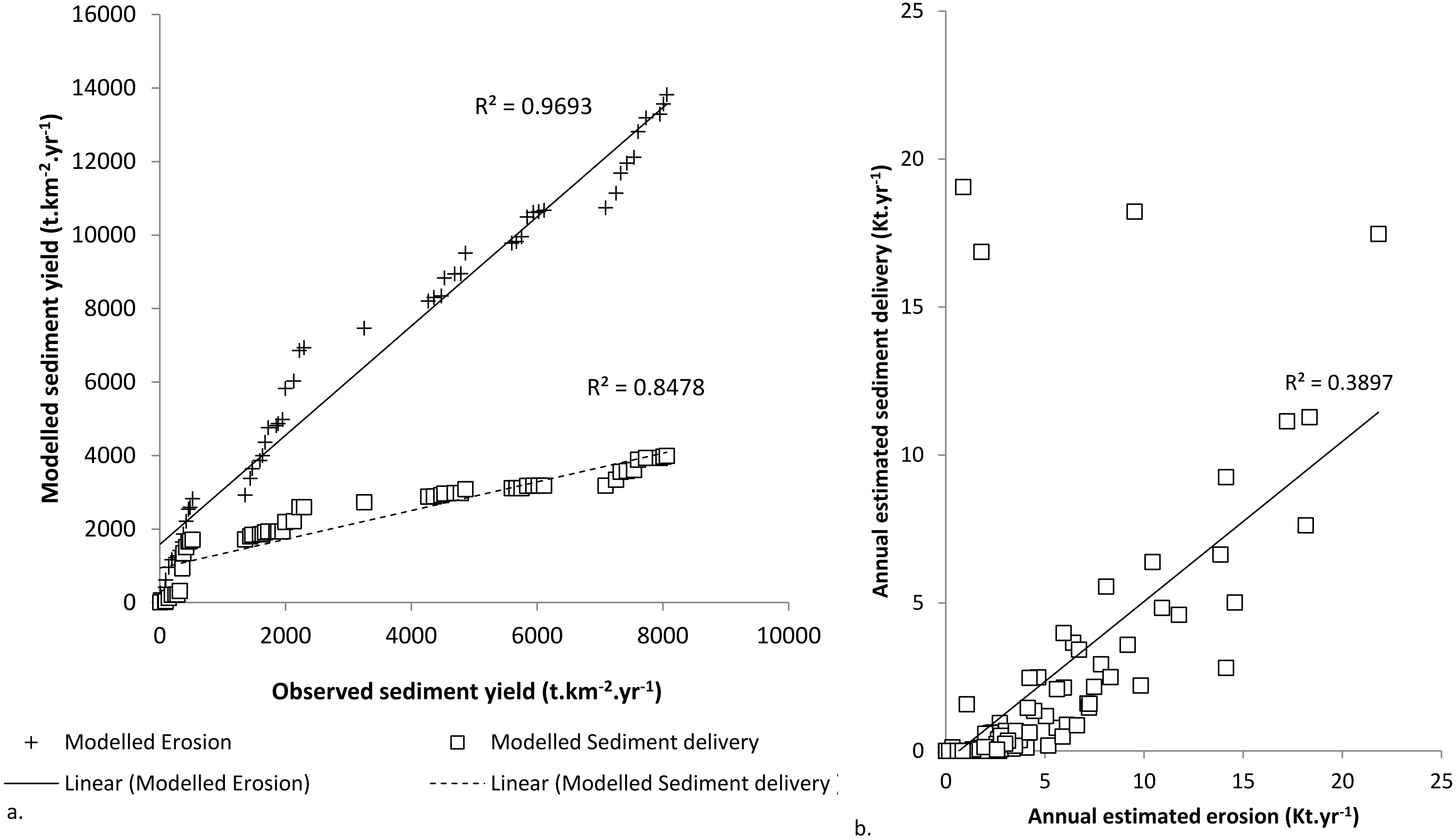


Figure 6.17 The correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield (a) and the correlation of annual modelled sediment delivery to annual modelled erosion (b) for the Cranemere dataset testing Scenario 2.

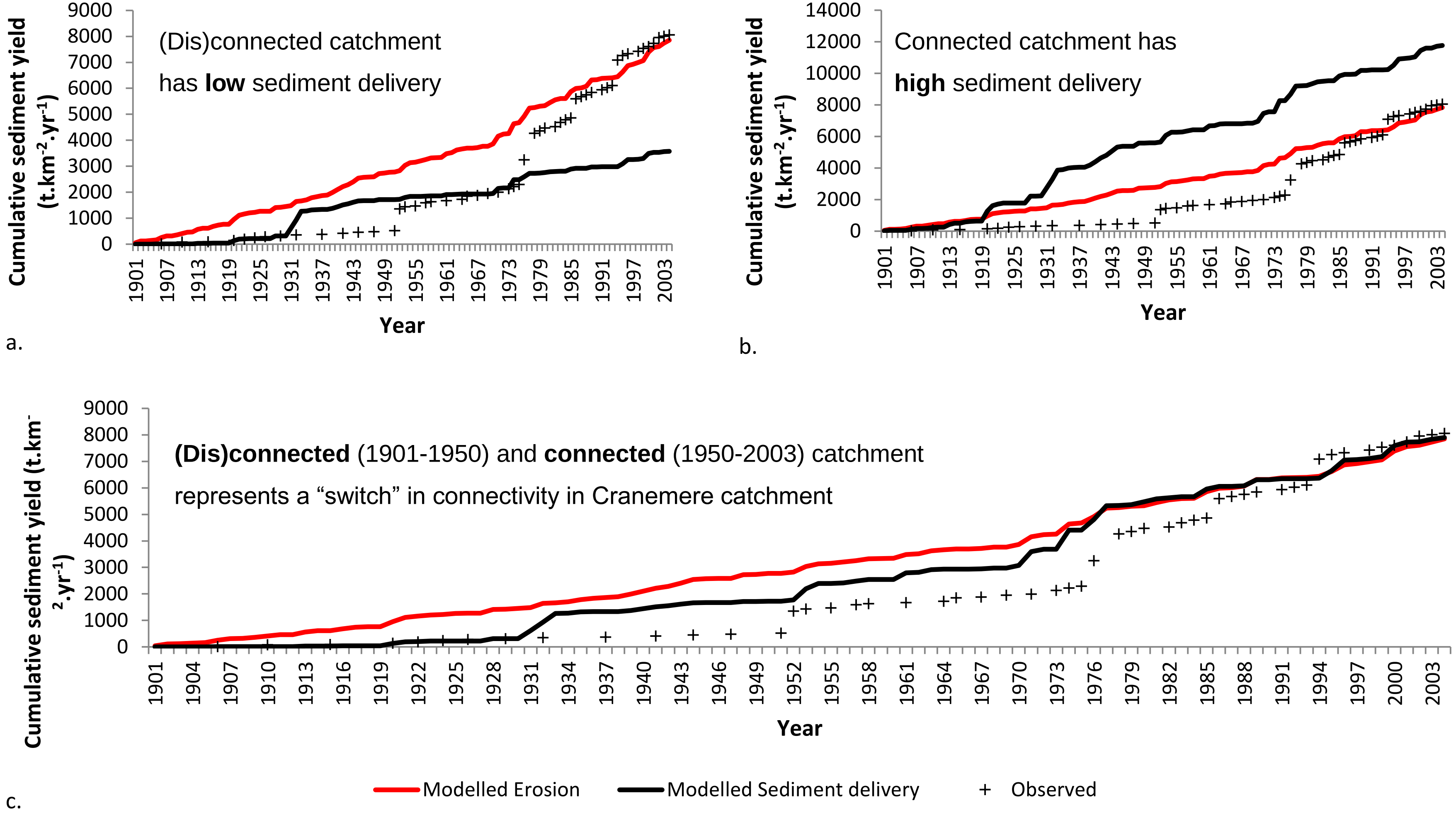


Figure 6.18 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Cranemere dataset testing Scenario 3. The model was first run with low connectivity parameters (producing outputs for a) and then the model was run with increased connectivity parameters (producing outputs for b). The model outputs from (b) were merged with (a) to produce outputs for (c).

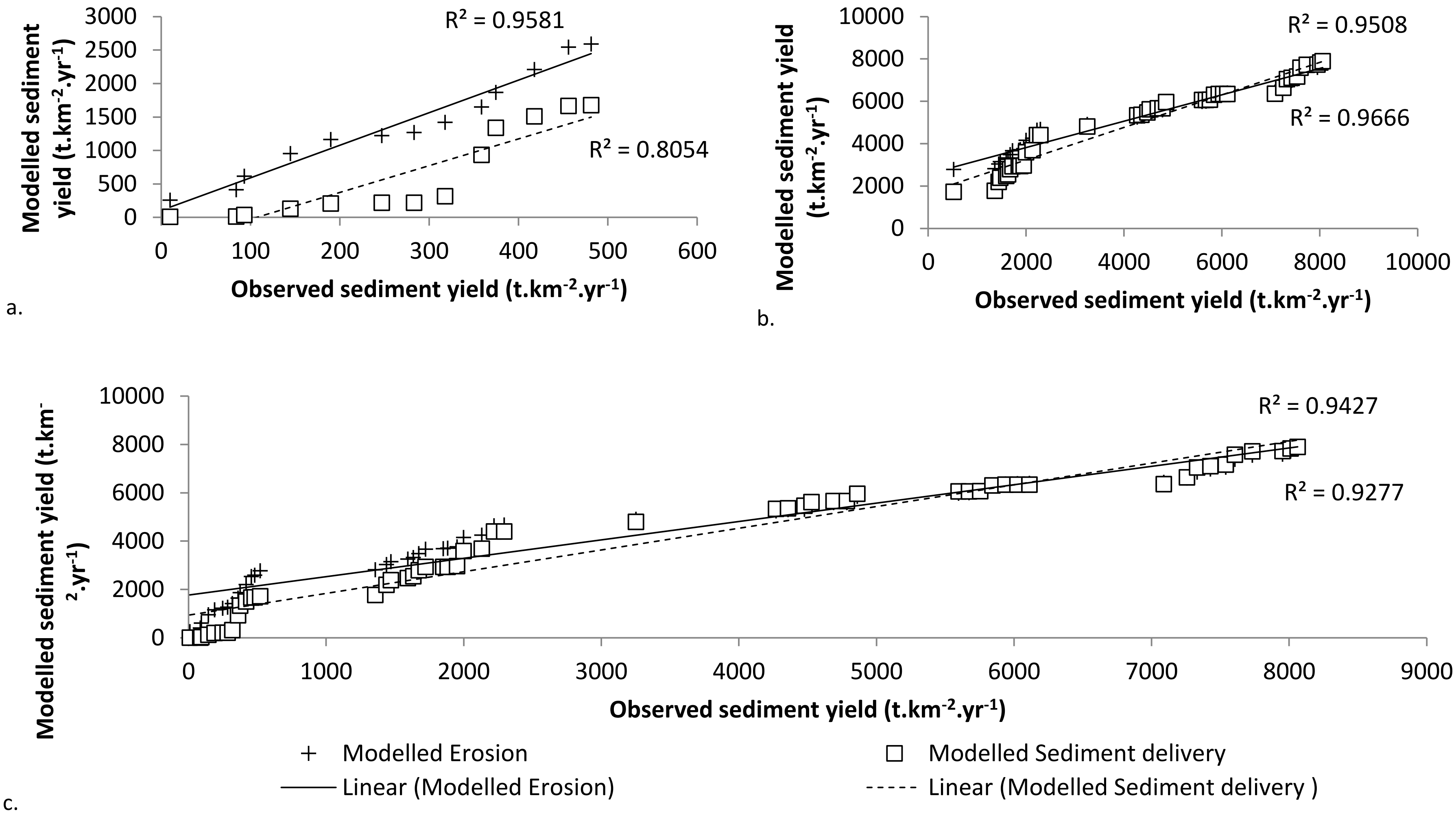


Figure 6.19 The correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield from 1901 to 1950 (a), from 1950 to 2004 and from 1901 to 2004 for the Cranemere dataset testing Scenario 3. Modelled sediment delivery and erosion estimates are better correlated after the "switch" in connectivity.

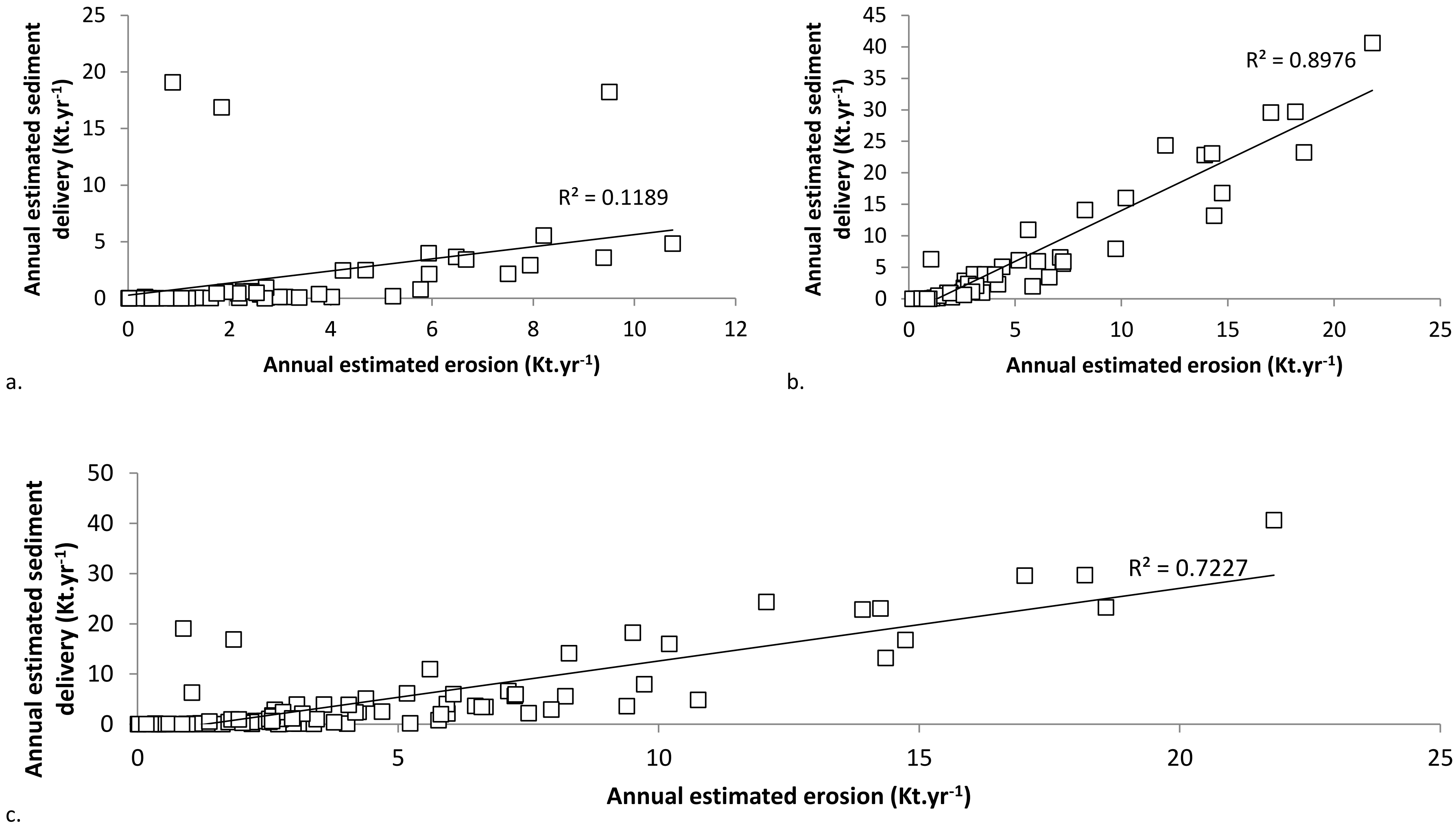


Figure 6.20 The correlation of annual modelled sediment delivery to annual modelled erosion from 1901 to 1950 (a), from 1950 to 2004 and from 1901 to 2004 for the Cranemere dataset testing Scenario 3. Sediment delivery is less correlated to erosion before the "switch" in connectivity.

In both the Ganora and Cranemere datasets it was noticeable that a change to the erosion parameter (i.e. "decreased vegetation cover") would have a direct impact on the erosion component of the model and an indirect impact on the sediment storage and delivery component of the model. As the model already incorporates the heterogeneity of the cover factor via probability distribution functions it was not considered applicable to manually adjust these parameters in order to emulate a change in sediment delivery.

In the Ganora dataset rainfall was an important driver for the increased sediment delivery in the latter half of the century but in the Cranemere dataset a similar relationship was not evident. This was a consequence of the Cranemere catchment being a much larger catchment with a lower elevation. The Cranemere dataset had a higher threshold flow for delivery than the Ganora dataset, which meant that low flow events did not always result in sediment delivery.

Foster et al. (2011) concluded that it is the combination of the effects of rainfall, vegetation and connectivity which resulted in an increase in sediment yield in the Ganora and Cranemere catchments during the latter half of the century. The overstocking until the 1930s reduced the resilience of the Karoo landscape to erosive forces, and catchments crossed a threshold from low erosion to high erosion (Foster et al., 2012). The trigger that caused the shift is different for each catchment. In the case of the Ganora catchment, badland erosion may have begun in the 1930s, but only when connectivity increased did the sediment cascade connect with the main channel. In the Cranemere catchment anthropogenic changes to connectivity as well as increased rainfall amounts are reworking temporary sediment stores. Rainfall acts as a key driver of sediment transport in an already degraded landscape. Where increased rainfall intensity is coupled with increased connectivity, the impact on sediment yield is likely to be dramatic.

This indicates that a "switch" in connectivity within the catchment effectively represents the increased sediment yield from the 1950s onwards. Although changes to vegetation cover are not explicitly represented during the "switch" in connectivity, it can be assumed that the heterogeneity of vegetation cover change is well represented by the probability distribution function of the erosion component of the model. As rainfall is the driver of the rainfall-runoff model and all associated surface flow estimation procedures it can be assumed that the increased rainfall in the latter half of the century is effectively represented by the model. By manually incorporating a "switch" in catchment connectivity it was possible to relate both the Ganora and Cranemere datasets to a shift in sediment delivery, as a consequence of connectivity changes within the catchments. This provided a good correlation of modelled sediment delivery with observed sediment yield.

6.3.3 Nqweba dataset

As Nqweba is a much larger catchment, the changes to connectivity and erosion are difficult to interpret. Lessons learnt from the Ganora and Cranemere datasets were that the incorporation of a “switch” in connectivity (Scenario 3) during the time series represented the hypotheses as described by Foster et al. (2011) for the Karoo. The characteristic increase in sediment yield in the latter half of the century due in part to overgrazing until the 1930s was incorporated with a similar “switch” as that which was used for the Ganora and Cranemere catchments (Table 6.8). This change to connectivity was incorporated by running the model twice, with different sediment storage parameters (Figure 6.21). The proportion of gully or channel connectivity from 1901 to 1930 was higher than the Ganora and Cranemere catchments due to the size of the Nqweba catchment, meaning that more connectivity is expected in all runoff zones. These proportions were increased accordingly to represent an increase in connectivity from 1930 to 1999. The same threshold flow was used as that used for the Ganora dataset in order to represent a degraded catchment.

Table 6.8 The parameters used to represent an increased connectivity for Nqweba catchment.

Scenario 3	Parameter	Nqweba	
		1901-1930	1930-1999
Increased connectivity	C_{prop} (H)	0.1	0.2
	C_{prop} (M)	0.3	0.6
	C_{prop} (L)	0.3	0.6
	Threshold flow ($mm.hr^{-1}$) for delivery	0.4	0.3

To represent a “change in connectivity” the model was first run with low connectivity (Table 6.8 and Figure 6.21a) and then run with high connectivity (Table 6.8 and Figure 6.21b). The outputs from 1930 to 1999 from the second model run were cut and pasted into the first model run to produce a new time series (Figure 6.21c). The cumulative annual modelled sediment delivery estimates were well correlated to cumulative annual observed sediment yield estimates (Table 6.9 and Figure 6.22). In comparison to the Ganora and Cranemere datasets, cumulative annual modelled erosion was much better correlated to cumulative annual observed sediment yield (Table 6.9 and Figure 6.22). This may be a feature of the structural confines of the model at larger spatial scales. High lying areas should produce more erosion than low lying areas, but if there are not enough runoff events in these high lying areas this characteristic will not be represented in the model outputs. At large spatial scales the model also does not account for transmission losses. The structural confines of the model may also be the reason why from 1940 to 1950 there is low modelled sediment delivery (Figure 6.21).

Table 6.9 The correlation of modelled outputs to observed sediment yield for Nqweba dataset.

	Correlation (R^2) of cumulative annual yields		Correlation (R^2) of annual yields
	Sediment delivery vs Observed sediment yield	Erosion vs Observed sediment yield	Sediment delivery vs erosion
Increased connectivity	0.908	0.967	0.781

6.3.4 Analysis of model outputs

The model effectively represented the "flashiness" of flow in all catchments as significant peaks in surface flow throughout the time series (Figure 6.23a, Figure 6.24a and Figure 6.25a). These were important events in the model as they acted to effectively "flush" out sediment from temporary stores. There was a trend for all catchments having an increase in frequency and magnitude of runoff events during the latter half of the time series (Figure 6.27, Figure 6.28 and Figure 6.29). This is indicative of an increase in the amount and intensity of rainfall in the latter half of the century.

Foster et al. (2011) noted a similar trend in rainfall records for the Karoo. An increase in extreme rainfall was considered to increase the potential for erosion and the delivery of sediments via floods. According to the authors the most notable flood in the Karoo occurred on the 3rd of March 1974. At the Cranemere catchment, where the rainfall was not especially intense, the storm fell on an already wet landscape. Although this storm resulted in high runoff, soil erosion was considered to be less severe due to the good vegetation cover resulting from the rain over the previous two months. Foster et al. (2011) raised the question of whether these floods caused widespread soil erosion, or whether the increase in sediment delivery was due to floodwaters mobilizing temporary sediment. This hypothesis was alluded to in the previous section. Running the model with low connectivity and no change in vegetation cover or catchment connectivity produced a sediment delivery time series without a large increase in sediment delivery related to the 1974 flood. Running the model with a "switch" in connectivity produced sediment delivery results which were impacted by the high runoff event in 1974. This indicates that surface flow alone was not the driving force behind an increases sediment yield to the Cranemere dam in 1974 and that the reworking of temporary sediment stores as the catchment increased in connectivity was the dominant process. Floodwaters were effective at “flushing” out stored sediment from the entire catchment.

Similarly historical droughts and times when Nqweba dam overflowed were also represented in the surface flow time series (Figure 6.25a). According to Minaar (1987) the first time Nqweba dam overflowed was just six years after it was built in 1932. Following this there were significant years of droughts up until 1961 when the dam experienced its third period of overflow. Apparently the dam overflows became more frequent from this point as sedimentation decreased the storage capacity of the dam. These wet and dry periods were significant when considering the application of the model at a larger scale as a long dry period resulted in a long period of sediment storage, with limited sediment delivery events. A high runoff event following these long periods of storage resulted in high sediment delivery potential as temporary storage zones are “flushed” out.

The modelled daily erosion time series for all catchments closely followed the surface flow time series (Figure 6.23b, Figure 6.24b and Figure 6.25b). Each surface flow event resulted in a corresponding erosion event. It was noticeable that the erosion component of the model produced more available sediment than the sediment delivery component for the Ganora and Cranemere datasets. The Nqweba dataset exhibited large sediment delivery events which were significantly higher than erosion during the time series.

The erosion outputs for the Ganora catchment closely followed flow, noticeable by the two significant peaks in runoff resulting in similar peaks in erosion during the 1930s and the 1970s (Figure 6.23a and Figure 6.23b). The sediment delivery also followed flow, as the peaks can be identified in the sediment delivery time series, but there are more extreme “pulses” of sediment delivery (Figure 6.23c). The erosion outputs for the Cranemere dataset also closely followed flow, although the large runoff event in 1932 resulted in a comparatively small erosion event due to the start of the time series representing a (dis)connected catchment (Figure 6.24a and Figure 6.24b). The sediment delivery outputs also had extreme “pulses” of sediment delivery, following periods of low flow (Figure 6.24c). For the Nqweba catchment, although the erosion time series closely followed the surface flow time series (Figure 6.25b), the sediment delivery time series was indicative of large sediment delivery events following long periods of low surface flow (Figure 6.25c).

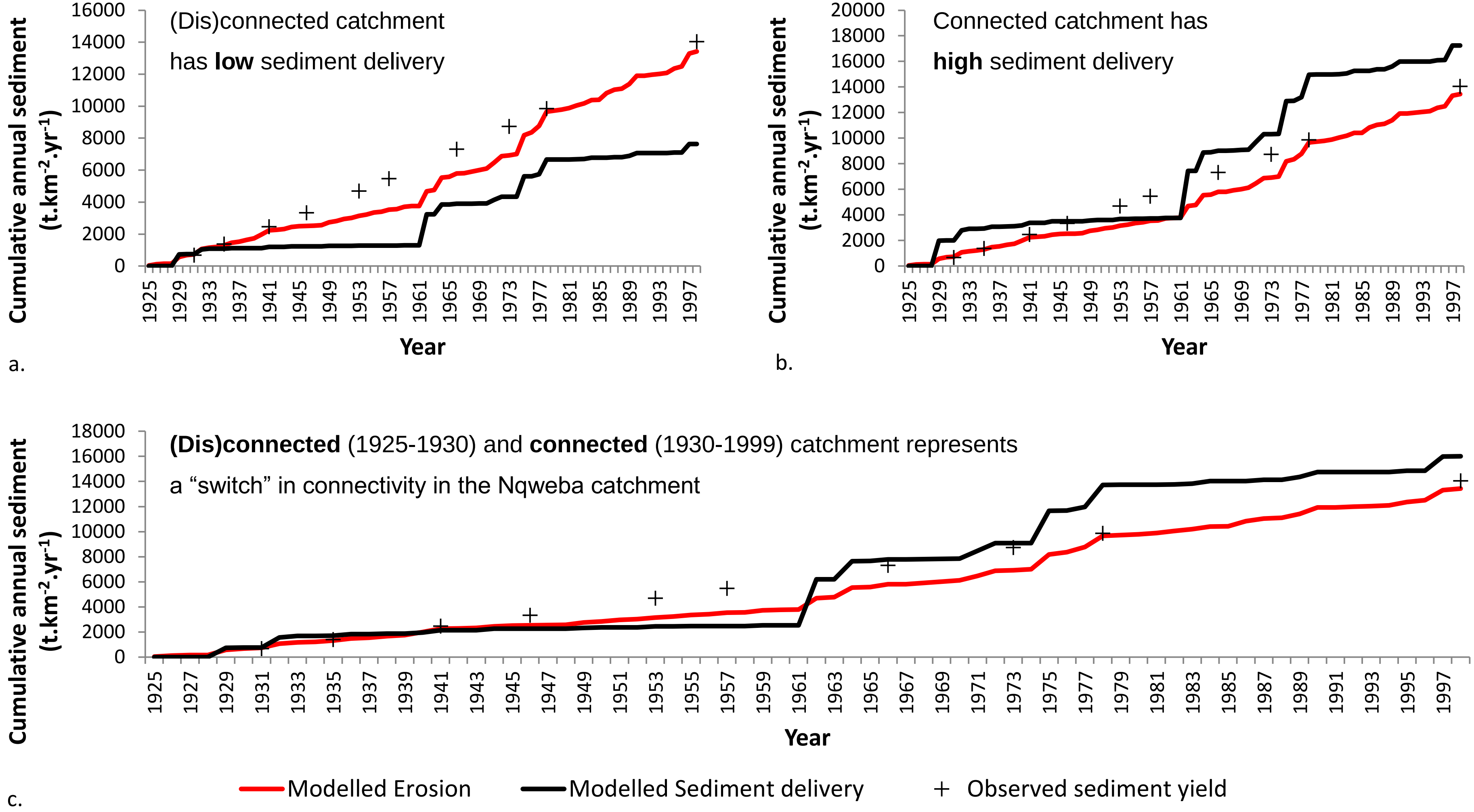


Figure 6.21 The cumulative annual modelled sediment delivery, erosion and observed sediment yield for the Nqweba dataset with different connectivity parameters (a and b) and as a merged output (c).The model was first run with low connectivity parameters (producing outputs for a) and then the model was run with increased connectivity parameters (producing outputs for b). The model outputs from (b) were merged with (a) to produce outputs for (c).

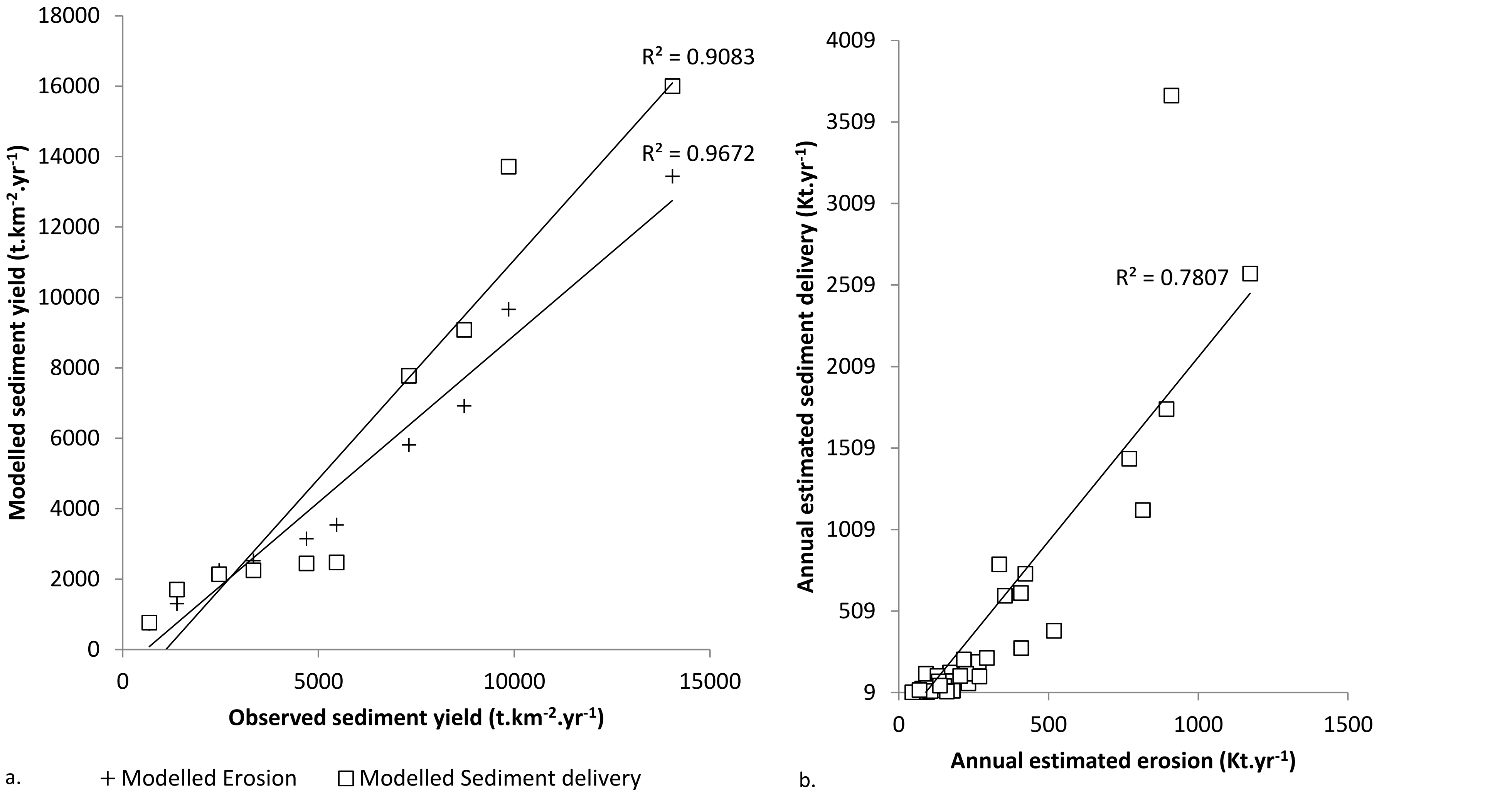
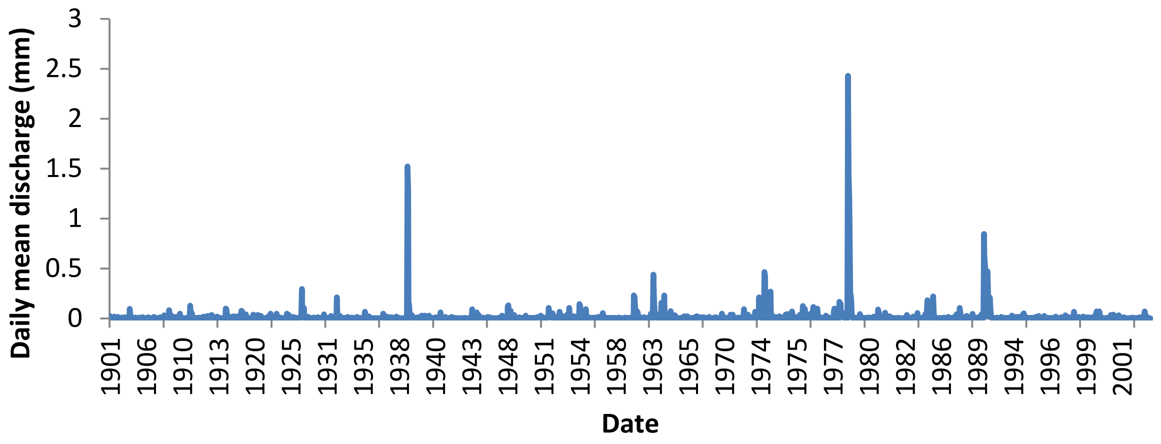
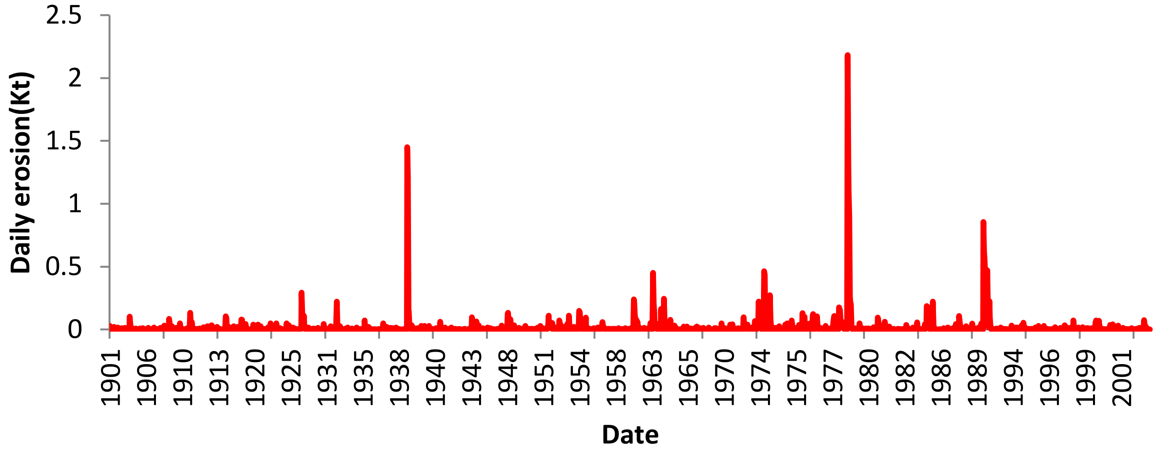


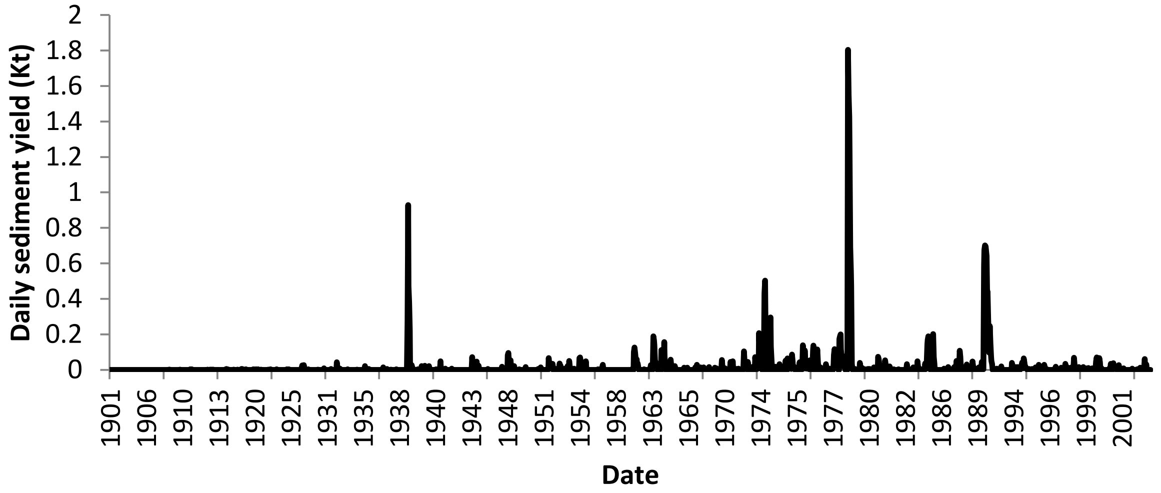
Figure 6.22 The correlation of cumulative annual modelled sediment delivery and erosion to cumulative annual observed sediment yield (a) and the correlation of annual modelled sediment delivery to annual modelled erosion (b) for the Nqweba dataset with a "change in connectivity" over the time series.



a.

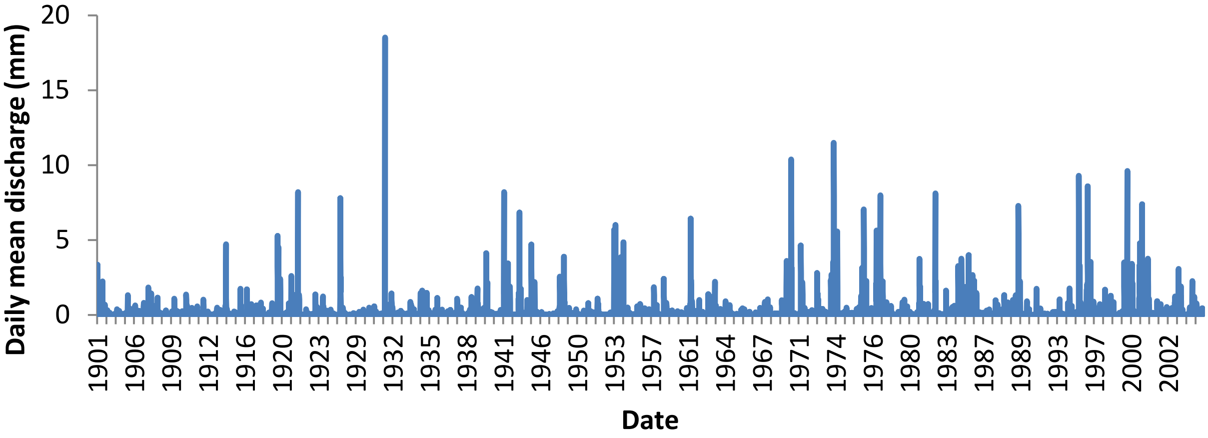


b.

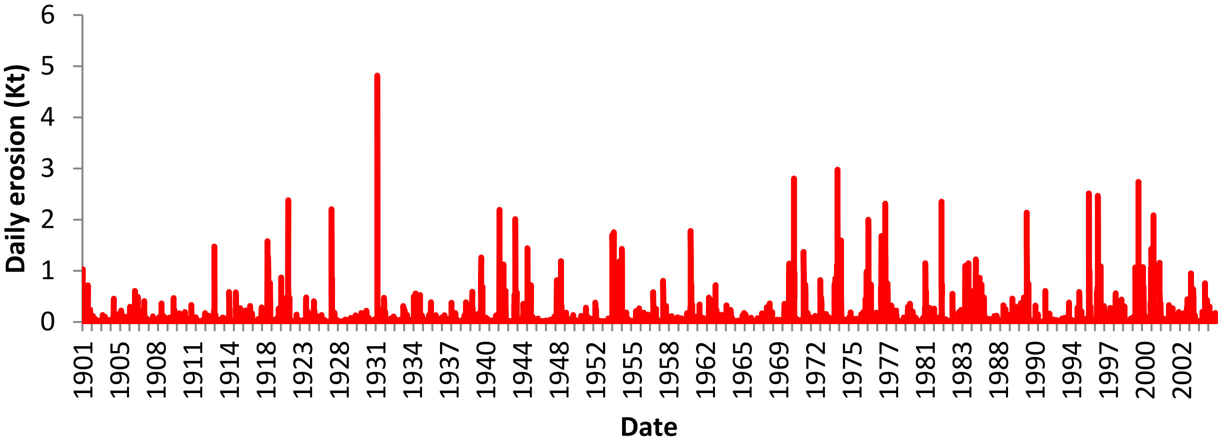


c.

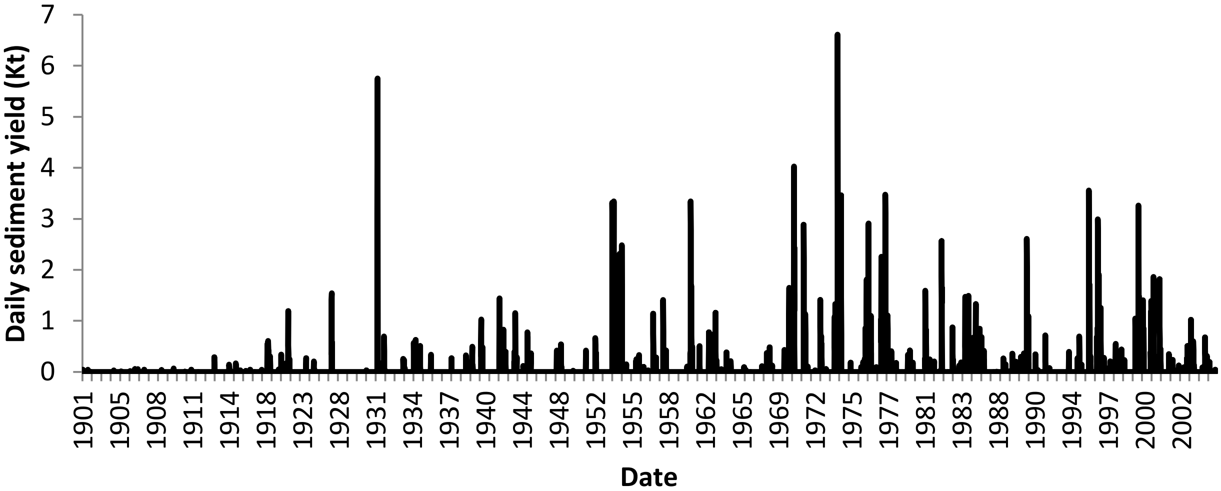
Figure 6.23 The model outputs in terms of daily surface flow (a), daily erosion (b) and sediment delivery (c) with an integrated switch for Ganora catchment. Significant erosion and sediment delivery events relate to significant surface flow events in 1938 and 1978. There are more sediment delivery events in the latter half of the century which relates to an increase in the number of runoff events.



a.

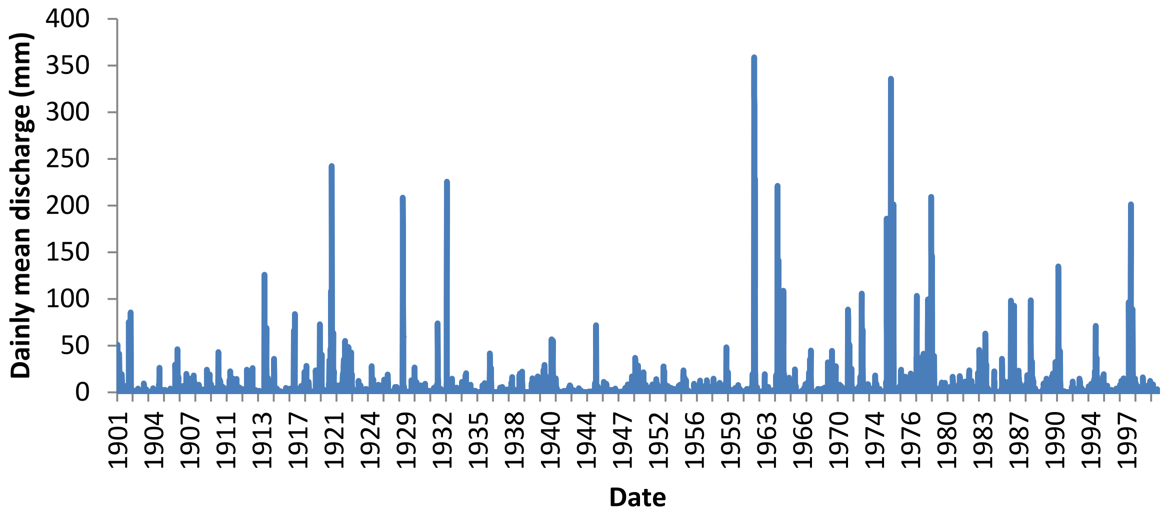


b.

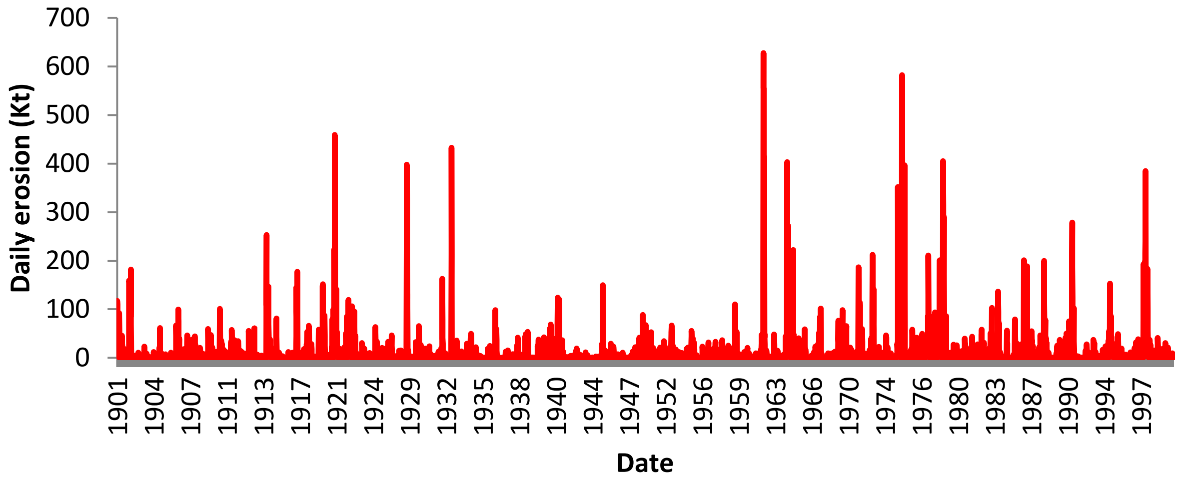


c.

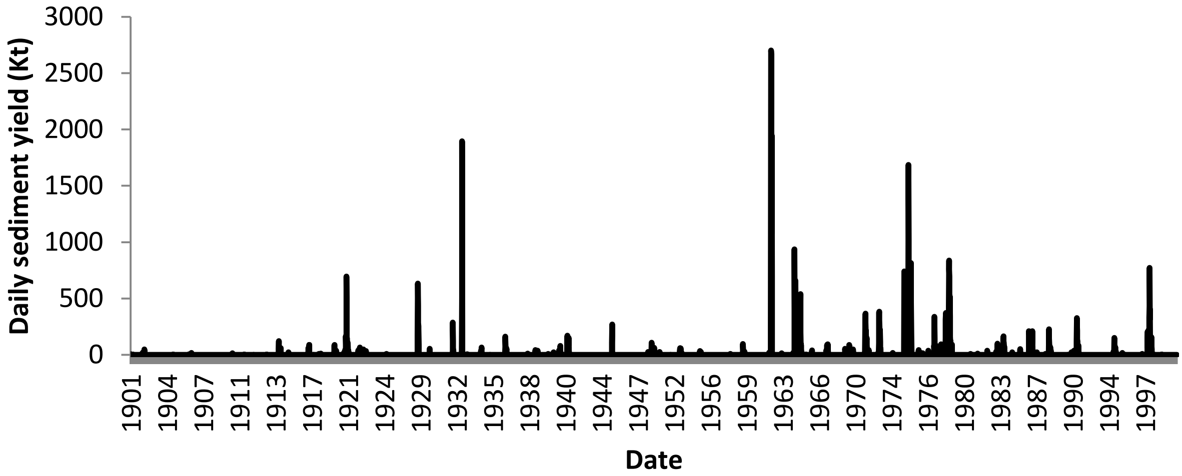
Figure 6.24 The model outputs in terms of daily surface flow (a), daily erosion (b) and daily sediment delivery (c) with an integrated switch for Cranemere catchment. Erosion events closely follow the surface flow events whilst the sediment delivery peaks tend to occur after long periods of low runoff.



a.



b.



c.

Figure 6.25 The model outputs in terms of daily surface flow (a), daily erosion (b) and daily sediment delivery (c) with an integrated switch for Nqweba catchment. Erosion events closely follow the surface flow events whilst the sediment delivery peaks tend to occur after long periods of low surface flow.

The modelled daily sediment delivery time series had the general trend of high sediment delivery events following long dry periods (Figure 6.23c, Figure 6.24c and Figure 6.25c). This characteristic became more pronounced as the catchment size increased. The size of the sediment delivery event depended on the length of the dry period, as a long dry period allowed for a large temporary storage build up which would effectively have been “flushed” out during the infrequent high magnitude surface flow event. As the Nqweba dataset had a much larger capacity for sediment storage there was more potential for the build-up of significant sediment stores. These large sediment stores were effectively “flushed” out following high flow events, which accounts for the much larger sediment delivery events in the Nqweba dataset.

By comparing the cumulative annual erosion and sediment yield for all catchments it is apparent that the Ganora and Nqweba catchments had larger estimates (Figure 6.26). Although the relationship of erosion and sediment delivery was different in all catchments, a similar trend for all was the “switch” in dominance of erosion to sediment delivery following an increase in catchment connectivity. After the 1950s both the Ganora and Nqweba catchments experienced a significant increase in sediment delivery, whilst the Cranemere catchment experienced a more gradual increase in sediment delivery.

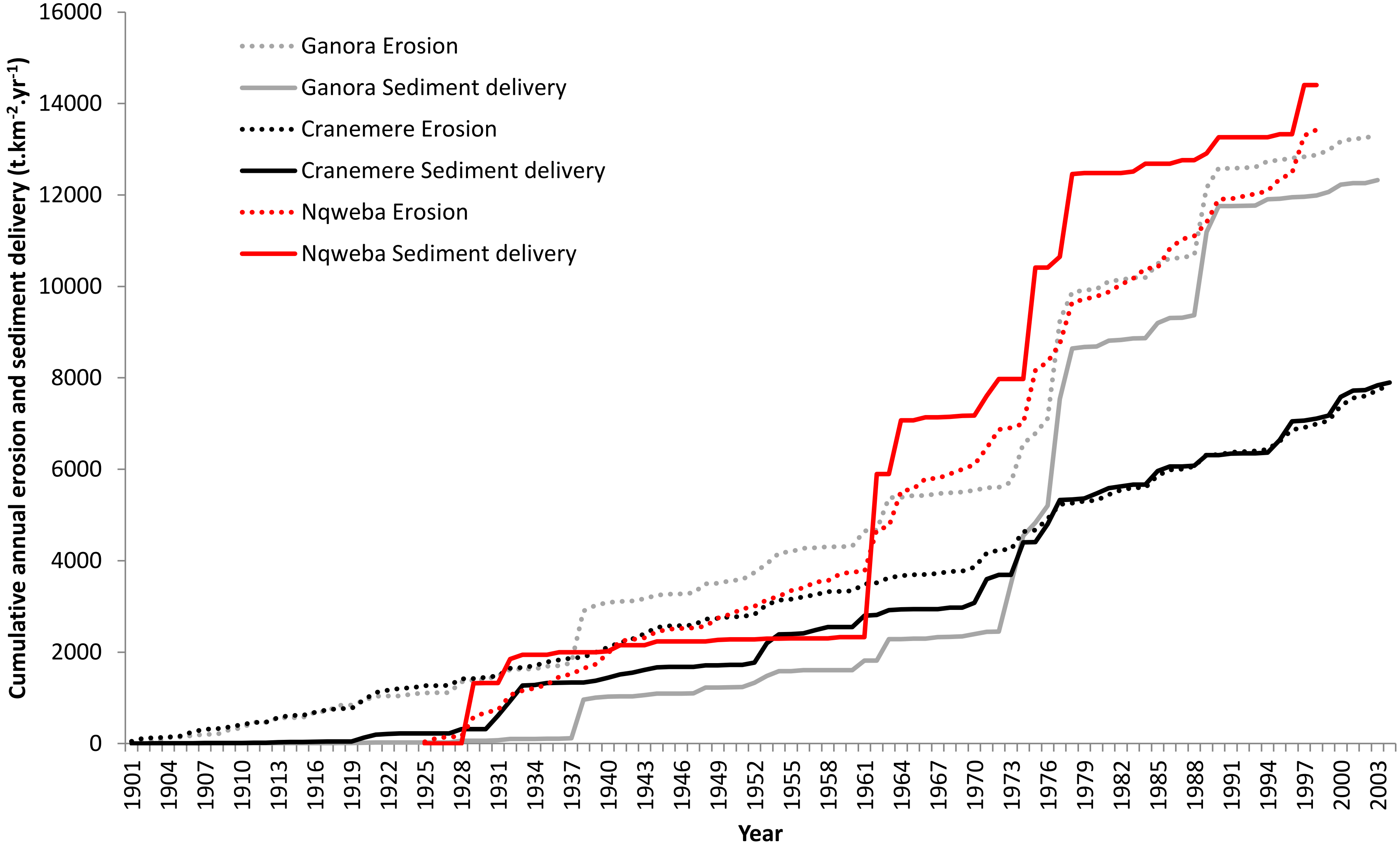


Figure 6.26 The cumulative annual sediment delivery for the Ganora, Cranemere and Nqweba catchments.

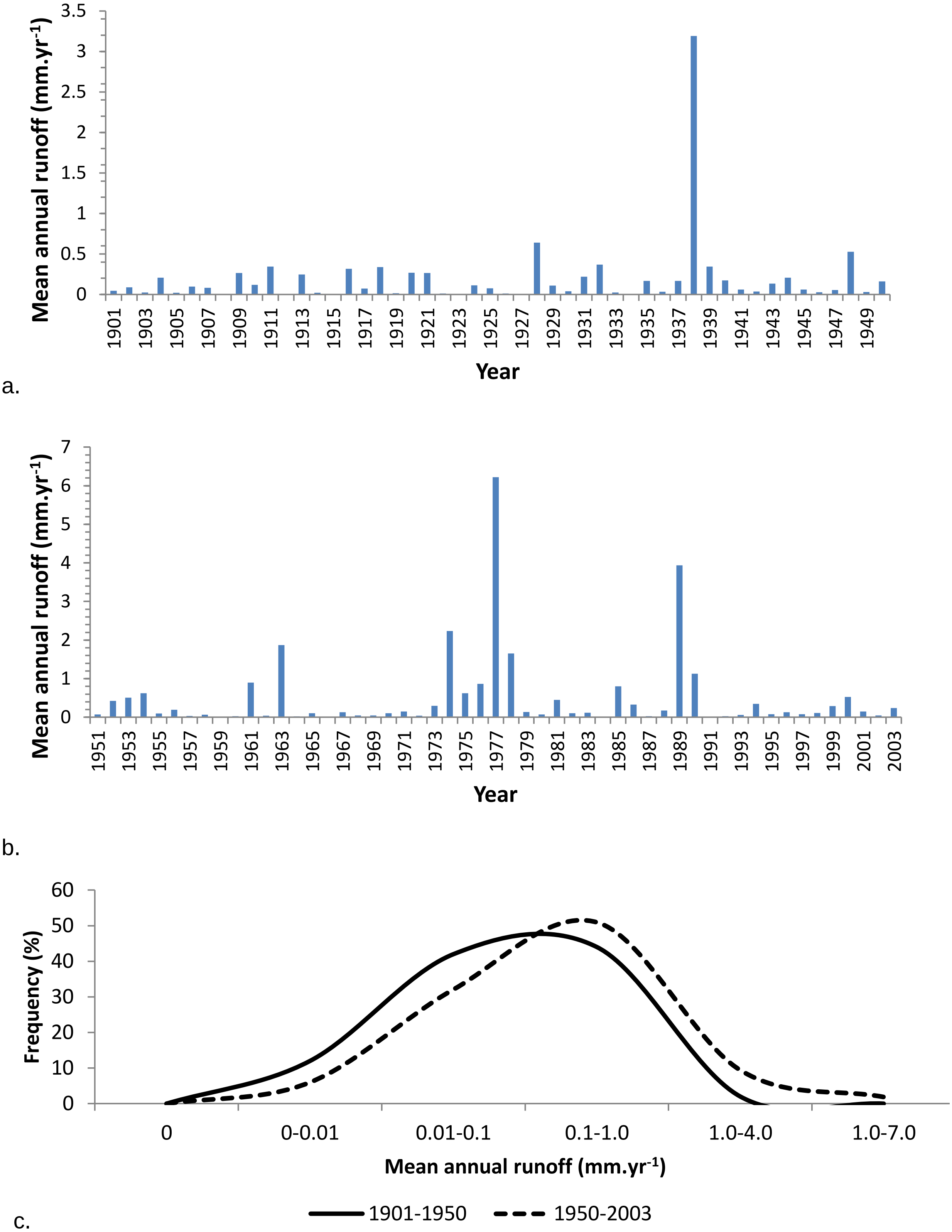


Figure 6.27 The distribution of the mean annual runoff for the Ganora catchment from 1901 to 1950 (a) and from 1951 to 2003 (b). The frequency distribution of annual runoff from 1901 to 1950 and from 1950 to 2003 indicates that there is an increased frequency of higher runoff events in the latter half of the century.

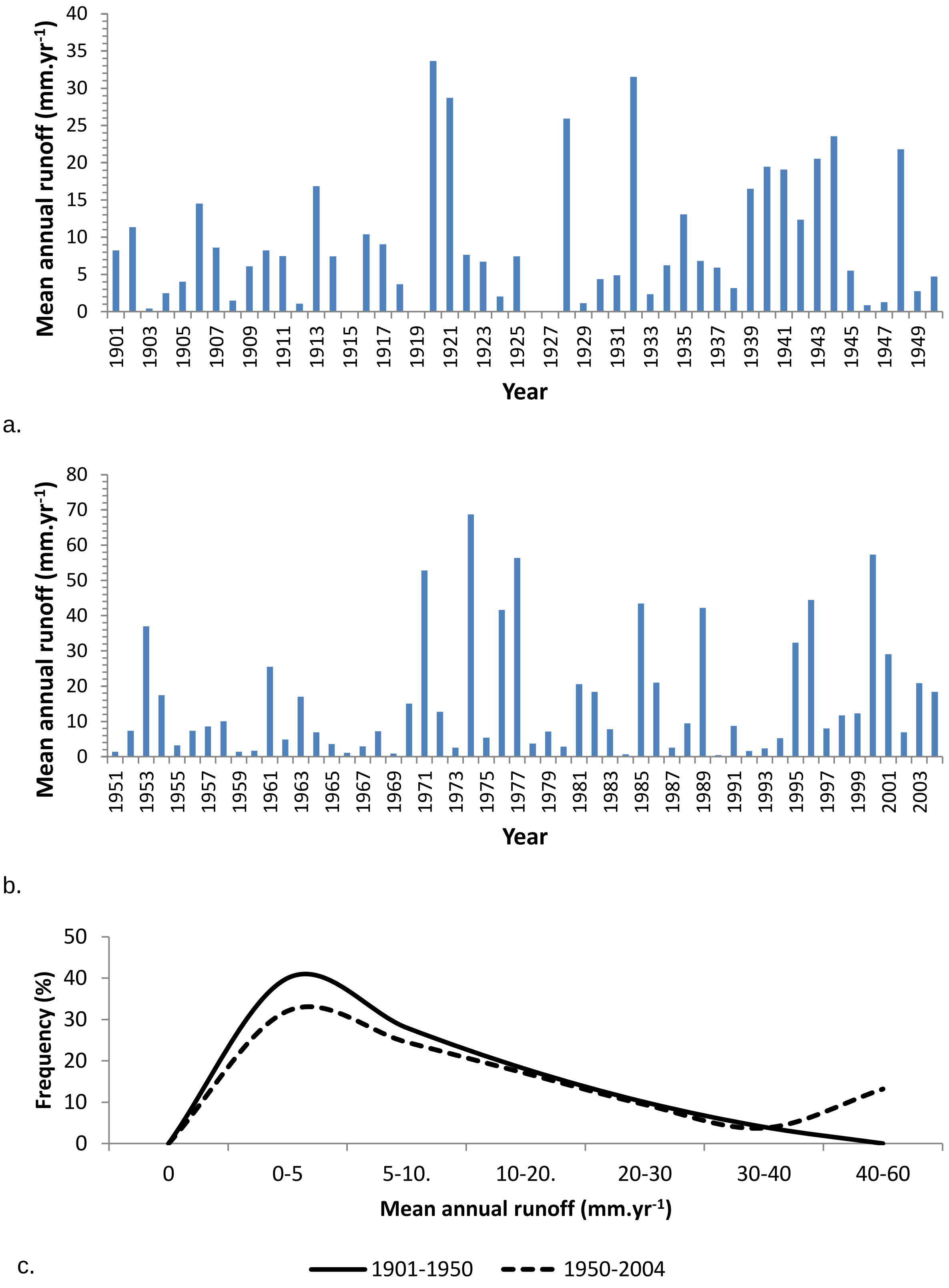


Figure 6.28 The distribution of the mean annual runoff for the Cranemere catchment from 1901 to 1950 (a) and 1950 to 2004 (b). The frequency distribution of annual runoff from 1901 to 1950 and from 1950 to 2004 (c) indicates that there is an increased frequency of extreme runoff events in the latter half of the century.

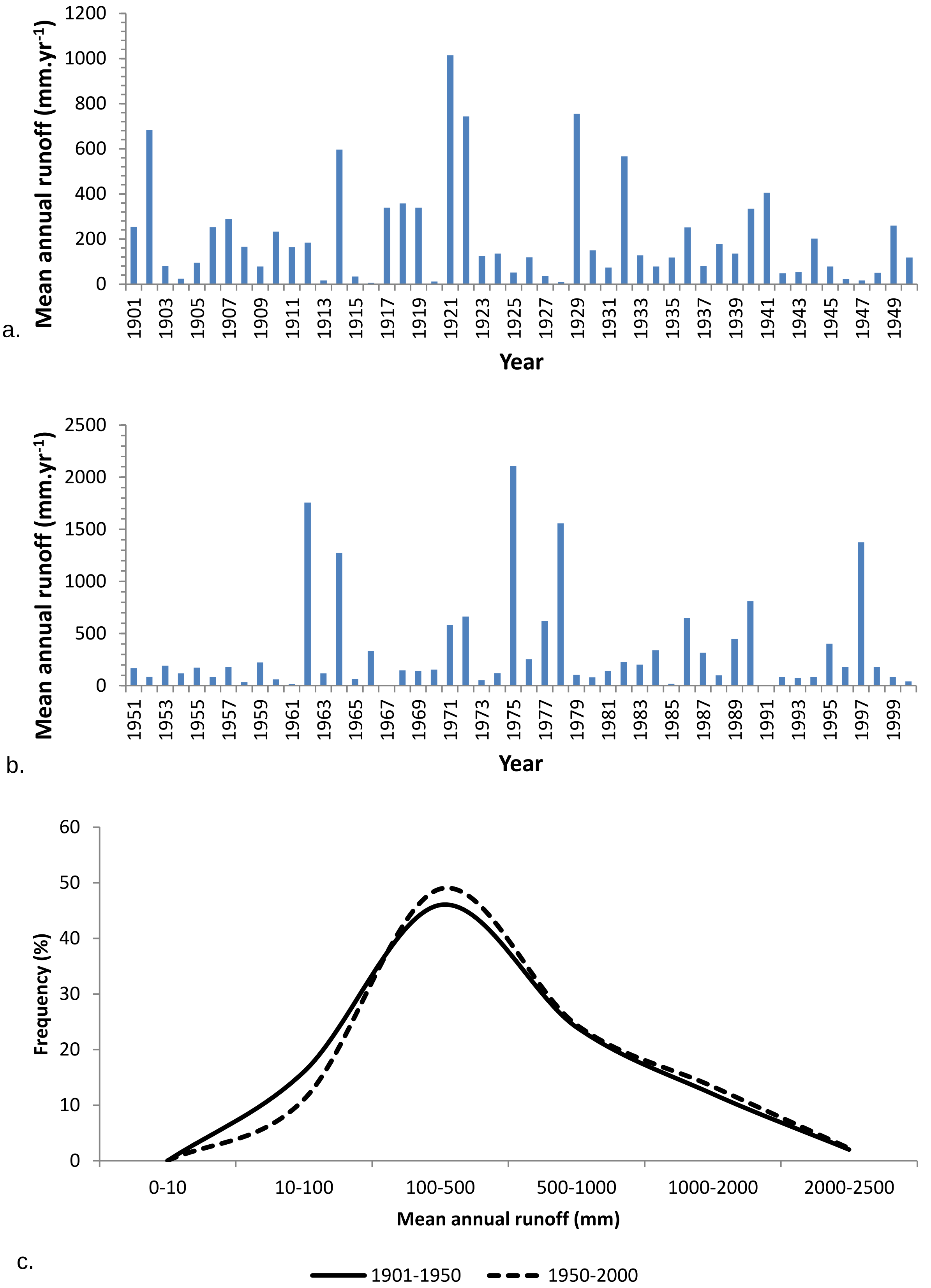


Figure 6.29 The distribution of the annual runoff for the Nqweba catchment from 1901 to 1999 (a) indicates that there was an increase in mean annual runoff (MAR) from 1950 to 1999. The frequency distribution of annual runoff from 1901 to 1950 and from 1950 to 1999 (b) indicates that there is a slight increased frequency of higher runoff events in the latter half of the century.

6.4 Concluding remarks

All catchments experienced a similar increase in sediment delivery and erosion during the latter half of the century. The exact timing of this increase was different for each catchment but the increased sediment delivery in the Nqweba catchment was most pronounced due to a large “pulse” of sediment delivery following a long dry period. It was proposed by Foster et al. (2011) that this increased sediment yield in the latter half of the century in the Ganora and Cranemere catchments was due to a combination of a degraded landscape following the impact of overgrazing in the 1930s, an increased connectivity within the catchment and an increase in the frequency of runoff events. The model was able to represent these hypotheses effectively and identify that a combined effect caused the increase in sediment yield. In order to represent an increase in sediment yield in the latter half of the century it was determined that an incorporation of a “switch” was needed. This involved running the model twice with different assumed conditions to represent a (dis)connected catchment and a connected catchment. The timing of this “switch” was different in all catchments.

The surface flow estimation component of the model effectively represented the “flashiness” of flow, which acted to effectively “flush” out sediment from temporary stores. The erosion estimation component of the model resulted in a modelled daily erosion time series which closely followed the surface flow time series as each surface flow event resulted in a corresponding erosion event. High sediment delivery events occurred following large dry periods as sediment stores were replenished before a high magnitude runoff event “flushed” out the large sediment stores. This characteristic became more pronounced as the catchment size increased. A focus on individual runoff events indicated that for the smaller catchments a peak in sediment delivery occurred on the following day to the peak in surface flow and erosion. This was representative of the “sediment cascade” as sediment would move through individual storage zones before being released as sediment delivery at the catchment outlet. Another characteristic was identifiable in that when a runoff event closely followed another runoff event that runoff would be less effective in “flushing” out sediment as sediment stores were usually depleted in the previous sediment delivery event. These examples indicate that both runoff and sediment availability are driving factors in the sediment delivery component of the model. For larger catchments these characteristics were less pronounced as large temporary sediment stores were less affected by low runoff events. High runoff events following a long dry period resulted in the “flushing” out of large temporary storage zones and a very high sediment delivery.

The erosion and sediment delivery model was able to effectively represent the sediment dynamics of both small and large catchments. The inclusion of the sediment storage or “sediment cascade” component was an important feature of the model. The discontinuous and “flushing” nature of flow with corresponding peaks in erosion and a lagged peak in sediment delivery were characteristics of semi-arid catchments which the model was able to represent. A limitation to the model is that when it is applied to large catchment the sediment has to travel through the storages of three runoff zones before reaching the main channel and generating sediment at the outlet. In reality, different parts of the catchment are better connected to the main channel than is represented in the model when it is applied at such a large scale. The implication is that the model structure requires modification, or that smaller sub-basins should be modelled with the current structure and their sediment outputs combined through a further ‘main channel’ delivery storage.

7 DISCUSSION

The aim of this chapter is to provide an overview of the key findings of this thesis. The applicability of the model in semi-arid catchments will be discussed with regards to the theoretical framework and important features identified in the study catchments. The approach to model development will be critically assessed on the basis of the inputs and outputs of the erosion and sediment delivery model. This will be assessed with regards to data requirements, uncertainties and parameter estimation. Following these assessments recommendations for future model development will be discussed in chapter eight.

7.1 The approach to the sediment delivery problem

The overall aim of this thesis was to develop a catchment scale model that represents the sediment dynamics of semi-arid regions of South Africa as a simple and practically applicable tool for water resource managers. Although water resource managers require quantifiable results to make decisions, it is also necessary to have a qualitative understanding of the processes being modelled. This meant that development of a conceptual framework for the model relied on an understanding of both the sediment dynamics of South African catchments and applicable modelling techniques. Representation of scale was an issue in both cases as much of our understanding of the physical processes of runoff generation and sediment transport, which informs erosion and sediment delivery models, has been derived from plot scale studies. Natural variability over both space and time have meant that quantifying these processes is difficult, leading to misrepresentation of sediment delivery at the catchment scale.

A strategy proposed by Wasson (2002) was to use a top-down approach when analysing erosion and sediment delivery processes. This would “immediately lift the modeller’s gaze” from the detail of low level processes (Wasson, 2002) and effectively “prune” superfluous process descriptions that do not improve results and only add uncertainty (Beven, 2002). As river systems are the integrated product of their environmental setting, it is possible to define general environmental characteristics as defining or emergent properties when describing a semi-arid catchment. The predominance of an erosion or sediment transport process depends on the spatial scale, topographic thresholds, rainfall, initial soil moisture content, and soil biological activity (Cammeraat, 2002); and the spatial configuration of land use, land cover, topography and lithology (De Vente et al., 2007). Above certain thresholds, when rill erosion, gully erosion, bank erosion and mass movements are initiated, connectivity will increase until slope gradient decreases and sediment yield becomes transport-limited (De Vente & Poesen, 2005). These factors can be grouped into climatic, topographic and catchment connectivity drivers which relate to particular emergent properties of semi-arid catchments. Emergent properties such as variable rainfall, flashiness of flow and event driven (dis)connectivity as well as the close relationship of vegetation density with rainfall are driven by climatic drivers. Topographic drivers are defined as the short-term control of slope on discharge and the long-term control of geology and tectonics and catchment connectivity is defined by the pattern of sediment sources and sinks within the landscape.

These emergent properties, defined as important characteristics of semi-arid catchments, were associated with surface flow, erosion and sediment storage and delivery components in the model. The conceptual framework was translated into a set of model equations which rely on a set of parameters. These parameters and runoff outputs from the disaggregated Pitman rainfall-runoff model are the inputs to the model. The model output is the total mass of daily erosion and sediment delivery (Figure 7.1) at various points within the system. The model relies on estimation of surface flow for areas of high, moderate and low runoff; erosion based on probability distribution functions for runoff, topography, soil erodibility, vegetation cover and management practices (through the MUSLE approach); and sediment storage and connectivity based on storage and connectivity equations. This can be conceptualised through a step-by-step process in that first runoff is estimated, then erosion, then sediment storage and sediment yield for each runoff zone and the main channel zone. This represents a “sediment cascade”.

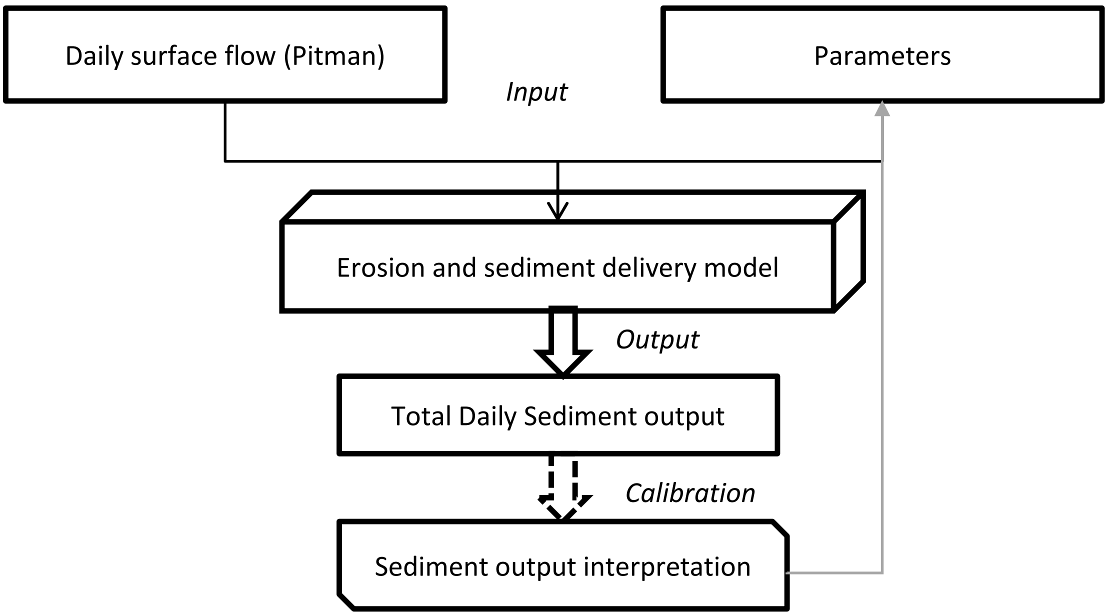


Figure 7.1 The structure of the erosion and sediment delivery model.

7.2 Applicability of the model to semi-arid catchments

The applicability of the model was critically assessed with regards to its ability to represent the emergent properties identified in chapter two. As described above emergent properties for semi-arid catchments were identified with regards to hydrological drivers, topographic drivers and catchment connectivity drivers. It was determined that these properties were effectively represented by using the Pitman rainfall-runoff model disaggregated to a daily timescale, the MUSLE model incorporating probability distribution function theory and the incorporation of several sediment storages within a single sub-catchment. This type of model provides a simple representation of the stochastic nature of erosion and sediment delivery over large spatial and temporal scales.

7.2.1 Applicability of the surface flow component

Hydrological drivers produce emergent properties for semi-arid catchments such as variable rainfall, "flashiness" of flow and event driven (dis)connectivity. The Pitman rainfall-runoff model disaggregated to a daily timescale was identified as a good hydrological model to represent the spatial and temporal variability of flow. However, the main reason for using this model was because it is being used within a broader water quality model that will eventually incorporate the sediment model developed within this study. Surface flow estimates are made for high, moderate and low runoff zones as well as the main channel zone. Each of these zones has different surface flow properties according to their position in the landscape. At the small catchment scale this representation of runoff was effective but as the catchment scale increased the structural constraints of the model meant that surface flow was not effectively represented throughout the whole catchment.

According to Cameraat (2002) connectivity of runoff-generating and runoff-absorbing areas is important at all scales, although at larger scales there are different critical thresholds that have to be surpassed to connect the high runoff zones with the low runoff zones. In semi-arid catchments transmission losses play a major role in hydrological connectivity at larger spatial scales. The high intensity, short duration storms are usually localized in semi-arid catchments, meaning that while runoff may be generated in the high runoff zone it may not always survive to contribute runoff at the catchment outlet (Hughes, 1995). When the model is applied to a larger catchment this characteristic is emphasized as runoff generated may be absorbed in deeper valley bottom soils, infiltrate into the bed and banks of alluvial river (Hughes & Sami, 1992) or be decreased by channel evaporative losses (McKenzie et al., 1993). In some instances high rates of upstream runoff can also be lost through infiltration into fractured bedrock channels and contribute to groundwater recharge (Sami, 1992). Only during more widespread rainfall events, or after several events closely following each other, may runoff reach the catchment outlet (Hughes, 1995).

In relation to the Nqweba and Cranemere catchments it can be expected that transmission losses are experienced as the flow frequency characteristics of the lower runoff zone are likely to be different to the high runoff zone, yet the model uses a single input time series to determine these characteristics. This indicates that surface flow characteristics have not been effectively represented in the surface flow component of the model. The effects of transmission losses are not accounted for within a single sub-catchment of the hydrological model. This represents a significant limitation to the surface flow estimation component of the model as surface flow is important for both the erosion and sediment delivery components of the model. This could be overcome by using more and smaller sub-catchments and including an additional channel sediment storage-routing function to link them.

The representation of variable rainfall was reliant on the daily rainfall data which was the input to the Pitman rainfall-runoff model. The "flashiness" of flow was effectively represented in all three catchments through significant peaks over the time series. These were important events in the model as they acted to effectively "flush" out sediment from temporary stores. Although there was a trend for an increase in magnitude and intensity of rainfall during the latter half of the century this was not considered to be the only factor causing an increased sediment yield.

7.2.2 Applicability of the erosion component

The close relationship between both vegetation density and topographic slope with flow are important properties of semi-arid areas. The steep uplands of a catchment will usually have low vegetation cover and high surface runoff associated with lower rates of infiltration due to thinner soils and higher hydraulic energy gradients. These relationships between erosion forcing factors and the spatial variation of erosion factors was accounted for by using the MUSLE model with a simple probability distribution approach to allow for uncertainties associated with sub-grid effects. The three runoff zones allowed the MUSLE model to be applied at a sub-grid scale by associating probability distributions of each erosion factor with these zones. This also allowed for the relationships between each factor to be effectively represented. Within the model the erosion algorithm is run at the sub-grid scale using simple Monte Carlo samples from the parameter distributions and then aggregating the erosion to get the total erosion for each runoff zone.

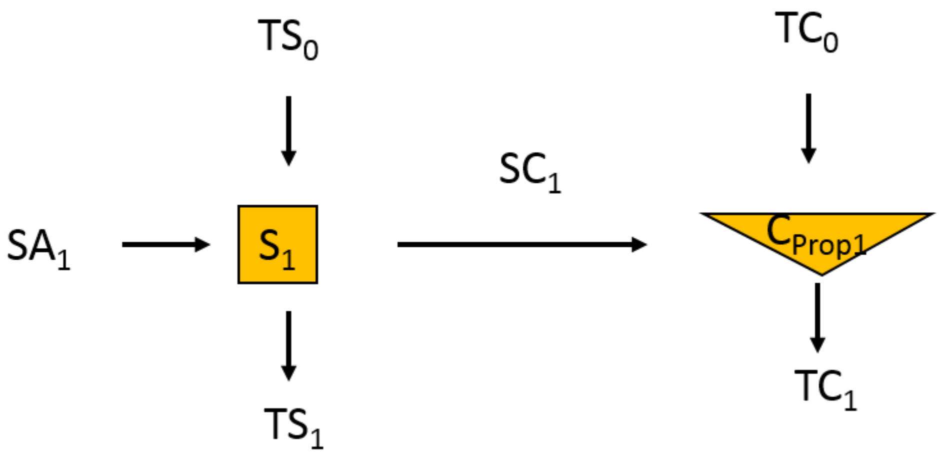
The runoff component of the erosion model is based on estimates of the peak instantaneous surface runoff rate with a fixed power function (Equation 5.6 and 5.5). The instantaneous runoff rate has to be estimated from the daily input flow data and relies on assumptions about the likely shape of hydrographs at sub-daily time scales (through parameter values). In the absence of adequate data to determine the relevant parameters the runoff inputs into the erosion model are likely to be very uncertain. This will be discussed in more detail in Section 7.3.

In general topography may determine the degree of connectedness or level of sediment yield of a catchment. With regards to its role in the erosion model topography relates to the amount of sediment made available for delivery. A steep catchment promotes the generation of sediment, whilst in contrast a gentle gradient catchment promotes sediment storage. The Ganora catchment can be considered to be in a high relief setting, in that most of the small catchment is relatively steep. In comparison the Cranemere catchment may be considered to consist mainly of low relief terrain as most of the catchment has a gentle gradient, providing a large capacity for temporary storage in the form of floodouts and alluvial fans. This difference in relief was represented through the topography factor. A high topography factor may be associated with high erosion values, whilst a low topography factor may be associated with a (dis)connected catchment with low erosion values.

The cover factor is associated with the extent of vegetation cover that protects the soil surface from rainwater impact or runoff detachment. It is considered an important property to consider in the MUSLE model (Sadeghi et al., 2014) but one that is difficult to estimate due to temporal and spatial variations. As vegetation cover in the Karoo is considered to be poor the cover factor was initially estimated to be quite high (i.e. conducive to erosion). Although it is expected that the cover factor may be lower in the headwater regions of a catchment the much lower cover factors used for the Ganora and Cranemere catchments were not considered to be representative. This adjustment in the cover factor parameter was considered necessary as when a high cover factor was used the erosion estimates in these small catchments was too high. Erosion and sediment yield estimates in small catchments should be closely related therefore the large erosion estimation in comparison to sediment delivery may be a structural fault in the model which will require further investigation. The Nqweba catchment performed well with regards to erosion estimation with a high cover factor. This may be a case of getting the right results for the wrong reasons as the effects of transmission losses (as described above) were not accounted for in the model.

7.2.3 *Applicability of the sediment storage and connectivity component*

The use of a storage and connectivity component in the model was considered very important as sediment which is made available by the erosion model does not immediately reach the catchment outlet but moves within a “sediment cascade”. This was represented through the storage zones and gully or channel connectivity within each zone (Figure 7.2). The sediment delivery during any day of the time series is determined partly by the relative amount of sediment in storage and partly by the relative size of any day’s runoff event compared to the maximum size of a runoff event expected in the specific catchment and a parameter representing a flow threshold for sediment movement. Only during infrequent, high magnitude events would the entire catchment area be considered effectively connected and the maximum storage zones would be “flushed” of stored sediment.



$$S_1New = S_1Old + SA_1 + TS_0 - CS_1 - TS_1$$

$$C_{Prop1}New = C_{Prop1}Old + SC_1 + TC_0 - TC_1$$

Figure 7.2 An example of the “sediment cascade” through the moderate runoff zone. Where $S_{A0,1,2}$ = Erosion in the zones; $S_{0,1,2}$ = Slope storage in the zones; $C_{Prop0,1,2}$ = Channel storage in the zones; $S_{C0,1,2}$ = Slope to channel store in the zones; $T_{S0,1,2}$ = Slope to slope transfer between the zones; $T_{C0,1,2}$ = Channel to channel transfer between the zones.

In general, topography may determine the degree of connectedness or level of sediment yield of a catchment. A steep catchment tends to be more connected than a catchment in gently sloping terrain (Fryirs et al., 2007). High relief promotes the generation of sediment and efficiency of sediment conveyance of hillslope derived sediments, whilst in contrast a low relief, low drainage density catchment, with relatively small source areas and extensive sediment stores represents a (dis)connected catchment. In a low energy setting sediment conveyance is restricted to episodic, infrequent, large magnitude events, with temporary stores having the potential to reside for many years. The Ganora catchment can be considered to be in a high relief setting, in that most of the small catchment is relatively steep and badland areas on the hillslopes are generally buffered from the channel network by alluvial fans. In comparison the Cranemere catchment may be considered to consist mainly of low relief terrain as most of the catchment has a gentle gradient, providing a large capacity for temporary storage in the form of floodouts and alluvial fans.

The Ganora and Cranemere catchments experienced significant changes in catchment connectivity during their sedimentation history. This relates to the reworking of landscape units which act to (dis)connect a catchment (Fryirs et al., 2007). The temporal variability of catchment (dis)connectivity is related to the size and sedimentary composition of the landscape unit or temporary storage zone and the magnitude-frequency of geomorphically effective events that rework these obstructions to sediment delivery. This provides a conceptualisation of a catchment system reliant on event driven connectivity to rework temporary sediment stores. The spatial pattern of these landscape units influences the timeframe over which sediments are reworked in different landscape compartments. In the Ganora catchment it was hypothesised by Foster & Rowntree (2012) that a change in connectivity occurred in 1967, when the badland areas in the west of the catchment were connected to the main channel. In the Cranemere catchment it was hypothesised by Rowntree & Foster (2012) that a change in connectivity occurred in 1950, when the main channel was connected to the catchment outlet. This "switch" in connectivity was effectively represented with the model by changing the connectivity parameters during the time series.

In the Ganora catchment the connectivity change was at the decadal scale, not just at the storm scale. This was notable in the need to incorporate a "switch" in catchment connectivity after the 1960s to represent an increased connectivity. This meant that the observed increase in sediment yield was not just dependent on increased rainfall magnitude and intensity but also due to the reworking of obstructions to sediment delivery. Similarly the Cranemere catchment connectivity change was at the decadal scale. Only once the "switch" in catchment connectivity was incorporated after the 1950s was the increased sediment yield represented in the sediment yield time series. This reflects the characteristic of semi-arid catchments having a pattern of sediment source, transfer and storage zones, and a degree of (dis)connectivity which is more likely to reflect the last infrequent high magnitude event that was able to "flush" sediment through the system (Schumm, 1977; Graf, 1988; Trimble, 1995). Sediment moves in infrequent bursts each time the floodplain channel is rejuvenated by a switch (Grenfell et al., 2014). The "sediment cascade" component of the model is reliant on both available sediment and the magnitude of the runoff event. By incorporating a "switch" in catchment connectivity in the model it was possible to represent this important characteristic in both the Ganora and Cranemere catchments.

During 1901-1967 the Ganora catchment was considered to have low catchment connectivity (Figure 7.3). The proportion of sediment store transferred to the gully or channel connections was low in all runoff zones during this time. This was represented by keeping the proportion of sediment storage for the gully or connectivity parameters low and the threshold flow high. From 1967-2003 there was a "switch" in connectivity as the badlands in the eastern half of the catchment were connected to the main channel (Figure 7.4). This was represented in the model by an increase in the proportion of sediment moved to gully or channel connections within the moderate and low runoff zones. This meant that the gully or channel connections in these zones directly contributed sediment to the main channel, which increased the sediment yield at the catchment outlet. The threshold flow was also decreased as the catchment was considered to be more effective at sediment delivery. The same process was followed with the Cranemere catchment to produce a "switch" in catchment connectivity after the 1950s (Figure 7.5 and Figure 7.6).

The general trend of high sediment delivery events following long dry periods was most pronounced in the larger Nqweba catchment. As the Nqweba catchment had a much larger capacity for sediment storage there was more potential for the build-up of sediment in temporary stores. Long dry periods protracted over years or even decades, result in an accumulation of sediment in channels and hillslopes, which may even decrease vegetation cover (Grenfell et al., 2014). These large sediment stores were effectively "flushed" out following high flow events, which accounts for the large sediment delivery events. A limitation of the model is that when it is applied to a large scale catchment the sediment has to travel through the storages of three runoff zones before reaching the main channel and generating sediment at the outlet. In reality, different parts of the catchment are better connected to the main channel than is represented in the model when it is applied at such a large scale. The implication is that the model structure requires modification, or that smaller sub-catchments should be modelled with the current structure and their sediment outputs combined through a further 'main channel' delivery storage.

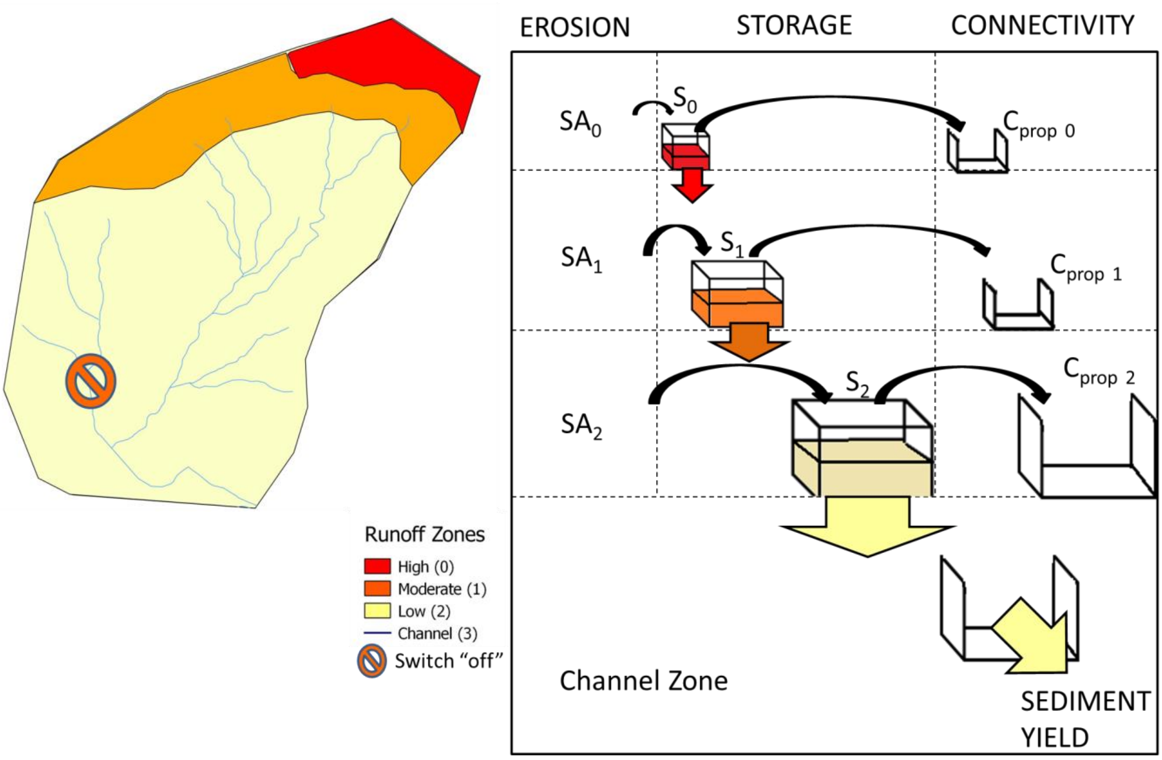


Figure 7.3 A conceptualisation of a (dis)connected Ganora catchment. Gully or channel zones are not effective at sediment transfer therefore most sediment moves through the sediment cascade via storage zones.

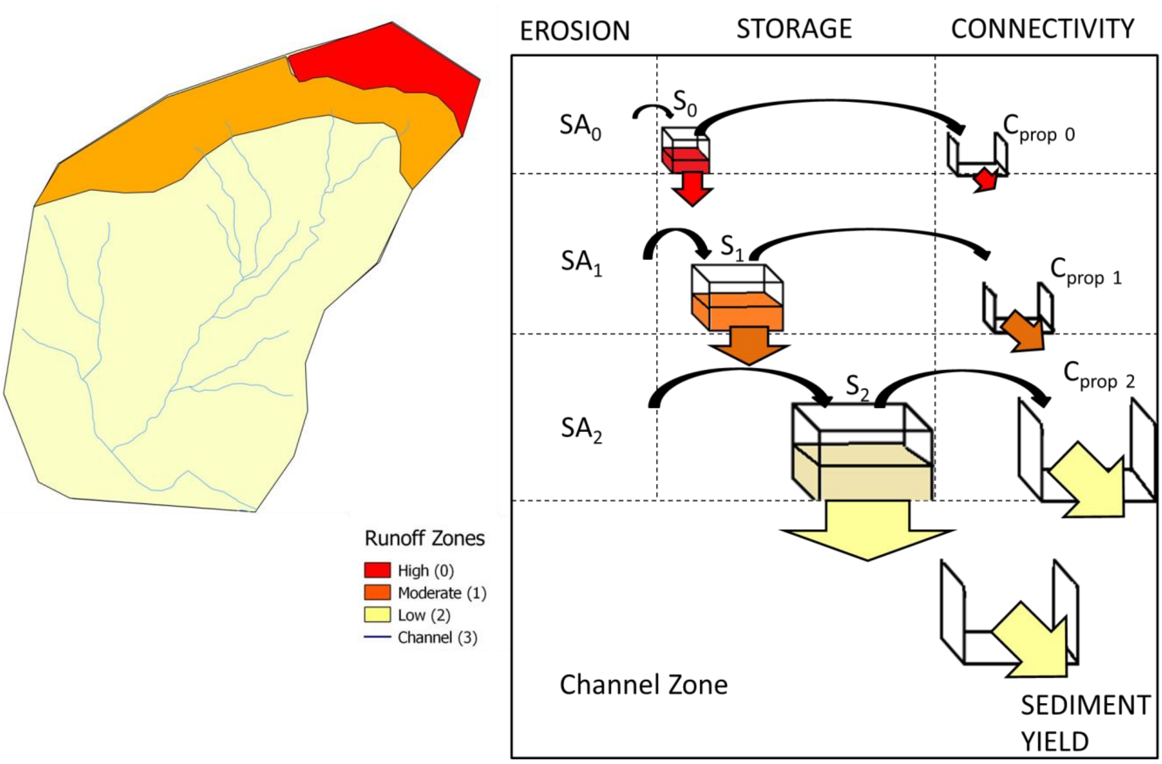


Figure 7.4 A conceptualisation of a connected Ganora catchment. Gully or channel zones are effective at sediment transfer and sediment moves through the sediment cascade via both storage zones and gully or channel transfer zones.

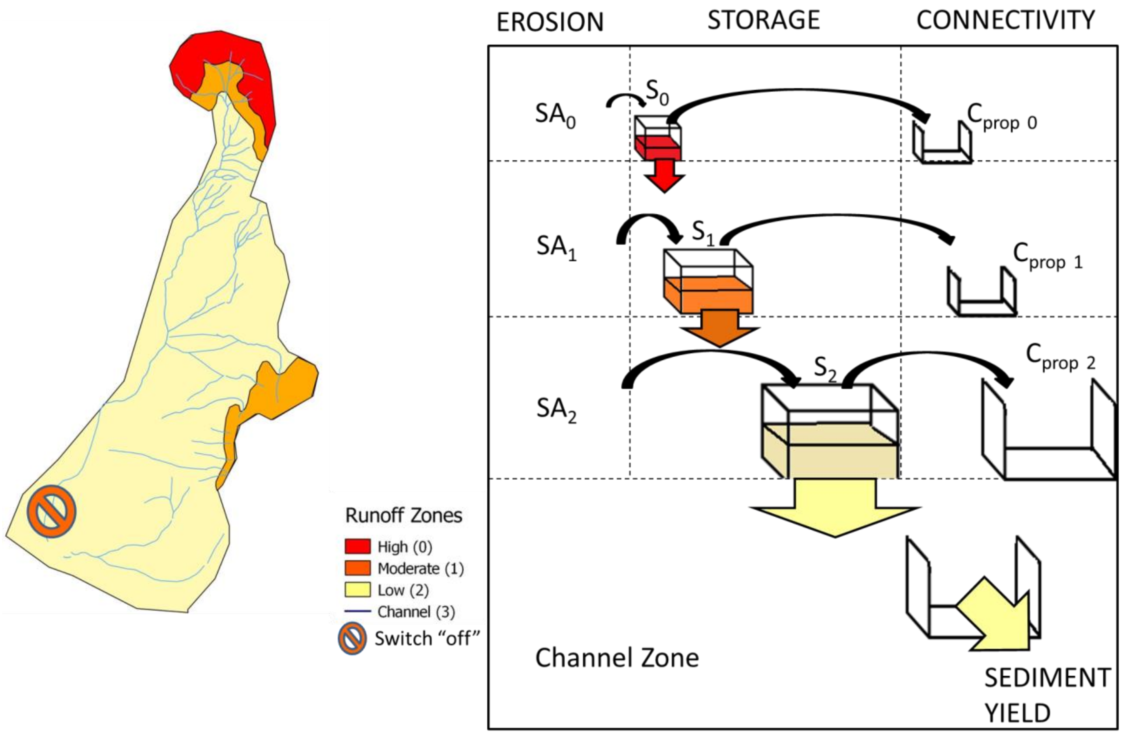


Figure 7.5 A conceptualisation of a (dis)connected Cranemere catchment. Gully or channel zones are not effective at sediment transfer therefore most sediment moves through the sediment cascade via storage zones.

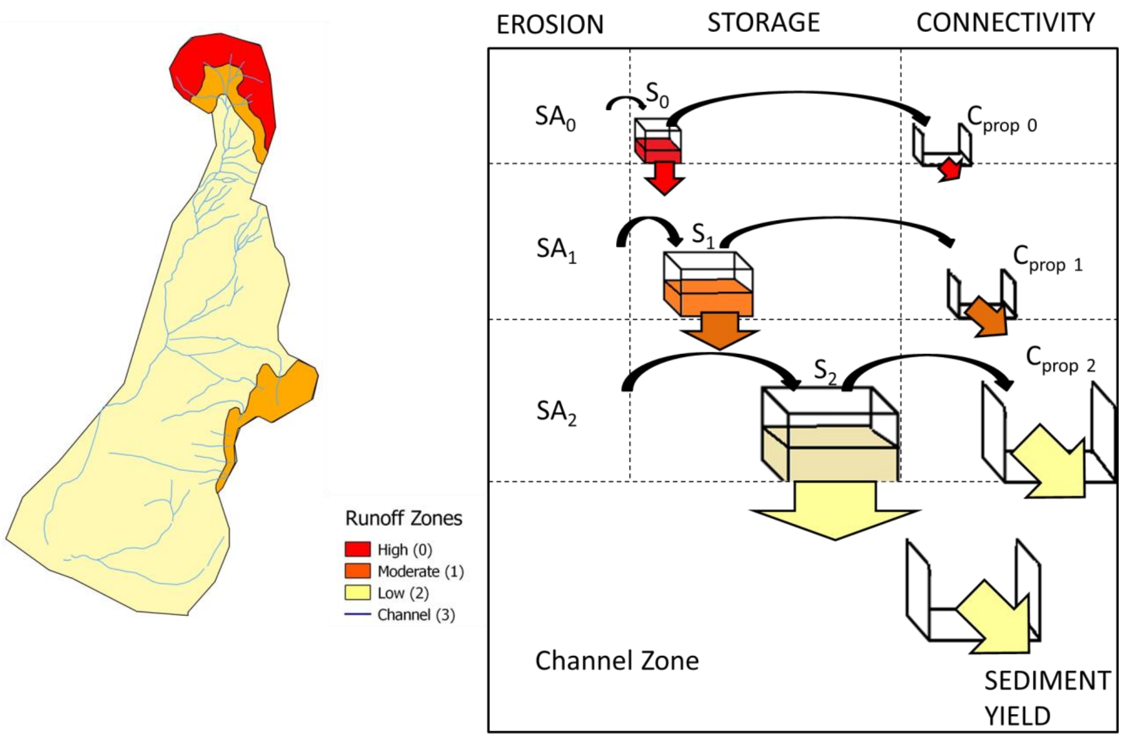


Figure 7.6 A conceptualisation of a connected Cranemere catchment. Gully or channel zones are effective at sediment transfer and sediment moves through the sediment cascade via both storage zones and gully or channel transfer zones.

7.3 Critical assessment of the model

A model structure needs to be developed through its parameters in order to determine realistic predictions. Calibration is the process of setting parameter values to give expected results, which involves continuously adjusting the parameters until a simulated time series is a close match to an observed time series. In most cases parameters will be calibrated on the basis of very limited measurements, by extrapolation from other sites or by inference by comparing observed responses with model outputs (Beven, 2009). The challenge in South Africa is finding consistency in parameter values in a region where the reliability and accuracy of input data is questionable (Hughes, 2004). The model structure used for the model parameters also makes calibration difficult as using statistical distributions introduces a degree of uncertainty and there may be strong interactions between parameters. Assessment of the model is therefore associated with what goes in (data) and what comes out (outputs). By scrutinising the model inputs and outputs it is possible to identify limitations and provide recommendations for future model development.

7.3.1 Inputs

There are inherent uncertainties involved in any use of a model, particularly those which include a large number of difficult to estimate parameters. The full erosion and sediment delivery model uses 25 parameters and this is far too many for a practical model, if they are all estimated with a relatively high degree of uncertainty. While it was recognised that the parameter space of the initial model is too great, the focus of this study was mainly on establishing a model that conformed as far as possible to the conceptual understanding of sediment erosion and delivery processes at the catchment scale. Future attention must be given to reducing the parameter space and the uncertainties in parameter estimation, possibly through more direct links between the parameters and measurable physical catchment properties. This is particularly true for the sediment storage zone parameters that are expected to be largely linked to topography, geomorphology and geology. There are many sophisticated GIS tools available that could be used to pre-process topographic information and automatically generate some of the parameter values, given some additional information on geology or sediment source rock type and perhaps climate. For the erosion parameters a series of look-up tables based on typically available information (soils, vegetation cover and topography) might solve some of the issues associated with parameter estimation uncertainty and reduce the task of trying to calibrate a large number of parameters.

The model structure accounts, to a certain extent, for sub-grid effects (i.e. spatial variability at more detailed scales than the main modelling scale) and this has contributed to the large parameter space. However, it is apparent from the example catchments used in this study that there are additional structural constraints associated with catchment size. Two of these have already been noted and were referred to earlier. The first is the fact that connectivity to the main river channel may extend into the high and moderate runoff zones within large catchments, while the model assumes that sediment delivery has to cascade through these zones before it reaches the main channel. The second is the known existence of channel transmission losses that may not be accounted for within a single sub-catchment of the hydrological model. Structural constraints within the model tend to dominate with an increase in catchment size. It may be necessary to reduce the catchment size by incorporating sub-basins with an additional in-stream sediment delivery component.

7.3.1.1 Surface flow inputs and parameters

Many of the uncertainties associated with the simulations of sediment delivery are linked with the uncertainties in the hydrological models used to provide the inputs to the sediment model developed during this study. This includes the monthly time step Pitman model (Hughes, 2013), as well as the disaggregation model used to obtain daily time series (Slaughter et al., 2014). In the absence of any observed stream flow, as is the case in the three example catchments, these uncertainties will inevitably be quite large, but assessing their impact was beyond the scope of this study.

Similarly, there are some parameters in the sediment model that are used to estimate instantaneous peak flow rates from the daily data and these are also difficult to evaluate without adequate observed data. The runoff factor relies on a power function to determine peak flow during each day of the model run. This power function may be highly sensitive and its application over an extended period of time may exacerbate any error. This feature of the model is outlined in more detail below.

7.3.1.2 Erosion parameters

There are many sources of error when using spatial data. In particular inputs are usually created from limited field data and with a lot of assumption allows for a degree of subjectivity (Jetten et al., 1999). This may be the case when determining the sub-basin distribution. The sub-basin scale of the model is based on the distribution of a catchment into high, moderate and low runoff zones as well as a main channel zone. This distribution is based on topographic characteristics through interpretation of GIS data. While the calculation steps are based on sophisticated tools, it is still important to analyse the results critically. In all catchments the largest proportion of the catchment was in the low runoff zone and the smallest in the channel zone. The distribution of the channel zone was calculated by delineating the main channel length and average width via aerial photography. The reliability of this technique is uncertain as it relies on individual interpretation. With an increase in catchment scale this technique becomes more uncertain and labour intensive. It is recommended that a less time consuming approach to drainage line interpretation should be evaluated, possibly through the Hydro toolset in ArcGIS.

Calculation of the runoff zone distribution relied on the distribution of the topography factor over a catchment through the incorporation of flow accumulation and slope estimation procedures in GIS. This was considered to provide reliable estimates, as runoff depth was assumed to be reliant on these factors. In general, the limitation with this process when applied to the large catchment scale occurred due to the main channel zone not “conceptually” extending into the high runoff zone. In reality at larger spatial scales the main channel would extend to such areas. It is for this reason that it is recommended that the catchment size be reduced by incorporating sub-catchments with an additional in-stream sediment delivery component. This component will inevitably be required if the model is to be applied at even larger scales with much higher degrees of spatial variability. The hydrological models are already designed to operate as semi-distributed model based on sub-catchment divisions so it should be relatively easy to extend this sub-division to the sediment model.

An erosion model parameter that needs further investigation is the power parameter for the peak flow determination for the runoff factor. This is considered to be a sensitive parameter and one that may be the cause for uncertainties in the erosion estimation procedures. Jetten et al. (1999) found that catchment scale models did not perform well in the prediction of peak discharge. The models also performed poorly with regards to the prediction of total sediment output. Although this did not say anything about the way erosion or sedimentation processes are modelled, what it did say was that erosion and sedimentation are controlled by water flux. If the peak discharge is not well predicted then this is reflected in the sediment export.

The adjustment of the cover factor for the Ganora and Cranemere catchment was necessary in order to force the model to make reasonable erosion estimates. Poor cover factors produced much larger erosion estimates than sediment delivery estimates, which meant that the model was very unstable. The large estimates of eroded sediment develop large sediment stores, with the potential to be removed following a large runoff event. A more reasonable erosion estimate was required to reduce the potential for large sediment delivery and make the model more stable. As the cover factor is considered to be such an important parameter in the erosion model it is recommended that more advanced techniques be used to develop a lookup table which incorporates both the Wischmeier and Smith (1978) table and specific information for South African vegetation types.

The soil erodibility and practice factors were estimated through the use of tables with reference to specific site information. In particular the prior knowledge of the site was required for these factors. Jetten et al. (1999) emphasises that knowledge related to agricultural activities, degree of soil structure change in the climatic context and a general feel for soils and relief were considered imperative to improved results. This was noticed through modelling a catchment with a straightforward geomorphology and field layout, with soils of homogenous texture can be very heterogeneous due to agricultural practices. The procedures followed for this study did not consider the spatial and temporal scale of these changes fully. This may need to be developed in future parameter estimation procedures.

7.3.1.3 Sediment delivery and storage parameters

The starting sediment store had a significant impact on the amount of sediment delivery in a catchment as a high starting sediment store would yield much higher sediment delivery than erosion. This was due to high starting sediment stores providing large sediment storage at the start of the time series, allowing for a potentially large sediment output. This was not considered realistic as all sediment stores would fill up much quicker. If delivery exceeds erosion in the long-term then it may be due to erosion being under-estimated through the erosion component of the model or due to over-estimating the starting storage and possibly the total storage.

The estimation of the maximum sediment storage is dependent on the distribution of the catchment into runoff zones, the maximum depth of sediment expected in the catchment and the bulk density of the sediment. The estimation of the maximum depth of sediment may require refinement as it relied on very limited background information for each catchment. It is recommended that a look-up table be developed with expected depth of sediment depending on the topography of a catchment. Steep areas would be expected to have small sediment stores in comparison to areas with a gentle gradient.

The gully or connectivity parameters also relied on a prior knowledge of the study area and a sense of the degree of connectivity in a catchment. Identification of gully systems was not only necessary at the spatial scale but as these systems are relatively recent features of the landscape their temporal changes was also required. This relied on a modeller's geomorphic knowledge to assess recent and historic aerial imagery and as mentioned above, a prior knowledge of the study area. This was apparent in the need to introduce a "switch" in the time series to represent a change in connectivity for the Ganora and Cranemere catchments. Connectivity of a catchment was also considered when determining the threshold flow parameter. The threshold flow parameter was adjusted to be low for highly connected catchments and high for (dis)connected catchments. This means that in a highly connected catchment a moderate magnitude runoff event may result in a sediment delivery event, as opposed to a high magnitude runoff event being needed in a (dis)connected catchment.

7.3.2 Outputs

In terms of calibration, the modelled results were compared to limited observed data. For the two smaller catchments sediment yield data was available over a long time period, but these data were available as average annual values. This is quite a coarse scale to work with when calibrating daily estimates. It was necessary to compare cumulative annual estimates with the available cumulative annual observed values in order to note significant trends in sedimentation history. This method of calibration means that the modeller needs to rely heavily on a qualitative understanding of a catchment to make sure that there is an understanding of both observed and modelled results.

Erosion and sediment delivery modelling is very error prone (Jetten et al., 1999) due in part to spatial and temporal variability in processes at the catchment scale. Although models do much better at estimating long term averages, attention must be paid to the finer time scale. There may be some overestimates, particularly of large sediment delivery events as a catchment is “flushed” of sediment, but overestimation during days with minimal surface flow need to be noted. These errors may not be observable when estimates are averaged out to an annual scale.

The erosion estimates were much larger than observed sediment yield in both of the smaller study catchments when reasonable cover factor parameter values were used. This indicates that the use of the MUSLE model by itself overestimates sediment yield or that the input parameters were wrong or that the MUSLE model cannot be applied directly at the catchment scale. It is considered more likely the application of the power function in the peak flow calculation for the runoff factor in the MUSLE model which caused this overestimation and not the cover factor. As has been outlined before, Jetten et al. (1999) found that it was the estimation of peak discharge which affected water flux and in turn the erosion and sediment outputs. It does not necessarily say anything about the way that the erosion or sedimentation processes are modelled. Adjustment of any of the erosion factors may result in similar results but the core of the problem is likely to be within the surface flow estimation procedure. Overestimation of erosion is considered to be a problem as this would mean that over an extended period of time temporary sediment stores would fill up with sediment and following an extreme runoff event the stores would be released as a significant peak in sediment yield. This is representative of the entire catchment being flushed of significant sediment stores, which is unrealistic. Although in this study the cover factor was adjusted to provide better correlation with sediment yield, the peak flow part of the MUSLE equation should be re-considered in future model developments.

The difference between erosion estimates and sediment delivery estimates as the catchment size increased may be caused by a flaw in the sediment storage component of the model. In larger catchments there is a larger capacity for storage, and whilst looking into transmission losses may be relevant it should also be noted that there may be a flaw in the sediment storage component of the model. Too much sediment may be stored, rather than being moved to the catchment outlet. If transmission losses were effectively modelled it would be expected that there would be an increase in erosion estimates, creating more sediment storage and compounding the effects of a flaw in the sediment storage component of the model.

As small scale catchments were more sensitive to connectivity changes it was necessary to incorporate a “switch” in connectivity during the time series. The “switch” allowed for the representation of significant changes in sediment yield after the 1950s in both of the small scale catchments. The manual adjustment of the connectivity parameters was not considered the optimum modelling procedure as it relies on the modellers understanding of the sedimentation history for study catchments. The large scale catchment was not as sensitive to changes in connectivity which may be a result of the application of the hydrological model at this scale.

8 GENERAL CONCLUSIONS

The overall aim of this thesis was addressed through the use of a conceptual framework which considered both an understanding of the sediment dynamics and applicable modelling techniques for semi-arid catchments. This thesis presents the conceptual framework as a useful first step towards development of a catchment scale erosion and sediment delivery model which can be used for short-term and long-term water quality modelling. There are both structural and data limitations which have been identified in this thesis which should be investigated further in the next step of model development. This chapter identifies the limitations and recommendations for further model development.

8.1 Applicability of the model for water resource management

The overall aim of this thesis was to develop a catchment scale model that represents the sediment dynamics of semi-arid regions of South Africa as a simple and practically applicable tool for water resource managers. The need for such a model was identified due to the importance of quantifying the significance of sedimentation and related water quality on scarce water resources in semi-arid regions of South Africa. Water resource managers will be able to use the model for long-term management of reservoir sedimentation, siltation of water diversion and irrigation schemes over an annual time-scale and short-term management of water quality over a daily time-scale. High sediment loads cause reservoir sedimentation and the siltation of water diversion and irrigation schemes, as well as increasing the cost of treating water abstracted from a river (Walling, 2009). High sediment loads can also result in pollution and habitat degradation in river systems and high sediment inputs into lakes and coastal seas can result in sedimentation and changes in nutrient cycling (Walling, 2009). These impacts have significant economic and environmental costs, which is why water resource managers need a tool to quantify the problem.

8.1.1 Long-term management of sedimentation

The source of sediment and sediment associated pollutants are of increasing concern to water resource managers, especially when considering the long-term consequences of sedimentation. An issue for managers is that whilst erosion factors are well understood at the plot scale, when scaling up to the more applicable catchment scale the role of these factors becomes less certain. The erosion and sediment delivery model is useful in this regard as it uses an overarching framework of connectivity to deal with the issue of scale. Connectivity will reflect the interactions and feedbacks of different catchment compartments or “runoff zones” under changing conditions and will determine the propagation of the effects of the change as the structure of the landscape is transformed (Lexartza-Artza & Wainwright, 2011).

An important consideration in long-term water resource management is an understanding of the issue of climate change. Understanding the impact of climate change on landscape processes is critical in determining what management strategies are necessary in the future (Grenfell et al., 2014). With regards to future projections for the effects of climate change on erosion and sediment yield it is noticeable that the sediment dynamics of semi-arid catchments are complex, making it difficult to predict how climate change will affect landscape processes and dynamics. As model results have indicated, the landscape is not completely controlled by climate, and where climate is important, its effect may be variable. Change can cascade through a system therefore it is extremely important to consider the spatial and temporal scale of a catchment. Given that extreme magnitude runoff events dominate sediment delivery, focussing on the impact on climate change in extreme events is crucial (Fryirs, 2013). Any changes in sediment flux associated with changes to the flow regimes will be mediated through changes in connectivity, therefore climate change may be identified through its effects upon landscape connectivity (Fryirs, 2013).The erosion and sediment delivery model will help to answer questions such as “if climate does influence a landscape, how will change be manifested in time and space?”; “will change be sudden and rapid?” (Grenfell et al., 2014) and “how will climate change impact upon the magnitude and frequency of different flow events, and whether this will change the typical sediment delivery and transfer regimes of catchments” (Fryirs, 2013).

8.1.2 Short-term management of water quality

One of the key approaches to managing water resources in South Africa is though the ecological Reserve that is associated with the determination of environmental water requirements. The ecological Reserve is made up of two components, water quantity (related to flow) and water quality. The water quantity determination methodology is relatively advanced in comparison with the water quality determination methodology (Slaughter, 2011). Along with limited research into water quality determination, South Africa also suffers from a lack of water quality data, in particular sedimentation data.

The linkage of the model with the Pitman rainfall-runoff model allows for an effective integration of a widely used hydrological model, which many South African water resource managers are already accustomed to. The linkage with the Pitman rainfall-runoff model also allows for the model to be used as a sub-model of a more comprehensive water quality model that has already been linked, but currently lacks a sediment sub-model. The model will be able to be linked to this model due to the modular structure of the water quality model.

The erosion and sediment delivery model will act as an informative tool for other water quality models. As the erosion and sediment delivery model is run on a daily timescale, water quality predictions may be related to specific sediment delivery events. The “sediment cascade” component of the model will allow for the identification of particular storage zones where nutrients may collect along with sediments.

The benefit of linking with an existing water quality model is in its attempt to address the challenges associated with limited resources in South African water resource management. The existing model’s simplicity and incorporation of uncertainty provides managers with an indication of risk associated with management decisions (Slaughter et al., 2012).

8.2 Recommendations for model development

Water resource managers in South Africa are faced with significant infrastructural, logistical and environmental challenges with limited resources in which to face these challenges. This has meant that models need to be designed to give useful predictions using available observed data (Slaughter et al., 2012). Data is a major issue in South Africa, where daily observed flow data may be available for main rivers and not for tributaries. Corresponding water quality data are even scarcer, with data being collected on a temporal scale ranging from twice-weekly to once every few years (Slaughter et al., 2012). This constrained the development of the model to be for situations with limited data.

The erosion and sediment delivery model outlined in this thesis relied on a conceptual framework for semi-arid South African catchments which provided a general overview of what was important in a catchment scale model. There were certain properties which were considered “defining” properties for semi-arid catchments which needed to be modelled effectively. Assessment of the modelling situation in South Africa was also important as this determined the choice in modelling technique. Data limitations and the need to provide a simple and practical tool for water resource managers constrained the model structure to be a simple representation of reality.

Although the number of parameters used was large, it was considered necessary as an initial step in model development. The issue of scale was dealt with by using a sub-grid scale with probability theory being used for the erosion component of the model and storages and connectivity functions being used for the sediment delivery component of the model. It is apparent that there are inherent structural constraints for both the small and large scale application of the model, possibly related to the hydrological model.

Before the model may be applicable to short-term and long-term water quality modelling, certain aspects of the model need to be investigated further (Figure 8.1). The next steps in model development are to reduce the parameter space through more direct links between the parameters and measurable physical catchment properties. This may be achieved through linking the storage zone parameters to GIS and erosion parameters based on typically available information. Seasonal changes in vegetation may also be incorporated in this way. This may reduce parameter uncertainty and decrease the time spent on calibration. A set of calibration data should also be developed for model users to compare model results to. This may be available in an excel spreadsheet, which could be used in accordance with analysis of model results.

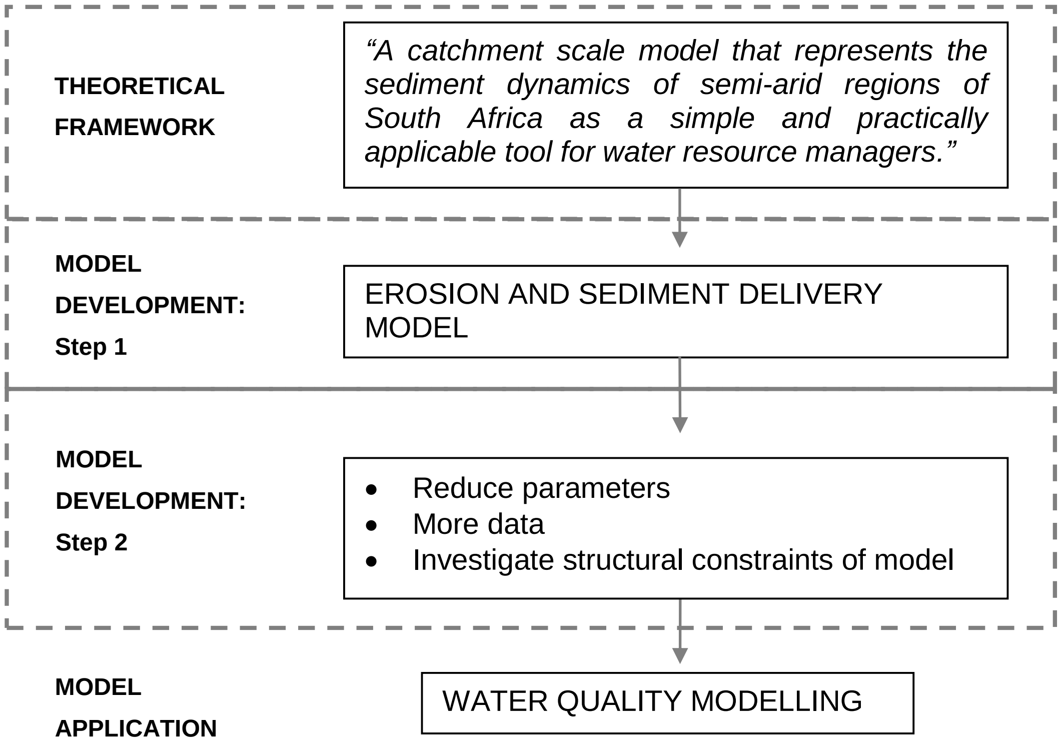


Figure 8.1 The way forward for the model development before application as a water quality model.

The structural constraints of the model also need to be assessed. This refers to the connectivity of the main channel with the high and moderate runoff zones when the model is applied to large scale catchments and the incorporation of channel transmission losses within a single sub-catchment of the hydrological model. The problem with large scale catchment application may be reduced by incorporating sub-basins with an in-stream sediment delivery component. Although data limitations constrain the functioning of the hydrological model it may also be necessary to look into the power function of the peak flow calculation on the erosion model.

8.3 Conclusions

The erosion and sediment delivery model is representative of semi-arid catchments in South Africa, where sediment delivery usually occurs during infrequent, high magnitude runoff events. This model potentially fills a gap in the available water resources modelling tools of South Africa, where available models are either too complex for data poor environments or do not account for important processes within a semi-arid catchment. It provides a simple representation of the stochastic nature of erosion and sediment delivery over large spatial and temporal scales. It is considered a useful tool for long-term management of sedimentation in reservoirs and short-term management of water quality in semi-arid regions where water is a limited resource. The identification of defining properties driving surface flow, erosion and sediment storage and delivery components may provide a simplistic conceptualisation of a complex system but in effect it is the stripping down of “superfluous” processes that allows for an effective representation of the important properties in semi-arid catchments in South Africa. This provides the foundation for a simple and practically applicable tool for South African water resource managers.

REFERENCES

Acocks, J. P. (1953). Veld types of of South Africa. *Memoirs of the Botanical Survey of South Africa* , 28: 1-192.

Aksoy, H., & Kavvas, M. (2005). A review of hillslope and watershed scale erosion and sediment transport models. *Catena*, 64: 247-271.

ARC-ISCW (Agricultuaral Research Council- Institute for Soil, Climate and Water. Land Type Survey Staff, 1972 – 2006. Land Types of South Africa: Digital map. Pretoria.

Beasley, D. B., Huggins, L. F., & Monke, E. J. (1980). ANSWERS: A model for watershed planning. *Transactions of the American Society of Agricultural Engineers*, 23: 938–944.

Beven, K. J. (2009). *Environmental Modelling: An Uncertain Future?* London: Routledge.

Beven, K. (2001). *Rainfall-Runoff Modelling: The Primer.* Chichester: John Wiley & Sons.

BGIS (Biodiversity GIS), (2007). *Vegmap*. Retrieved from Biodiversity GIS: http://bgis.sanbi.org/vegmap/map2009.asp.

Boardman, J. (2012). Soil erosion and land degradation. In P. Holmes, & M. Meadows (Eds.), *Southern African Geomorphology: Recent trends and new directions.* (pp. 307-328). Bloemfontein: SUN media.

Boardman, J. (2006). Soil erosion science. Reflections on the limitations of current approaches. *Catena*, 68: 73-86.

Boardman, J., & Foster, I. D. (2008). Badland and gully erosion in the Karoo, South Africa. *Journal of Soil and Water Conservation*, 63: 121-125.

Boardman, J., Parsons, A. J., Hollard, R., Holmes, P. J., & Washington, R. (2003). Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa. *Cantena*, 50: 165-184.

Bracken, L. J., & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, 21: 1749–1763.

Brierley, G. J., Fryirs, K. A., Boulton, A., & Cullum, C. (2008). Working with change: the importance of evolutionary perspectives in framing the trajectory of river adjustment. In G. J.

Brierley, & K. A. Fryirs, *River futures an integrative scientific approach to river repair.* Island press: Washington.

Bryan, R., & Yair, A. (1982). Perspectives on studies of badland geomorphology. In R. Bryan, & A. Yair, *Badland Geomorphology and Piping.* Norwich: Geo Books.

Bull, L. J., & Kirkby, M. J. (2002). Dryland river characteristics and concepts. In L. J. Bull, & M. J. Kirkby, *Dryland rivers: hydrology and geomorphology of semi-arid channels* (pp. 3–15). Chichester: John Wiley & Sons.

Bull, W. B. (1979). Threshold of critical power in streams. *Geological Society of America Bulletin*, 90: 453-464.

Bunn, S. E., Thoms, M. C., Hamilton, S. K., & Capon, S. J. (2006). Flow variability and dryland rivers: boom', 'bust' and the bits in between. *River Research and Applications*, 22:179-186.

Cammeraat, E., van Beek, R., & Kooijman, A. (2005). Vegetation succession and its consequences for slope stability in South East Spain. *Plant Soil*, 278: 135-147.

Cammeraat, L. H. (2002). A review of two strongly contrasting geomorphologicalsystems within the context of scale. *Earth Surface Processes and Landforms*, 27: 1201-1222.

Cammeraat, L. H. (2004). Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in Southeast Spain. *Agriculture, Ecosystems and Environment*, 104: 317-332.

Cantón, Y., Domingo, F., Sole-Benet, A., & Puigdefabregas, J. (2001). Hydrological and erosion response of a badlands system in semiarid SE Spain. *Journal of Hydrology*, 252: 65–84.

Cantón, Y., Solé-Benet, A., de Vente, J., Boix-Fayos, C., Calvo-Cases, A., Asensio, C., and Puigdefábregas, J. (2011). A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. *Journal of Arid Environments*, 75: 1254-1261.

Chapra, S. C. (2003). Engineering Water Quality Models and TMDLs. *Journal of Water Resources Planning and Management*, 247 – 257.

Clarke, M. L., Vogel, J. C., Botha, G. A., & Wintle, A. G. (2003). Late Quaternary hillslope evolution recorded in eastern South African colluvial badlands. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 197(3): 199-212.

Dardis, G. F. (1990). Late Holocene erosion and colluvium deposition in Swaziland. *Geology*, 18: 934-937.

De Roo, A. P., Wesseling, C. G., & Ritsema, C. J. (1996). LISEM: a single event physically-based hydrologic and soil erosion model for drainage basins: I. Theory, input and output. *Hydrological Processes*, 10(8):1107–1117.

De Vente, J., & Poesen, J. (2005). Predicting soil erosion and sediment yield at the basin scale: Scale-issues and semi-quantitative models. *Earth-Science Reviews*, 71: 95–125.

De Vente, J., Poesen, J., Arabkhedri, M., & Verstraeten, G. (2007). The sediment delivery problem revisited. *Progress in Physical Geography*, 31 (2): 155-178.

De Villiers, J. W., & Basson, G. R. (2007). Modelling of long term sedimentation at Welbedacht reservoir, South Africa. *Journal of South African Institute of Civil Engineering*, 49:4: 10-18.

Dunne, T. (1978). Field studies of hillslope flow processes. In M. Kirkby, *Hillslope Hydrology* (pp. 227-294). Chichester: John Wiley & Sons.

DWS (Department of Water Affairs and Sanitation) Retrieved from DWS Hydrological services: https://www.dwaf.gov.za/hydrology/

Ebisemiju, F. S. (1990). Sediment delivery ratio prediction equations for short catchment slopes in a humid tropical environment. *Journal of Hydrology*, 114: 191–208.

Faulkner, H., Alexander, R. W., & Zukowskyj, P. (2008). Slope-channel coupling betweenpipes, gullies and tributary channels in the Mocatán catchment badlands,Southeast Spain. *Earth Surface Processes and Landforms*, 33: 1242-1260.

Ferguson, R. I. (1981). Channel forms and channel changes. In J. Lewin, *British Rivers* (pp. 90–125). London: Allen and Unwin.

Flanagan, D. C., & Nearing , M. A. (1995). *USDA Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation, NSERI Report No. 10.* West Lafayette: USDA-ARS National Soil Erosion Research Laboratory.

Flanagan, D. C., Ascough, J. C., Nearing, M. A., & Laflen, J. M. (2001). The Water Erosion Prediction Project (WEPP) model. In R. S. Harmon, & W. W. Doe, *In Landscape Erosion and Evolution Modelling* (pp. 145–199). New York: Kluwer Academic.

Foster, I. D., & Rowntree, K. M. (2012). Sediment yield changes in the semi-arid Karoo: a palaeoenvironmental reconstruction of sediments accumulating inCranemere Reservoir, Eastern Cape,SouthAfrica. *Zeitschrift für Geomorphologie, Supplementary Issues* , 56(3): 131-146.

Foster, I. D., Boardman, J., & Gates, J. B. (2008). Reconstructing historical sediment yields from the infilling of farm reservoirs, Eastern Cape, South Africa. *IAHS Publication*, 325: 440-447.

Foster, I. D., Boardman, J., & Keay-Bright, J. (2007). Sediment tracing and environmental history for two small catchments, Karoo uplands, South Africa. *Geomorphology*, 90: 126-143.

Foster, I. D., Rowntree, K. M., Boardman, J., & Mighall, T. M. (2012). Changing sediment yield and sediment dynamics in the Karoo uplands, South Africa; Post-European impacts. *Land Degradation & Development*, 23(6), 508-522.

Foster, I. D., Rowntree, K., Boardman, J., & Mighall, T. (2012). Changing sedimentary yield and sediment dynamics in the Karoo uplands, South Africa; post-European impacts. *Land Degradation and Development*, 23: 508–522.

Frissell, C. A., Liss, M. D., Warren, C. E., & Hurley, M. D. (1986). A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management*, 10: 199-214.

Fryirs, K. A. (2013). (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*, 38: 30–46.

Fryirs, K. A., Brierley, G. J., Preston, N., & Kasai, M. (2007). Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Cantena*, 70: 49-67.

Fryirs, K., & Brierley, G. (1999). Slope-channel decoupling in Wolumla catchment, New South Wales, Australia: the changing nature of sediment sources following European settlement. *Catena*, 35: 41–63.

Garland, G. G., Hoffman, M. T., & Todd, S. (2000). Soil degradation. In M. T. Hoffman, S. Todd, Z. Ntshona, & S. Turner, *A National Review of Land Degradation in South Africa* (pp. 69-107). Pretoria: South African Biodiversity Institute.

Glymph, L. M. (1954). Studies of sediment yields from watersheds . *International Association of Hydrology 10th General Assembly* (pp. 1: 178-191). Rome: International Union of Geodynamics and Geophysics.

Graf, W. L. (1988). *Fluvial Processes in Dryland Rivers.* New Jersey: Blackburn Press.

Grenfell, M. C., Ellery, W. N., & Grenfell, S. E. (2009). Valley morphology and sediment cascades within wetland systems in Kwazulu Natal Drakensberg foothills, eastern South Africa. *Cantena*, 78: 20-35.

Grenfell, S. E., Grenfell, M. C., Rowntree, K. M., & Ellery, W. N. (2014). Fluvial connectivity and climate: A comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa. *Geomorphology*, 205: 142-154.

Haan, C. T., Barfield, B. J., & Hayes, J. C. (1994). *Design Hydrology and Sedimentology for Small Catchments.* San Diego: Academic Press.

Harvey, A. M. (2001). Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity illustrated from the Howgill Fells, northwest England. *Catena*, 42: 225–250.

Harvey, A. M. (2002). Effective timescales of coupling within fluvial systems . *Geomorphology*, 44: 175–201.

Harvey, A. M. (1977). Event frequency in sediment production and channel change. In K. J. Gregory, *River Channel Changes* (pp. 301-315). Chichester: John Wiley & Sons.

Harvey, A. M. (1974). Gully erosion and sediment yield in the Howgill Fells, Wellmorland. In K. J. Gregory, & D. E. Walling, *Fluivial Processes in Instrumental Watersheds* (pp. 6: 45-58). London: Institute of British Geographers.

Harvey, A. M. (2012). The coupling status of alluvial fans and debris cones: a review and synthesis. *Earth Surface Processes and Landforms*, 37: 64-76.

Hewlett, J. D., & Hibbert, A. R. (1967). Factors affecting the response of small watersheds to precipitation in humid areas. *Forest Hydrology: Proceeds of the International Symposium on Forest Hydro!ogy* (pp. 275-290). Pennsylvania: Pennsilvia State Univiversity.

Hoffman, M. T., & Ashwell, A. (2001). *Nature divided: Land degradation in South Africa.* Cape Town: Cape Town Univiversity Press.

Hoffman, T., Todd, S., Ntoshona, Z., & Turner, S. (1999). *Land degradation in South Africa.* Cape Town: Cape Town National Botanical Institute.

Hoffman, M.T., Carrick, P.J., Gillson L., West A.G. (2009). Drought, climate change and vegetation response in the succulent karoo, South Africa. *South African Journal of Science* 105: 54-60.

Hooke, J. (2003). Coarse sediment connectivity in river channel systems: a conceptual framework and methodology . *Geomorphology*, 56(12): 79-94.

Hooke, J. M. (2006). Human impacts on fluvial systems in the Mediterranean region. *Geomorphology*, 79 (3–4): 311–315.

Hughes, D. A. (1995). Monthly rainfall-runoff models applied to arid and semiarid catchments for water resource estimation purposes. *Hydrological Sciences Journal*, 40(6): 751-769.

Hughes, D. A. (2004). Three decades of hydrological modelling research in South Africa. *South African journal of science*, 100(11 & 12): p-638.

Hughes, D.A. (2008). Simulating the hydrology and total dissolved solids (TDS) of an ephemeral river in South Africa for environmental water requirement determinations. *River Research and applications*, 24: 1-11.

Hughes, D.A. (2013). A review of 40 years of hydrological science and practice in southern Africa using the Pitman rainfall-runoff model. *Journal of Hydrology*, 501: 111-124.

Hughes, D. A., & Sami, K. (1992). Transmission losses to alluvium and associated moisture dynamics in a semiarid ephemeral channel system in southern Africa. *Hydrological Processes*, 6: 45-53.

Jetten, V., Govers, G., & Hessel, R. (2003). Erosion models: quality of spatial predictions. *Hydrological Processes*, 17: 887–900.

Kaey-Bright, J., & Boardman, J. (2009). Evidence from field-based studies of rates of soil erosion on degraded land in the central Karoo, South Africa. *Geomorphology*, 103: 455-465.

Kakambo, V., & Rowntree, K. M. (2003). The relationship between land use and soil erosion in the communal lands near Peddie town, Eastern Cape, South Africa. *Land Degradation and Development*, 14: 39-49.

Kakembo, V., Xanga, W. W., & Rowntree, K. M. (2009). Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa. *Geomorphology*, 110: 188-194.

Kavvas, M. L. (1999). On the coarse-graining of hydrologic processes with increasing scales. *Journal of Hydrology*, 217: 191–202.

Keay-Bright, J. B. (2006). Changes in the distribution of degraded land over time in the central Karoo, South Africa. *Catena*, 67: 1 – 14.

Keay-Bright, J., & Boardman, J. (2006). Changes in the distribution of degraded land over time in the central Karoo, South Africa. *Catena*, 67: 1–14.

Keay-Bright, J., & Boardman, J. (2007). The influence of land management on soil erosion in the Sneeuberg Mountains, Central Karoo, South Africa. *Land degradation & development*, 18(4): 423-439.

Keay-Bright, J., & Boardman, J. (2007). The influence of land management on soil erosion in the Sneeuberg Mountains, Central Karoo, South Africa. *Land degradation & development*, 18(4): 423-439.

Kirkby, M. J., Abrahart, R., McMahon, M. D., Shao, J., & Thornes, J. B. (1998). MEDALUS soil erosion models for global change. *Geomorphology*, 24(1): 35-49.

Kinnell, P. I. (2004). Sediment delivery ratios: a misaligned approach to determining sediment delivery from hillslopes. *Hydrological Processes*, 18(16): 3191-3194.

Kinnell, P. I. (2001). The USLE-M and modeling erosion within catchments. In D. E. Slott, R. H. Mohtar, & G. C. Steinardt, *Selected papers from the 10th international soil conservation organization meeting, 24–29 May 1999* (pp. 924–928). Purdue University and the US Department of Agriculture-ARS National Soil Erosion Research Laboratory.

Kinnell, P. I. (2005). Why the universal soil loss equation and the revised version of it do not predict event erosion well. *Hydrological Processes*, 19: 851–854.

Knighton, A. D., & Nanson, G. C. (1997). Distinctiveness, diversity and uniqueness in arid zone river systems. In D. S. Thomas, *Arid Zone Geomorphology: Process, Form and Change in Drylands, 2nd Edition* (pp. 185–203). Chichester: JohnWiley & Sons.

Knighton, D. A., & Nanson, G. C. (2002). Inbank and overbank velocity conditions in an arid zone anastomosing river. *Hydrological Processes*, 16(9): 1771-1791.

Knisel, W. G. (1991). CREAMS/GLEAMS: a development overview. In D. B. Beasley, W. G. Knisel, & A. P. Rice, *Proceedings of the CREAMS/GLEAMS Symposium* (pp. 9–17). Athens, GA: Publication 4, Agricultural Engineering Department, University of Georgia.

Lal, R. (2001). Soil degradation by erosion. *Land Degradation and Development*, 12: 519–53.

Langbein, W. B., & Schumm, S. A. (1958). Yield of sediment in relation to mean annual precipitation. *Transactions American Geophysical Union*, 39: 1076– 1084.

Le Roux, J. J., Morgenthal, T. L., Malherbe, J., Pretorius, D. J., & Sumner, P. D. (2008). Water erosion prediction at a national scale for South Africa. *Water SA, 34* (3), 305-314.

Le Roux, J. J., Newby, T. S., & Sumner, P. D. (2007). Monitoring soil erosion in South Africa at a regional scale, review and recommendations. *South African Journal of Science*, 103: 329-335.

Le Roux, J. J., Sumner, P. D., Lorentz, S. A., & Germishuyse, T. (2013). Connectivity aspects in sediment migration modelling using the Soil and Water Assessment Tool. *Geosciences*, 3(1):1–12.

Leopold, L. B., Wolman, M. G., & Miller, J. P. (1964). *Fluvial processes in geomorphology.* San Francisco: Freeman.

Lesschen, J. P., Cammeraat, L. H., & Niemann, T. (2008). Erosion and terrace failure due to agricultural abandonment in a semi-arid environment. *Earth Surface Processes and Landforms*, 33: 1574-1584.

Lewin, J., Macklin, M., & Woodward, J. (1995). *Mediterranean Quaternary River Environments.* Rotterdam: Balkema.

Lexartz-Artza, I., & Wainwright, J. (2011). Making connections: changing sediment sources and sinks in an upland catchment . *Earth Surface Processes and Landforms*, 36 (8): 1090-1104.

Livesey, R. H. (1975). *Corps of Engineers methods for predicting sediment yields.* USDA, Agricultural Research Service ARS-S-40.

Ludwig, J. A., Wilcox, B. P., Breshears, D. D., Tongway, D. J., & Imeson, A. C. (2005). Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology*, 86(2): 288-297.

Maner, S. B., & Barnes, L. H. (1953). *Suggested Criteria for Estimating Gross Sheet Erosion and Sediment Delivery Rates for the Blackland Prairies Problem Area in Soil Conservation.* Washington: U.S. Department of Agriculture, Soil Conservation Service.

Marzolff, L., Ries, J. B., & Poesen, J. (2011). Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. *Earth Surface Processes and Landforms*, *36*(12), 1604-1623,

McCarthy, T. S., & Ellery, W. N. (1998). The Okavango Delta. *Transactions of the Royal Society of South Africa*, 53(2): 157-182.

McCarthy, T., & Rubridge, B. (2005). *The Story of Earth & Life; a Southern African Perspective on a 4.6 Billion Year Journey.* Cape Town: Struik.

McKenzie, R. S., Roth, C., & Stoffberg, F. (September 1993). Orange River losses. *Sixth South African National Hydrological Symposium*, (pp. 351-358). Pietermaritzburg, South Africa.

McMahon, T. (1979). Hydrological characteristics of arid zones. *IAHS Publication of the Proceeds of the Canberra Symposium on the hydrology of areas of low precipitation*, 128: 105-123.

Meade, R. H. (1982). Sources, sinks and storage of river sediment in the Atlantic drainage of the United States. *Geology, 90*: 235-252.

Merritt, W. S., Letcher, R. A., & Jakeman, A. J. (2003). A review of erosion and sediment transport models. *Environmental Modelling and Software*, 18: 761–799.

Meyer, L. D., & Wischmeier, W. H. (1969). Mathematical simulation of the process of soil erosion by water. *American Society of Agricultural Engineering Trans ASAE*. 12(6):754-758.

Midgley, D. C. (1952). Sediment yield map of southern Africa. *Unpublished map, University of Natal. Durban.*

Midgley, D. C., Pitman, W. V., & Middleton, B. J. (1994). *Surface Water Resources of South Africa 1990.* Pretoria: Water Research Commission.

Minaar, A. V. (1987). Graaf-Reinet's water problems. *Contree, 22*: 23-30.

Mitchell, J. K., & Bubenzer, G. D. (1980). Soil loss estimation. In M. J. Kirkby, & R. P. Morgan, *Soil erosion* (pp. 17-62). Chicester: John Wiley & Sons.

Moore, R. J. (1984). A dynamic model of basin sediment yield. *Water Resources Research*, 20(1): 89-103.

Moore, R. J., & Clarke, R. T. (1983). A distribution function approach to modelling basin sediment yield. *Journal of Hydrology*, 65: 239-257.

Moore, R. J., & Clarke, R. T. (1981). A distribution function approach to rainfall—runoff modelling. *Water Resources Research*, 17(5): 1367--1382.

Morgan, R. P. (2005). *Soil Erosion and Conservation, Third edition.* Oxford: Blackwell Science Ltd.

Morgan, R. P., Quinton, J. N., Smith, R. E., Govers, G., Poesen, J. W., Auerswald, K.,. Chisci, G., Torri, D., and Styczen, M. E. (1998). The European soil erosion model (EUROSEM): a process-based approach for predicting soil loss from fields and small catchments. *Earth Surface Processes and Landforms*, 23: 527–544.

Msadala, V., Gibson , L., Le Roux , J., Rooseboom, A., & Basson, G. (2010). Revised sediment yield maps for South Africa. *The new sediment yield map for southern Africa, WRC Project K5/765*.

Mucina, L., & Rutherford, M. C. (2006). *The vegetation of South Africa, Lesotho and Swaziland.* South African National Biodiversity Institute.

Nanson, G. C., Tooth, S., & Knighton, A. D. (2002). A global perspective on dryland rivers: perceptions, misconceptions and distinctions. In L. J. Bull, & M. J. Kirkby, *Dryland rivers: hydrology and geomorphology of semi-arid channels* (pp. 17–54). Chichester: John Wiley & Sons.

Nearing, M. A., & Hairsine, P. B. (2011). The Future of Soil Erosion Modelling. In R. P. Morgan, & M. A. Nearing, *Handbook of Erosion Modelling* (pp. 387–397). Chichester: Wiley-Blackwell Publishers.

Nearing, M. A., Lane, L. J., & Lopes, V. L. (1994). Modeling soil erosion. *Soil erosion research methods*, 2: 127-156.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2005). *Soil and Water Assessment Tool – Theoretical Documentation, Version 2005.* Texas.

Palmer, E. (2012). *The Plains of the Camdeboo: The Classic Book of the Karoo.* London: Penguin.

Parsons, A. J., Wainwright, J., Brazier, R. E., & Powell, D. M. (2006). Is sediment delivery a fallacy? *Earth Surface Processes and Landforms*, 31: 1325–1328.

Parsons, A. J., Wainwright, J., Powell, D. M., Kaduk, J., & Brazier, R. E. (2004). A conceptual model for determining soil erosion by water. *Earth Surface Processes and Landforms*, 29(10): 1293-1302.

Pitman, W. V. (1973). *A Mathematical Model for Generating Monthly River Flows from Meteorological Data in South Africa.* Johannesburg: Hydrological Research Unit, University of the Witwatersrand.

Pitman, W. V. (2011). *Overview of water resource assessment in South Africa: Current state and future challenges.* Water SA Vol. 37 No. 5 WRC 40-Year Celebration Special Edition.

Pitman, W. V., Kakebeeke, J. P., & Bailey, A. K. (2008). *WRSM2000 (enhanced).* Pretoria: Water Research Commission.

Poesen, J., Vanderkerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G., & Wesemael, B. (2002). Gully erosion in dryland environments. In L. J. Bull, & M. J. Kirkby, *Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels* (pp. 229–262). Chichester: John Wiley & Sons.

Poessen, J., Nachtergaele, J., Verstraeten, G., & Valentin, C. (2003). Gully erosion and environmental change: importance and research needs. *Catena*, 50: 91-133.

Pretorius, D. J. (1995). *The Development of a Soil Degradation Management Support System.* Pretoria: Unpublished ISCW Report. ARC – Institute for Soil, Climate and Water.

Pretorius, D. J. (1998). *The Development of Land Degradation Monitoring and Auditing Techniques with the Aid of Remote Sensing and GIS Technology.* Pretoria: ISCW Report No. GW/A/98/27. ARC – Institute for Soil, Climate and Water.

Price Williams, D., Watson, A., & Goudie, A. S. (1982). Quaternary colluvial stratigraphy, archaeological sequences and palaeoenvironments in Swaziland, southern Africa. *Geography Journal*, 148: 50-67.

Quibell, G., Pegram, G.C., Moolman, J., Matji, M.P., Hols, B., and Gorgens, A.H.M. (2003). Development of a nonpoint source assessment guide: test case studies. WRC Report No. 96/2/03, Water Research Commission.

Reid, I., & Frostick, L. E. (1997). Channel form, flows and sediments in deserts. *Arid Zone Geomorphology: Processes, Form and Change in Drylands*, 205-229.

Reid, I., & Frostick, L. E. (1987). Flow dynamics and suspended sediment properties in arid zone flash floods. *Hydrological Processes*, 1: 239–253.

Renard, K. G., Foster, G. R., Weesies, G. A., & Porter, J. P. (1991). RUSLE: revised universal soil loss equation. *Journal Soil and Water Conservation*, 46(1): 30–33.

Risse, L. M., Nearing, M. A., Laflen, J. M., & Nicks, A. D. (1993). Error assessment in the universal soil loss equation. *Soil Science Society of America Journal*, 57(3): 825-833.

Risse, L. M., Nearing, M. A., Nicks, A. D., & Laflen, J. M. (1993). Error assessment in the Universal Soil Loss Equation. *Soil Science Society of American Journal*, 57: 825-833.

Robinson, A. R. (1977). The relationship between soil erosion and sediment delivery. Proceedings of the Paris Symposium on erosion and solid matter transport in inland waters. *IAHS*, 122: 159-167.

Rooseboom, A., & Lotriet, H. H. (1992). The new sediment yield map for southern Africa. *Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992), IAHS Publ. no. 210*: 527-538.

Rooseboom, A., Verster, E., Zietsman, H. L., & Lotriet, H. H. (1992). *The Development of the New Sediment Yield Map of South Africa.* Pretoria: WRC Report No. 297/2/92. Water Research Commission.

Rowntree, K. M. (2012). Fluvial Geomorphology. In P. Holmes, & M. Meadows, *Southern African Geomorphology: Recent trends and new directions* (pp. 97-140). Bloemfontein: SUN MeDIA.

Rowntree, K. M., & Foster, I. D. (2012). A reconstruction of historical changes in sediment sources, sediment transfer and sediment yield in a small, semi-arid Karoo catchment, South Africa. *Zeitschrift fur Geomorphology*, 56 suppl.1: 87-98.

Rowntree, K., & Wadeson, R. (1998). A geomorphological framework for the assessment of instream flow requirements. *Aquatic Ecosystem Health & Management*, 1(2): 125-141.

Sadeghi, S. H., Gholami, L., Khaledi Darvishan, A., & Saeidi, P. (2014). A review of the application of the MUSLE model worldwide. *Hydrological Sciences Journal*, 59(2): 365-375.

Sami, K. (1992). Recharge mechanisms and geochemical processes in a semiarid sedimentary basin, Eastern Cape, South Africa. *Hydrology*, 139: 27-48.

Saxton, K. E., Rawls, W. J., Romberger, J. S., & Papendick, R. I. (1986). Estimating generalized soil-water characteristics from texture. *Soil Scieince Society of America Journal*, 50(4):1031-1036.

Schulze, R. (1989). *ACRU: background, concepts and theory. Report 35.* Pietermaritzburg: Agricultural Research Unit, Department of Agricultural Engineering, University of Natal.

Schumm, S. A. (2005). *River variability and complexity.* New York: Cambridge University Press.

Schumm, S. A. (1977). *The fluvial system.* New York: Wiley.

Sidorchuk, A., Smith, A. and Nikora, V. (2004) Probability distribution function approach to stochastic modelling of soil erosion. In: Proceeding of Sediment Transfer through the Fluvial System symposium (IAHS Publ. 288, Moscow, Russia).

Slaughter, A. R. (2011). *Modelling the relationship between flow and water qulaity in South African rivers.* PhD Thesis. Grahamstown: Rhodes University.

Slaughter, A.R., Hughes, D,A. and Mantel, S.K. (2012) The development of a Water Quality Systems Assessment Model (WQSAM) and its application to the Buffalo River Catchment, Eastern Cape, South Africa. R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.) *International Environmental Modelling and Software Society (iEMSs) International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet,* Sixth Biennial Meeting, Leipzig, Germany.

Slaughter, A.R., Retief, D.C.H. and Hughes, D.A. (2014) A method to disaggregate monthly flows to daily using daily rainfall observations: model design and testing. Hydrological Sciences Journal (Accepted for Publication Nov 2014). http://dx.doi.org/10.1080/02626667.2014.993987

Slaymaker, O. (2006). Towards the identification of scaling relations in drainage basin sediment budgets. *Geomorphology*, 80(1): 8-19.

Smakhtin, V. U., & Masse, B. (2000). Continuous daily hydrograph simulation using duration curves of a precipitation index. *Hydrological Processes*, 14: 1083-1100.

Thornes, J. B. (1997). Channel changes in ephemeral streams: observations, problems and models. *River channel changes*, 317-335.

Tooth, S. (2013). Dryland fluvial environments: assessing distinctiveness and diversity from a global perspective. In J. Shroder, *Treatise on Geomorphology: Fluvial Geomorphology* (pp. 9: 612–644). San Diego: Academic Press.

Tooth, S., & Nanson, G. C. (2011). Distinctiveness and diversity of arid zone river systems. In S. Tooth, & G. C. Nanson, *Arid Zone Geomorphology: Process, Form and Change in Dryland: Third Edition* (pp. 269-300). Chichester: Wiley & Sons.

Tooth, S., Brandt, D., Hancox, P. J., & McCarthy, T. S. (2004). Geological control on alluvial river behavior: a comparative study of three rivers on the South African Highveld. *Journal of African Earth Sciences*, 38: 79-97.

Tooth, S., McCarthy, T. S., Brandt, D., Hancox, P. J., & Morris, R. (2002). Geological controls on the formation of alluvial meanders and floodplain wetlands: the example of the Klip River, Eastern Free State, South Africa. *Earth Surface Processes and Landforms*, 27: 797-815.

Toy, T. J., Foster, G. R., & Renard, K. G. (2002). *Soil erosion: processes, prediction, measurement and control.* New York: John Wiley & Sons.

Trimble, S. W. (1995). Catchment sediment budgets and change. In A. Gurnell, & G. Petts, *Changing River Channels* (pp. 201–215). Chichester: John Wiley & Sons.

Walling, D. E. (1988). Erosion and sediment yield research- some recent perspectives. *Journal of Hydrology*, 100: 113-141.

Walling, D. E. (1983). The sediment delivery problem. *Journal of Hydrology, 69*, 209-237.

Walling, D. E. (2009). The impact of global change on erosion and sediment transport by rivers: current progress and future challenges. UNESCO.

Walling, D. E., & Collins, A. L. (2008). The catchment sediment budget as a management tool. *Environmental Science and Policy*, 11: 136-143.

Walling, D. E., & Kleo, A. H. (1979). Sediment yield of rivers in areas of low precipitation: a global view. *International Association of Scientific Hydrology Publication*, 128: 479-493.

Ward, P. R. (1984). Measurement of sediment yields. In R. F. Hadley, & D. E. Walling, *Erosion and sediment yield: some methods of measurement and modelling* (pp. 37-70). Norwich: Geobooks.

Wasson, R. J. (2002). What approach to the modelling of catchment scale erosion and sediment transport should be adopted? In W. Summer, & D. Walling, *Modelling erosion, sediment transport and sediment yield* (pp. 1-12). Paris: Technical Documents in Hydrology No. 60, UNESCO.

Watson, H. K. (200). Land reform implications of the distribution of badlands in the Mfolozi Catchment, KwaZulu-Natal. *South African Geographical Journal*, 82(3): 143-148.

Wilk, J., & Hughes, D. A. (2002). Calibrating a rainfall-runoff model for a catchment with limited data. *Hydrological Sciences Journal*, 47(1): 3-17.

Williams, J. R. (1977). Sediment delivery ratios determined with sediment and runoff models. *Erosion and solid matter transport in inland water. Proceedings of Paris Symposium* (pp. 122: 168-179). Wallingford: IAHS Press.

Williams, J. R. (1975). Sediment yield prediction with universal equation using runoff energy factor . In *Present and Prospective Technology for Predicting Sediment Yield and Sources* (pp. 40: 244-254). Washington DC: USDA-ARS.

Williams, J. R. (1985). The physical components of the EPIC model. In S. A. El-Swaify, W. C. Moldenhauer, & A. Lo, *Soil Erosion and Conservation* (pp. 272–284). Ankeny: Soil Conservation Society of America.

Williams, J. R., & Berndt, H. D. (1977). Sediment yield based on watershed hydrology. *Transactions of the Society of Agricultural Engineers*, 20: 1100-1104.

Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses: A guide to conservation planning.* Washington: U.S. Government Printing Office.

Wolman, M. G. (1977). Changing needs and opportunties in the sediment field. *Water Resources Research , 13* (1), 50-54.

Young, R. A., Onstad, C. A., Bosch, D. D., & Anderson, W. P. (1989). AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *Journal of soil and water conservation*, 44(2): 168-173.

Zhang, X. C., Nearing, M. A., Risse, L. M., & Mc Gregor, K. C. (1996). Evaluation of WEPP runoff and soil loss predictions using natural runoff plot data. *Transactions of American Society of Agricultural and Biological Engineers*, 39(3): 855-863.

APPENDIX A

An example of the use of the Microsoft Excel worksheet for interpretation of the inputs and outputs of the erosion and sediment delivery model for the Ganora dataset.

Worksheet 1: Hydrological time series These are data from the Pitman rainfall-runoff model. No adjustments are to be made to these data.

This text file is an input to the model.

Ganora

Date			Daily rainfall (mm)	Daily total flow (mm)	Daily groundwater flow (mm)	Daily interflow (mm)	Daily surface flow (mm)
1901	10	1	0	0	0	0	0
1901	10	2	0	0	0	0	0
1901	10	3	0	0	0	0	0
1901	10	4	0	0	0	0	0
1901	10	5	0	0	0	0	0
1901	10	6	0	0	0	0	0
1901	10	7	0	0	0	0	0
1901	10	8	0	0	0	0	0
1901	10	9	0.762	0	0	0	0
1901	10	10	1.016	0	0	0	0
1901	10	11	5.08	0	0	0	0
1901	10	12	0	0	0	0	0
1901	10	13	0	0	0	0	0
1901	10	14	0	0	0	0	0
1901	10	15	0	0	0	0	0
1901	10	16	0	0	0	0	0
1901	10	17	0	0	0	0	0
1901	10	18	0	0	0	0	0
1901	10	19	0	0	0	0	0
1901	10	20	1.778	0	0	0	0
1901	10	21	0	0	0	0	0
1901	10	22	0	0	0	0	0
1901	10	23	0	0	0	0	0

1_Timeseries | 2_Parameters | 2.1 Surface flow | 2.2 Erosion estimation

Worksheet 2: Parameters for the model. Parameters 0-4 and 16-17 are adjusted directly on this worksheet. Surface flow, erosion and sediment storage and delivery parameters are calculated in separate worksheets (2.1-2.3) and incorporated into this final version via a connecting formula. The parameters for a connected and (dis)connected catchment are represented on this worksheet. Once the parameters have been calculated the three columns can be saved as a text file to be an input to the model.

This text file is an input to the model.

Ganora (dis)connected (1901-1967)

Parameter		Description
0	2.7	Catchment Area
1	100	Number of sub-area segments
2	16	Storm Duration V Volume Scaling Fac
3	0.5	Storm Duration V Volume Power
4	2	Storm Duration V Volume Constant
5	0.3	Mean Soil Erodibility Factor
6	0.01	Soil Erodibility Factor - Variability
7	0.05	Mean Cover Factor
8	0.02	Cover Factor - Variability
9	0.8	Mean Practice Factor
10	0.2	Practice Factor - Variability
11	5	Mean Catchment Slope Factor
12	1	Catchment Slope Factor - Variability
13	0.05	Runoff Depth Distribution High
14	0.25	Runoff Depth Distribution Mod
15	0.7	Runoff Depth Distribution Low
16	11.8	Scale in erosion-discharge model (A)
17	0.56	Power in erosion-discharge model (B)
18	75	Maximum store (High runoff) K tons
19	1050	Maximum store (Mod runoff) K tons
20	5700	Maximum store (Low runoff) K tons
21	6	Maximum Channel store K tons
22	0.1	Proportion Gully store (High runoff)
23	0.1	Proportion Gully store (Mod runoff)
24	0.1	Proportion Gully store (Low runoff)
25	0.29	Drainage Density

Ganora connected (1967-2003)

Parameter		Description
0	2.7	Catchment Area
1	100	Number of sub-area segments
2	16	Storm Duration V Volume Scaling Fac
3	0.5	Storm Duration V Volume Power
4	2	Storm Duration V Volume Constant
5	0.3	Mean Soil Erodibility Factor
6	0.01	Soil Erodibility Factor - Variability

1_Timeseries 2_Parameters 2.1 Sur

Ganora connected (1967-2003)

Parameter		Description
0	2.7	Catchment Area
1	100	Number of sub-area segments
2	16	Storm Duration V Volume Scaling Fac
3	0.5	Storm Duration V Volume Power
4	2	Storm Duration V Volume Constant
5	0.3	Mean Soil Erodibility Factor
6	0.01	Soil Erodibility Factor - Variability
7	0.05	Mean Cover Factor
8	0.02	Cover Factor - Variability
9	0.8	Mean Practice Factor
10	0.2	Practice Factor - Variability
11	5	Mean Catchment Slope Factor
12	1	Catchment Slope Factor - Variability
13	0.05	Runoff Depth Distribution High
14	0.25	Runoff Depth Distribution Mod
15	0.7	Runoff Depth Distribution Low
16	11.8	Scale in erosion-discharge model (A)
17	0.56	Power in erosion-discharge model (B)
18	75	Maximum store (High runoff) K tons
19	1050	Maximum store (Mod runoff) K tons
20	5700	Maximum store (Low runoff) K tons
21	6	Maximum Channel store K tons
22	0.1	Proportion Gully store (High runoff)
23	0.5	Proportion Gully store (Mod runoff)
24	0.5	Proportion Gully store (Low runoff)
25	0.29	Drainage Density

1_Timeseries 2_Parameters 2.1 Sur

Worksheet 2.1. Surface flow parameters estimation.

The surface flow distribution for each runoff zone may be adjusted in this worksheet.

Surface flow estimation		Ganora	Cranemere	Nqweba
	Area (km^2)	2.7	57	3667.7
Runoff depth distribution	High (H)	0.05	0.05	0.18
	Moderate (M)	0.25	0.15	0.32
	Low (L)	0.7	0.8	0.5

Notes:

The Topography factor calculation provided a LS distribution map over each catchment. This distribution was divided into three groups, and the proportional distribution of each group was calculated to provide the runoff depth distributions.

1_Timeseries | 2_Parameters | 2.1 Surface flow | 2.2 Erosion estimation | 2.3 Sediment storage & del

Worksheet 2.2. Erosion parameters estimation.

The surface flow distribution for each runoff zone may be adjusted in this worksheet. The soil erodibility, cover and practice factors may be estimated by referring to Tables 5.1, 5.2 and 5.3. The topography factor may be determined through GIS.

Erosion estimation		Ganora	Cranemere	Nqweba
Runoff factor (R)	D_{scale}	16	16	16
	D_p	0.5	0.5	0.5
	D_{con}	2	2	2
Topography factor (LS) *refer to LS raster map*	LS_{MN}	5	3.8	3.5
	LS_{RAN}	1	1	2
Soil erodibility factor (K) *refer to tables 5.1 & 5.2*	K_{MN}	0.3	0.3	0.3
	K_{RAN}	0.01	0.01	0.01
Cover factor (C) *refer to tables 5.2 & 5.3*	C_{MN}	0.05	0.05	0.15
	C_{RAN}	0.02	0.02	0.05
Practice factor (P) *refer to table 5.4*	P_{MN}	0.8	0.8	0.8
	P_{RAN}	0.2	0.2	0.2

Table 5.1: Soil Erodibility (Mitchell and Bubenzer, 1980)

Texture class	Organic matter content <0.5% K	2% K	4% K
Sand	0.05	0.03	0.02
Fine sand	0.16	0.14	0.1
very fine sand	0.42	0.36	0.28
Loamy sand	0.12	0.1	0.08
Loamy fine sand	0.24	0.2	0.16
Loamy very fine sand	0.44	0.38	0.3
Sandy loam	0.27	0.24	0.19
Fine sandy loam	0.35	0.3	0.24
Very fine sandy loam	0.47	0.41	0.33
Loam	0.38	0.34	0.29
Silt loam	0.48	0.42	0.33
Silt	0.6	0.52	0.42
Sandy clay loam	0.27	0.25	0.21
Clay loam	0.28	0.25	0.21
Silty clay loam	0.37	0.32	0.26
Sandy clay loam	0.14	0.13	0.12
Silty clay	0.25	0.23	0.19
Clay		.13-.29	

Table 5.2: The estimation of the cover factor (C) for permanent pasture, range, and idle land (Wischmeier and Smith, 1978)

Vegetative canopy		Cover that contacts the soil surface						
Type and height[1]	Percent cover	Type[3]	0	20	40	60	80	95+
No appreciable canopy		G	0.45	0.2	0.1	0.042	0.013	0.003
		W	0.45	0.24	0.15	0.091	0.043	0.011
Tall weeds or short bush with average drop fall height of 50 cm	25	G	0.36	0.17	0.9	0.038	0.013	0.003
		W	0.36	0.2	0.13	0.083	0.041	0.011
	50	G	0.26	0.13	0.07	0.035	0.012	0.003
		W	0.26	0.16	0.11	0.076	0.039	0.011
	75	G	0.4	0.18	0.22	0.04	0.013	0.003
		W	0.4	0.22	0.14	0.087	0.042	0.011
Appreciable bushes, with average drop fall height of 2 m	25	G	0.4	0.18	0.09	0.04	0.013	0.003
		W	0.4	0.22	0.14	0.087	0.042	0.011
	50	G	0.34	0.16	0.08	0.038	0.012	0.033
		W	0.34	0.19	0.13	0.082	0.041	0.011
	75	G	0.28	0.14	0.08	0.036	0.012	0.003
		W	0.28	0.17	0.12	0.078	0.04	0.011
Trees, but no appreciable low bush. Average drop fall height of 4 m	25	G	0.42	0.19	0.1	0.041	0.013	0.003
		W	0.42	0.23	0.14	0.089	0.042	0.011
	50	G	0.39	0.18	0.09	0.04	0.013	0.003
		W	0.39	0.21	0.14	0.087	0.042	0.011
	75	G	0.36	0.17	0.09	0.039	0.012	0.003
		W	0.36	0.2	0.13	0.084	0.041	0.011

Notes:

Table 5.3: Practice factor (Wischmeier and Smith, 1978)

Land slope (%)	Contouring	Contour strip cropping and irrigated furrows	Terracing
1 to 2	0.6	0.3	0.12
3 to 8	0.5	0.25	0.1
9 to 12	0.6	0.3	0.12
13 to 16	0.7	0.55	0.14
17 to 20	0.8	0.4	0.16
21 to 25	0.9	0.45	0.18

1_Timeseries | 2_Parameters | 2.1 Surface flow | 2.2 Erosion estimation | 2.3 Sediment storage & delivery | Sheet1 (3) | 3 Sediment output (NO CHANGE) | 3 Sediment output (d) | 3 Sedime

Worksheet 2.3. Sediment storage and delivery parameters estimation.

The sediment storage and delivery parameters are estimated by referring to Table 6.1.

Sediment storage and Delivery				Ganora	Cranemere	Nqweba
Maximum sediment (Kt) torage refer to Table 6.2	S_{max}		High	75	1500	990000
			Moderate	1050	13500	1761000
			Low	5700	138000	13206000
			Channel	6	110	29400
Sediment connectivity	(Dis)connected	C_{prop}	High	0.1	0.1	0.1
			Moderate	0.1	0.1	0.3
			Low	0.1	0.1	0.3
	Connected	C_{prop}	High	0.1	0.1	0.2
			Moderate	0.5	0.5	0.6
			Low	0.5	0.5	0.6
	DD			0.29	0.13	0.27

Table 6.2. The runoff zone area, maximum depth of sediment and bulk density of sediment for Ganora, Cranemere and Nqweba catchments.

		Ganora	Cranemere	Nqweba
Catchment area (km^2)		2.7	57	3667.7
Channel length (km)		0.77	7.3	984
Channel width (km)		0.005	0.01	0.01
Drainage density (channel length x catchment area)		0.29	0.13	0.27
Runoff zone area (km^2)	High	0.1 (5%)	2 (5%)	660(8%)
	Moderate	0.7 (25%)	9 (15%)	1174 (32%)
	Low	1.9 (70%)	46 (80%)	2201 (60%)
	Channel	0.004 (0.15%)	0.073 (0.12%)	9.8 (0.27%)
Runoff zone area (m^2)	High	100000	2000000	660000000
	Moderate	700000	9000000	1174000000
	Low	1900000	46000000	2201000000
	Channel	4000	73000	9800000
Maximum depth of sediment (m)	High	0.5	0.5	1
	Moderate	1	1	1
	Low	2	2	4
	Channel	1	1	2
Bulk density ($g.cm^{-3}$)		1.5	1.5	1.5
Maximum sediment storage (Kt)	High	75	1500	990000
	Moderate	1050	13500	1761000
	Low	5700	138000	13206000
	Channel	6	110	29400

1_Timeseries | 2_Parameters | 2.1 Surface flow | 2.2 Erosion estimation | 2.3 Sediment storage & delivery

Worksheet 3 Model outputs (Model outputs with different scenarios)

Ganora

Starting sed store	0.02
Sed store ratio power	0.8
Threshold flow for delivery	0.8

Leap year (1904...+4)

	Average sediment yield ($t/km^2/yr$)	Total sediment yield ($t/km^2/yr$)
Modelled erosion	129	13275
Modelled sediment delive	148	15258
Observed sediment yield	273	15693
Difference between observed and modelled erosion		-2417
Difference between observed and modelled sediment delivery		-434

date	Iteration
1967	23863

1901-2003		1901-1950		1950-2003	
MAR	0.32	MAR	0.16	MAR	0.47
CV	0.7484	CV	0.2571	CV	1.1651

Sediment output

Year	Iteration	Discharge (mm)	Erosion (Kt)	Sediment Delivery (Kt)	High (Kt)	Ghigh (Kt)	Moderate (Kt)	Gmod (Kt)	Low (Kt)	Glow (Kt)		Channel (Kt)
1901	28	0.027	0.028	0	1.348	0.15	18.9	2.099	102.628	11.397	0	0.125
1901	29	0.012	0.012	0	1.347	0.15	18.905	2.098	102.635	11.398	0	0.125
1901	30	0.005	0.004	0	1.348	0.15	18.906	2.098	102.638	11.398	0	0.125
1901	31	0.001	0.001	0	1.348	0.15	18.906	2.098	102.639	11.398	0	0.125
1901	32	0.002	0.001	0	1.348	0.15	18.907	2.098	102.64	11.398	0	0.125
1902	173	0.002	0.002	0	1.348	0.15	18.907	2.098	102.641	11.398	0	0.125
1902	174	0.001	0.001	0	1.348	0.15	18.908	2.098	102.641	11.398	0	0.125
1902	184	0.013	0.012	0	1.348	0.15	18.913	2.098	102.649	11.399	0	0.125
1902	185	0.02	0.021	0	1.346	0.15	18.92	2.096	102.663	11.399	0	0.127
1902	186	0.008	0.007	0	1.346	0.15	18.923	2.096	102.668	11.399	0	0.127
1902	187	0.003	0.002	0	1.346	0.15	18.923	2.096	102.669	11.399	0	0.127
1902	213	0.005	0.005	0	1.346	0.15	18.925	2.096	102.672	11.399	0	0.127
1902	214	0.004	0.003	0	1.347	0.15	18.926	2.096	102.674	11.399	0	0.127
1902	215	0.002	0.002	0	1.347	0.15	18.927	2.096	102.675	11.399	0	0.127
1902	216	0.001	0.001	0	1.347	0.15	18.927	2.096	102.676	11.399	0	0.127
1902	409	0.015	0.015	0	1.346	0.15	18.934	2.096	102.685	11.4	0	0.127
1902	410	0.007	0.006	0	1.346	0.15	18.936	2.096	102.689	11.4	0	0.127
1902	411	0.003	0.002	0	1.346	0.15	18.937	2.096	102.69	11.4	0	0.127
1902	440	0.001	0.001	0	1.347	0.15	18.937	2.096	102.691	11.4	0	0.127
1902	444	0.002	0.002	0	1.347	0.15	18.938	2.096	102.692	11.4	0	0.127
1902	445	0.001	0.001	0	1.347	0.15	18.938	2.096	102.693	11.4	0	0.127
1903	492	0.002	0.002	0	1.347	0.15	18.939	2.096	102.694	11.4	0	0.127
1903	493	0.011	0.011	0	1.346	0.15	18.943	2.095	102.7	11.4	0	0.127
1903	494	0.005	0.005	0	1.347	0.15	18.945	2.095	102.703	11.4	0	0.127
1903	495	0.001	0.001	0	1.347	0.15	18.945	2.095	102.704	11.4	0	0.127
1903	517	0.002	0.002	0	1.347	0.15	18.946	2.095	102.705	11.4	0	0.127
1903	518	0.002	0.001	0	1.347	0.15	18.946	2.095	102.706	11.4	0	0.127
1903	519	0.001	0.001	0	1.347	0.15	18.946	2.095	102.706	11.4	0	0.127

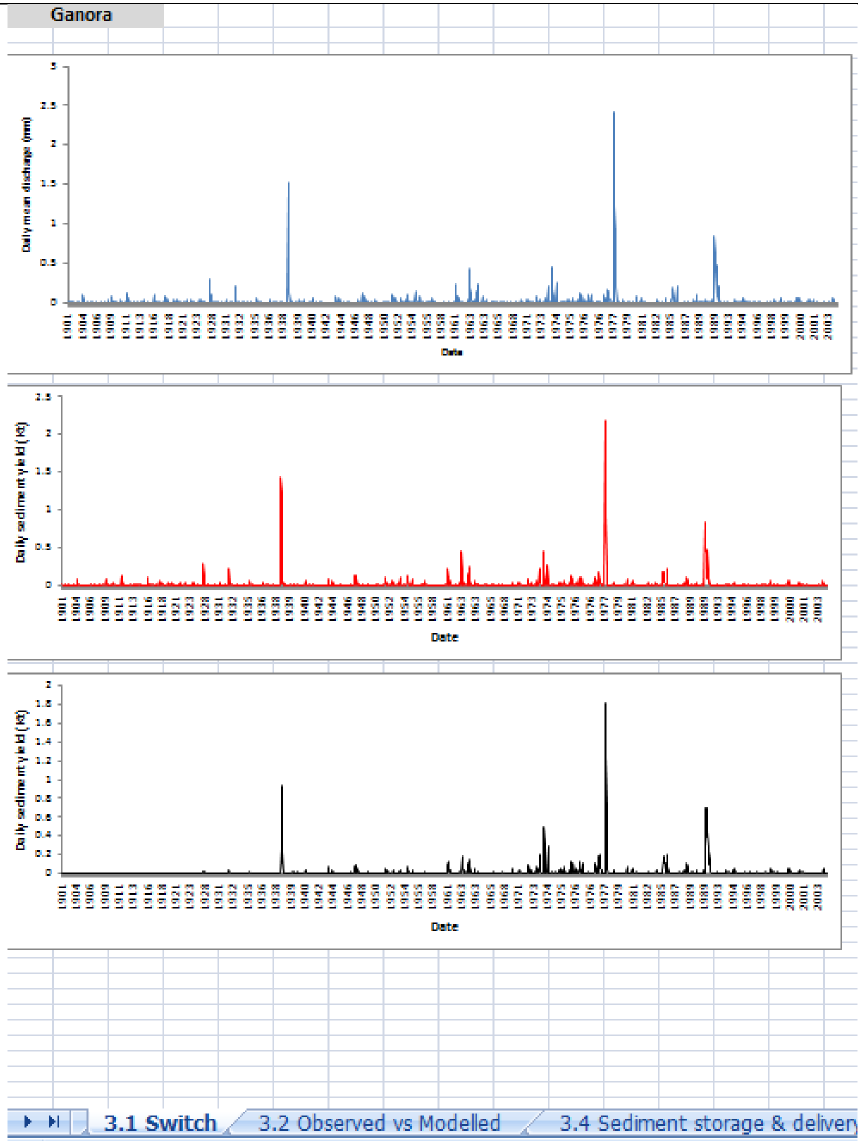
Observed vs Modelled

Year	Discharge (mm)	Erosion (Kt/yr)	Sediment Delivery (Kt/yr)	Erosion ($t/km^2/yr$)	Sediment delivery ($t/km^2/yr$)	Observed sediment yield (t/km2/yr)	Cumulative sediment yield ($t/km^2/yr$) Modelled Annual E	Modelled Annual SD	Observed Annual SY
1901	0.047	0.046	0	17.04	0.00		17.04	0.00	
1902	0.088	0.083	0	30.74	0.00		47.78	0.00	
1903	0.024	0.023	0	8.52	0.00		56.30	0.00	
1904	0.206	0.208	0.002	77.04	0.74		133.33	0.74	
1905	0.022	0.021	0	7.78	0.00		141.11	0.74	
1906	0.098	0.09	0	33.33	0.00		174.44	0.74	
1907	0.082	0.076	0	28.15	0.00		202.59	0.74	
1908	0.001	0.001	0	0.37	0.00		202.96	0.74	
1909	0.265	0.26	0.003	96.30	1.11		299.26	1.85	
1910	0.119	0.114	0.001	42.22	0.37	11.10099106	341.48	2.22	11.1009910
1911	0.343	0.342	0.012	126.67	4.44		468.15	6.67	
1912	0.006	0.005	0	1.85	0.00		470.00	6.67	
1913	0.248	0.24	0.007	88.89	2.59		558.89	9.26	
1914	0.02	0.016	0	5.93	0.00		564.81	9.26	
1915	-1	0	0	0.00	0.00		564.81	9.26	
1916	0.317	0.326	0.026	120.74	9.63		685.56	18.89	
1917	0.074	0.072	0.003	26.67	1.11	41.10110364	712.22	20.00	52.2020946
1918	0.337	0.341	0.031	126.30	11.48		838.52	31.48	
1919	0.015	0.013	0	4.81	0.00	91.99716704	843.33	31.48	144.199261
1920	0.267	0.263	0.02	97.41	7.41		940.74	38.89	
1921	0.264	0.257	0.018	95.19	6.67		1035.93	45.56	
1922	0.012	0.01	0	3.70	0.00	16.74802612	1039.63	45.56	160.947287
1923	0.003	0.003	0	1.11	0.00		1040.74	45.56	
1924	0.113	0.115	0.011	42.59	4.07		1083.33	49.63	
1925	0.076	0.07	0.001	25.93	0.37	465.4845695	1109.26	50.00	465.484569
1926	0.011	0.008	0	2.96	0.00		1112.22	50.00	
1927	0.002	0.001	0	0.37	0.00		1112.59	50.00	
1928	0.641	0.655	0.221	242.59	81.85	21.74661844	1355.19	131.85	487.23118

1 Timeseries / 2 Parameters / 2.1 Surface flow / 2.2 Erosion estimation / 2.3 Sediment storage & delivery / Sheet1 (3) / 3 Sediment output (NO CHANGE) / 3 Sediment output (d) / 3 Sedime

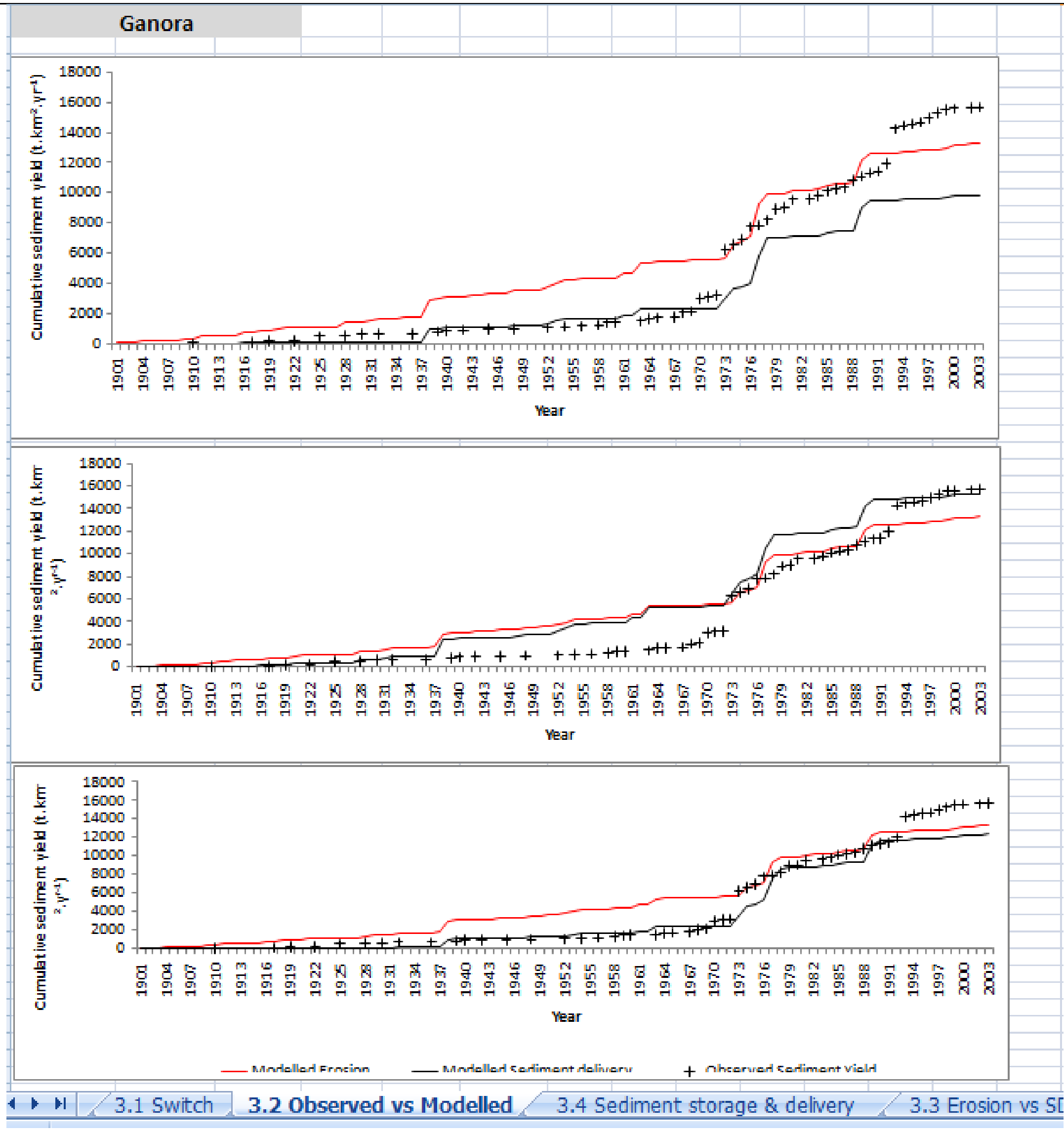
Worksheet 3.1. Surface flow, erosion and sediment delivery outputs.

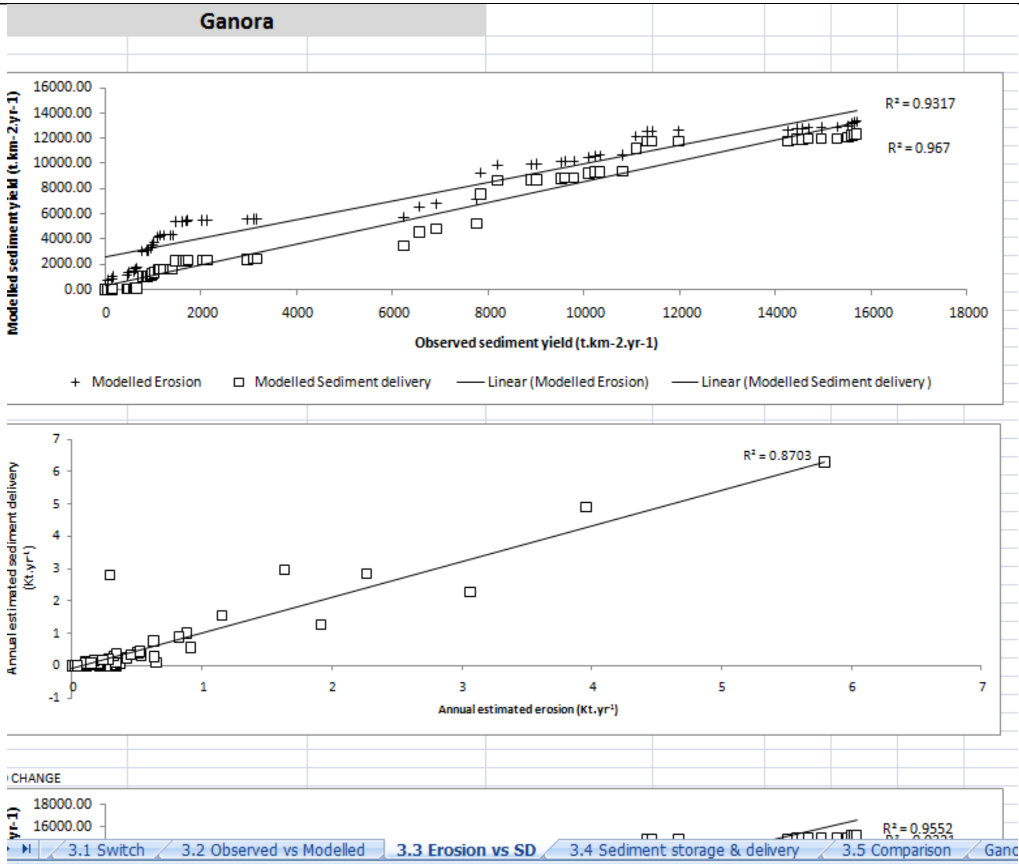
The outputs from Worksheet 3 are used to develop graphs for the time-series.

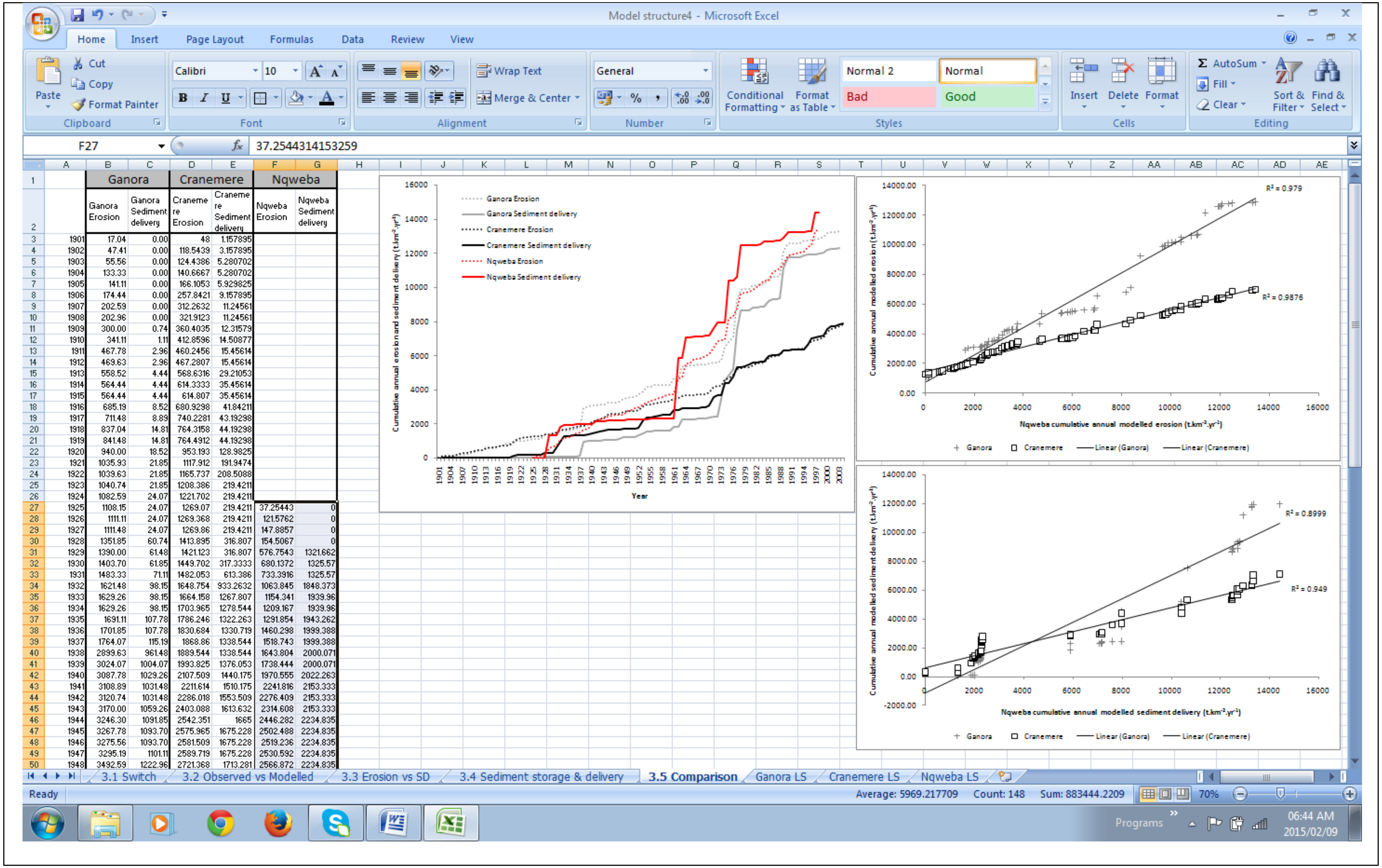


Worksheet 3.2. Cumulative annual modelled erosion and sediment delivery versus cumulative annual observed sediment yield.

The cumulative annual outputs and the cumulative annual observed sediment yield from Worksheet 3 are used to develop graphs for each scenario.



Worksheet 3.3. The correlation of modelled and observed data. The cumulative annual outputs were compared to the cumulative annual observed sediment yield from Worksheet 3 by defining the R^2 value.	
Worksheet 3.5. Comparison of modelled erosion and sediment delivery for each catchment.	



	A	B	C	D	E	F	G
1		Ganora		Cranemere		Nqweba	
2		Ganora Erosion	Ganora Sediment delivery	Cranemere Erosion	Cranemere Sediment delivery	Nqweba Erosion	Nqweba Sediment delivery
3	1901	17.04	0.00	48	1.157895		
4	1902	47.41	0.00	118.5439	3.157895		
5	1903	55.56	0.00	124.4386	5.280702		
6	1904	133.33	0.00	140.6667	5.280702		
7	1905	141.11	0.00	166.1053	5.929825		
8	1906	174.44	0.00	257.8421	9.157895		
9	1907	202.59	0.00	312.2632	11.24561		
10	1908	202.96	0.00	321.9123	11.24561		
11	1909	300.00	0.74	360.4035	12.31579		
12	1910	341.11	1.11	412.8596	14.50877		
13	1911	467.78	2.96	460.2456	15.45614		
14	1912	469.63	2.96	467.2807	15.45614		
15	1913	558.52	4.44	568.6316	29.21053		
16	1914	564.44	4.44	614.3333	35.45614		
17	1915	564.44	4.44	614.807	35.45614		
18	1916	685.19	8.52	680.9298	41.84211		
19	1917	711.48	8.89	740.2281	43.19298		
20	1918	837.04	14.81	764.3158	44.19298		
21	1919	841.48	14.81	764.4912	44.19298		
22	1920	940.00	18.52	953.193	128.9825		
23	1921	1035.93	21.85	1117.912	191.9474		
24	1922	1039.63	21.85	1165.737	208.5088		
25	1923	1040.74	21.85	1208.386	219.4211		
26	1924	1082.59	24.07	1221.702	219.4211		
27	1925	1108.15	24.07	1269.07	219.4211	37.25443	0
28	1926	1111.11	24.07	1269.368	219.4211	121.5762	0
29	1927	1111.48	24.07	1269.86	219.4211	147.8857	0
30	1928	1351.85	60.74	1413.895	316.807	154.5067	0
31	1929	1390.00	61.48	1421.123	316.807	576.7543	1321.662
32	1930	1403.70	61.85	1449.702	317.3333	680.1372	1325.57
33	1931	1483.33	71.11	1482.053	613.386	733.3916	1325.57
34	1932	1621.48	98.15	1648.754	933.2632	1063.845	1848.373
35	1933	1629.26	98.15	1664.158	1267.807	1154.341	1939.96
36	1934	1629.26	98.15	1703.965	1278.544	1209.167	1939.96
37	1935	1691.11	107.78	1786.246	1322.263	1291.854	1943.262
38	1936	1701.85	107.78	1830.684	1330.719	1460.298	1999.388
39	1937	1764.07	115.19	1868.86	1338.544	1518.743	1999.388
40	1938	2899.63	961.48	1889.544	1338.544	1643.804	2000.071
41	1939	3024.07	1004.07	1993.825	1376.053	1738.444	2000.071
42	1940	3087.78	1029.26	2107.509	1440.175	1970.555	2022.263
43	1941	3108.89	1031.48	2211.614	1510.175	2241.816	2153.333
44	1942	3120.74	1031.48	2286.018	1553.509	2276.409	2153.333
45	1943	3170.00	1059.26	2403.088	1613.632	2314.608	2153.333
46	1944	3246.30	1091.85	2542.351	1665	2446.282	2234.835
47	1945	3267.78	1093.70	2575.965	1675.228	2502.488	2234.835
48	1946	3275.56	1093.70	2581.509	1675.228	2519.236	2234.835
49	1947	3295.19	1101.11	2589.719	1675.228	2530.592	2234.835
50	1948	3492.59	1222.96	2721.368	1713.281	2566.872	2234.835