1. INTRODUCTION

Soil erosion is a major challenge confronting land and water resources in many parts of the world and the problem may get worse in the future due to population growth and potential climatic and land use changes (Prosser *et al.*, 2001; Poesen *et al.*, 2003; Kakembo *et al.*, 2009; Tibebe and Bewket, 2010). Although soil erosion is a natural process it is often accelerated by human activities, for example by the clearing of vegetation or overgrazing (Snyman, 1999). Poor farming practices as well as the trend toward agricultural intensification have been considered to be major causes of erosion. Soil formation is a relatively slow process and, therefore, soil is essentially a non-renewable and a limited resource (McPhee and Smithen, 1984). Prolonged erosion causes irreversible soil loss over time, reducing the ecological (e.g. biomass production) and hydrological functions (e.g. filtering capacity) of soil (Hallsworth, 1987). Boardman (2006) states that the cost of food production is increasing in many parts of the world due to erosion and loss of nutrients. Soil erosion not only involves the loss of fertile topsoil and reduction of soil productivity but is also coupled with serious off-site impacts related to increased mobilization of sediment and delivery to rivers. Furthermore, sediments are a carrier for pollutants which are stored by adhesion on their surfaces. Flügel *et al.* (2003) state that eroded soil material leads to sedimentation/siltation of reservoirs, as well as an increase in pollution due to suspended sediment concentrations in streams which affects water use and ecosystem health. Erosion also aggravates water management problems, especially in semi-arid regions such as South Africa (SA) where water scarcity is frequent.

Given the increasing threat to land resources, especially due to population growth and potential climatic changes, it is important to provide information that can help to target policy to focus on the areas of greatest need (Gobin *et al.*, 2003). It is imperative to prevent negative impacts and to remediate affected areas. Before prevention or remediation of soil erosion can be undertaken the spatial extent of the problem should be assessed and continually monitored. Assessment of erosion, however, is complicated by complex physical processes that involve interaction of a large number of spatial and temporal factors, regional differences and scale dependency (De Vente *et al.*, 2007; Vanmaercke *et al.*, 2011; Parsons, 2012). Soil erosion occurs over many spatial scales including the site of impact from a single raindrop to large catchments, as well as over a large variety of timescales such as a single storm to many decades (Stocking and Murnaghan, 2001). Table 1 summarizes the spatial and temporal scales over which the main soil erosion processes occur. Soil erosion assessments can thus be conducted at a variety of scales using a variety of different techniques (see broad categories and examples in Table 2). Although erosion control measures need to be implemented at the field or hillslope scale, allocation of scarce conservation resources and development of policies require erosion assessment at a regional (catchment to national) scale (Vrieling, 2006). Mapping and modelling are therefore key issues to be addressed as baseline for regional scale monitoring (Martinez-Casasnovas, 2003).

Table 1: Description of the spatial and temporal scales at which soil erosion processes occur.

<table>
<tr><th colspan="2">Spatial scale</th><th>Description/size</th><th>Associated erosion processes</th><th>Typical associated temporal scale</th></tr>
<tr><td colspan="2">Microplot</td><td>Area of about 1 m^2</td><td>Rainsplash[1] erosion</td><td>Seconds</td></tr>
<tr><td colspan="2">Land facet & runoff plot</td><td>An area of homogeneous topography, soil and land management (Van Zyl, 2004); runoff plots are typically rectangular, being about 20 m long and 2 to 3 m wide</td><td>Comprises above, sheet[2] and rill[3] erosion</td><td>Minutes – daily</td></tr>
<tr><td colspan="2">Hillslope</td><td>Typically extends from upslope/crest areas to a stream channel with varying topography, soil and land management (Van Zyl, 2007)</td><td>Comprises all above and gully[4] erosion</td><td>Minutes – daily</td></tr>
<tr><td rowspan="3">Regional scale</td><td>Catchment</td><td>A land surface which contributes water and sediment to any given stream network (Rowntree and Wadeson, 1999), including smaller (sub)catchments (<10 km^2) to a very large catchment (>10 km^2)</td><td>Comprises all above and bank[5] erosion, as well as mass movement[5] (sediment[6] storage in sinks may play a large role but is region-specific)</td><td>Daily – annual</td></tr>
<tr><td>National</td><td>Refers to countries generally large in extent</td><td>Comprises all above</td><td>Monthly – annual</td></tr>
<tr><td>Global</td><td>Refers to the whole world, or the combination of several countries including continental scale</td><td>Comprises all above</td><td>Annual – decadal</td></tr>
</table>

1. Rainsplash erosion is the action of raindrops on soil particles by disrupting and transporting soil particles, as well as compacting soil particles that leads to the formation of surface crust and runoff (Mutchler *et al.*, 1994).
2. Sheet erosion involves the detachment and transport of soil particles by rainsplash erosion and transport by shallow overland flow (Lal and Elliot, 1994).
3. Rill erosion is a process in which flow becomes channelled and numerous small channels of several centimetres up to about 30 cm are formed (Bergsma *et al.*, 1996). Sheet and rill erosion normally occur together and it is virtually impossible to assess them separately with modelling and remote sensing techniques at a regional scale.
4. Gully erosion is a process where surface (or subsurface) water concentrates in narrow flow paths and removes the soil resulting in incised channels that are too large to be destroyed by normal tillage operations (Kirkby and Bracken, 2009).
5. Outside scope of text.
6. The term sediment yield is used to refer to the amount of eroded soil (including suspended sediment and bedload) that passes a designated point at the outflow end or outlet of specific area or catchment during a specific time step (thus the cumulative product of all sediment producing processes in a catchment) (De Vente and Poesen, 2005).

Table 2: Broad categories of soil erosion assessment techniques at different scales.

Assessment technique		Description and examples	Typical scales of application
Field measurements		Physical measurement in the field using specific instrumentation such as plots with or without rainfall simulators (e.g. Dong *et al*., 2012)	Microplot to runoff plot
Modelling	Physical	Based on the solution of fundamental physical equations describing the conservation of mass and momentum of streamflow and sediment transport on a hillslope (Merrit *et al*., 2003). Models such as KINEROS are in many cases spatially distributed and event-based in order to estimate the response (loss and/or sediment yield) of the modelled area to single storm events (e.g. Al-Qurashi *et al*., 2008)	Hillslope
	Conceptual	Lump representative processes over the scale at which outputs are simulated, but incorporate important transfer mechanisms of runoff and sediment generation in their structure to assess soil loss and/or sediment yield (Merritt *et al*., 2003). Several conceptual models draw on MUSLE where sediment yield is computed using surface runoff and peak flow rate together with the widely used USLE factors e.g. SWAT. These models are often continuous simulation models in order to simulate long periods of time with a time step of 1 day (e.g. Srinivasan *et al*., 2010)	Hillslope to catchment
	Empirical	Based primarily on the analysis of observations with low input data (Merritt *et al*., 2003), these models, especially the (R)USLE, have been widely used across the globe to assess soil loss and/or sediment yield (e.g. Hagos, 2004).	Hillslope to catchment
	Semi-quantitative	A combination of descriptive and quantitative procedures to provide a semi-quantitative estimate of soil loss and/or sediment yield (De Vente and Poesen, 2005). Although developed for application to hillslopes, (R)USLE and its derivatives have been used this way in many regional scale erosion studies across the globe (e.g. Gobin *et al*., 2003; Lu *et al*., 2003).	Catchment to national
Remote sensing	Airborne	Their lower altitude allows much higher spatial resolutions than satellite based sensors (Smith and Pain, 2009) and have been widely used to map soil erosion features including photogrammetric methods using stereo images (Flügel *et al*., 2003), synthetic aperture radar interferometry (Hochschild and Herold, 2001), airborne laser altimetry and volumetric measurements e.g. LiDAR (Perroy *et al*., 2010)	Hillslope to catchment
	Satellite	In contrary to airborne systems, provide broad coverage and long time series of data (Smith and Pain, 2009). Techniques frequently used include visual interpretation (Dwivedi *et al*., 1997), correlation between spectral reflectance values (Price, 1993), automatic extraction/classification techniques (Servenay and Prat, 2003), change detection methods (Smith *et al*., 2000) and imaging radar instruments (Metternicht and Zinck, 1998). However, spatial resolutions similar to aerial photography are now obtainable (e.g. SPOT 5, IKONOS, Quickbird, WorldView and GeoEye) and subsequently utilized to map soil erosion features such as gullies at a national scale (e.g. Mararakanye and Le Roux, 2011)	Catchment to national
Qualitative or expert-based		Studies that rely heavily on the knowledge and interpretation of experts and that are generally applied in areas with limited spatial data (Gobin *et al*., 2003). GLASOD was the first study whereby the expert judgments of several soil scientists across the globe were collated to produce a world map of human-induced soil degradation (Oldeman *et al*., 1991), whereas LADA is the most recent expert-based project including six pilot countries (Argentina, China, Cuba, Senegal, South Africa and Tunisia) (Wiese, 2011)	National to global

GLASOD - Global Assessment of Human-induced Soil Degradation; KINEROS – Kinematic Runoff and Erosion model; LADA - Land Degradation Assessment in Drylands; LiDAR - Light Detection And Ranging, MUSLE – Modified Universal Soil Loss Equation; (R)USLE – (Revised) Universal Soil Loss Equation; SPOT 5 - *Syste`me Pour l'Observation de la Terre*, SWAT – Soil and Water Assessment Tool.

The combination of existing models and remote sensing techniques within a Geographical Information System (GIS) framework is commonly utilized for erosion risk assessment (Gau, 2008). In Australia, for example, the SOILOSS model modifies the (Revised) Universal Soil Loss Equation (R)USLE (Wischmeier and Smith, 1978; Renard *et al*., 1994) within a GIS framework according to Australian conditions (Lu *et al*., 2003). In the U.S.A. BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) developed by the U.S. Environmental Protection Agency is interfaced within a GIS framework and allows the user to choose different internally coupled models such as SWAT (the Soil and Water Assessment

Tool developed by USDA-ARS) (Arnold *et al*., 1998). BASINS is used by many federal and state agencies to assess water resource and nonpoint source pollution problems for a wide range of scales and environmental conditions (Gassman *et al*., 2007). In Europe two standardized approaches were developed to provide comparable information on the soil erosion problem across large areas in Europe (Baade and Rekolainen, 2006). The first is based on remote sensing techniques and a simplification of the USLE interfaced in a GIS (van der Knijff *et al*., 2000). The second, namely PESERA (Pan-European Soil Erosion Risk Assessment Project) is a physically-based and spatially distributed model capable of national assessment of soil erosion in Europe by combining plant growth, runoff and sediment transport models (Kirkby *et al*., 2004). In most other countries, however, especially in developing countries, there is still an absence of standardized methodological frameworks that deliver comparable results across large areas as a baseline for regional scale monitoring. For example in SA, soil erosion risk assessment has been conducted in different regions at various spatial scales but each region and scale required different techniques and input data (detail provided in Section 2).

Since no study can incorporate the knowledge of all aspects of erosion, it is important to understand to what spatial and temporal degree one needs to capture process dynamics for the purpose of the study and to apply the most appropriate and practical technique (Gao, 2008). Assessment techniques should be adapted and modified to combine sufficient simplicity for application at a regional scale with a proper incorporation of the most important processes (Gobin *et al*., 2003). Van Zyl (2007) suggests that the purpose and requirements of erosion studies be determined by its objective, the dominant erosion processes and the availability of data. A minimum information requirement approach should be followed where the simplest technique is applied that satisfies the study objectives whilst ensuring that the dominant erosion processes and factors are accounted for. Due to the fact that there are limitations to understanding each erosion process and scale at which assessment techniques can be applied, Kirkby *et al*. (1996) and Drake *et al*. (1999) recommend that three hierarchical levels be implemented. The first level allows for the assessment of the spatial distribution of the erosion risk at a relatively broad scale, followed by a second level that allows for more detailed assessment of the erosion risk. Level three assesses changes that occur rapidly at relatively fine spatial and temporal scales. Importantly, assessment techniques and data requirements should increase in complexity with progression from the first to third level (Van Zyl, 2007).

Research problem

The main research problem identified in this study is that there is a lack of practical methodological frameworks to provide a consistent baseline for regional scale monitoring, especially in developing countries such as South Africa (SA). Assessment at the regional scale is often problematic (worldwide in general but certainly in SA) due to spatial variability of the factors controlling erosion and the lack of input and validation data (Lenhart *et al.*, 2005; De Vente and Poesen, 2005). Water erosion is driven by complex physical processes that involve interaction of a large number of spatial and temporal factors, regional differences and scale dependency (De Vente *et al.*, 2007; Vanmaercke *et al.*, 2011; Parsons, 2012). The lack of appropriate/representative data often necessitates application of techniques outside areas and scales of intended use. However, the use of techniques outside of conditions for which it was developed may lead to large errors by either disregarding important erosion factors or overvaluing less important ones. For example, it appears that the inherent erodibility of soil and parent material are the overriding erosion risk factors in SA (Laker, 2004) and not the climate and slope gradient as frequently determined in the USA and Europe (Vanmaercke *et al.*, 2011). In addition, not all erosion types occurring in specific areas are always taken into account. Most regional studies in SA emphasize the sheet and rill aspects of the erosion cycle but exclude gully erosion thus underestimating soil losses in regions where gullies are prominent (Van Zyl, 2007). According to Boardman (2006) and Parsons (2012), gullying and sediment movement are often ignored due to variability at a regional scale.

The above-mentioned problems of spatial heterogeneity and lack of data in SA are coupled with the availability of a wide variety of approaches and techniques that causes measurement variability (Zhang *et al.*, 2002). Laker (2004) states that erosion research methodologies became more diversified over the preceding few decades but the methods used and the results produced are not comparable with each other. These problems hinder successful soil erosion risk assessment and the development of site- and scale-specific control measures to reduce and prevent soil erosion in developing countries such as SA. With the increase of human impacts on the environment, especially agricultural intensification, there is a need to standardize assessment and monitoring methodologies in order to support efficient environmental management strategies (Rubio and Bochet, 1998; Symeonakis and Drake, 2004). Such considerations highlight the need to establish a methodological framework that delivers comparable results across large areas and a baseline for regional scale monitoring in the country.

Aim and objectives

The study aims at establishing a methodological framework using the most feasible erosion assessment techniques and input datasets for which sufficient spatial information exists, emphasizing simplicity required for application at a regional scale with proper incorporation of the most important factors in South Africa (SA). Assessment will be limited to water erosion, as this is considered the most important form of soil erosion at a regional scale in SA (Garland *et al*., 2000). Due to limitations to understanding each erosion process and scale at which assessment techniques can be applied (Drake *et al*., 1999), a multi-process and -scale approach will be implemented by means of three Case Studies assessing the factors controlling: (*i*) sheet-rill erosion at a national scale, (*ii*) gully erosion in a large catchment and (*iii*) sediment migration for a smaller research catchment. These Case Studies will assist in the establishment of framework and provide relevant information on factor dominance and scale issues. The aim will be achieved through meeting the following objectives:

1. Review on the status of the application of technologies to estimate and monitor soil erosion and sediment processes at a regional scale;
2. Water erosion prediction emphasizing <u>sheet and rill erosion</u> at a **national** scale (Case Study *i*);
3. Establishing the factors controlling <u>gully erosion</u> in a **large catchment** (Case Study *ii*);
4. Modelling connectivity aspects in <u>sediment migration</u> for an agricultural **research catchment** (Case Study *iii*); and thus
5. Establishing a methodological framework for water erosion risk assessment in South Africa.

Due to the complexity of erosion processes, regional differences and scale dependency, a single assessment technique will not be feasible (Vrieling, 2006). Several authors state that the selection of assessment techniques should be determined by the objective of the study, the size of the area (scale), the dominant erosion processes and factors, as well as the availability of data (Morgan, 1995; Gobin *et al*., 2003; Merritt *et al*., 2003; Boardman, 2006; Van Zyl, 2007). A distinction should be made between factors that are useful to have and those which are practical to obtain (Warren and Khogali, 1992). Ideally such a framework needs to provide a comprehensive set of guidelines in order to allow evaluation of (at least) the dominant factors that contribute to different processes (Symeonakis and Drake, 2004). In a knowledge gap analysis for erosion risk assessment in SA, Van Zyl (2007) recommends development of a framework which allows the use of different techniques requiring readily available data, including gully erosion models/mapping and the assessment of agriculturally derived sediments. Therefore, the study does not intend to develop new erosion models or remote sensing techniques, but will utilize universally applied techniques and derive input parameter values within a GIS framework. The emphasis herein is on factor dominance as represented by the structure and spatial elements of frequently applied techniques and current datasets. It is envisaged this framework for water erosion risk assessment in SA will be useful to guide and standardize future regional assessment efforts in the country, including monitoring the effects of land use and climate change on erosion risk.

Project outline

Following the Introduction Section above, Section 2 provides a theoretical background, including a published state of knowledge review. Section 3 presents (in journal paper format) the three Case Studies assessing erosion processes using different techniques at different scales including: (*i*) sheet and rill erosion indicators in SA at a national scale; (*ii*) factors controlling gully erosion in a large catchment; and (*iii*) modelling sediment migration for an agricultural research catchment. Where applicable in the thesis, the text remains the same as that published, but has been reformatted for consistency of style. Given that the Figures are specific to the papers, a detailed list is not provided in the Contents Section. The three Case Studies support the establishment of the methodological framework in Section 4, providing relevant information and scale issues on the main contributing factors. Finally, a summary concludes the study in Section 5. Since Section 2 and 3 comprise of published papers, for completeness the references are included at the end of each section or paper.

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2. THEORETICAL BACKGROUND

Preface

Section 2 comprises one chapter as follows:

Le Roux JJ, Newby TS, Sumner PD. 2007. Monitoring soil erosion in South Africa at a regional scale: Review and recommendations. *South African Journal of Science* **103**: 329-335.

This section provides a state of knowledge review of approaches and techniques used to assess water erosion at a regional scale, including reference to some examples. In a comparative context, the review paper discusses available technologies that are recognized internationally and the techniques and approaches used in South Africa (SA). Since this chapter was published in 2007 it excludes reference to subsequent literature. More recent studies are listed in Table 2 of Section 1 and receive attention in the following sections. The review also provides a discussion of the major assessment-related deficits which have generally remained the same since 2007. These include spatial, temporal and measurement variability in erosion risk assessment studies across the globe, but especially in SA. Furthermore, in contrary to most international studies, previous studies conducted in SA at the regional scale have disregarded important erosion factors and have overvalued less important ones. The review concludes with recommendations for future research, including the need to establish a methodological framework to guide and standardize future regional soil loss monitoring efforts in SA.

The chapter is co-authored with Sumner and Newby. I conceptualized the paper, undertook chapter structure and main text compilation, submission and revision as discussed with co-authors.

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Monitoring soil erosion in South Africa at a regional scale: review and recommendations

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Published in: *South African Journal of Science*, 2007, volume 103, 329-335.

This paper was published in a special issue: South African Environmental Observation Network (SAEON) Reviews.

Abstract

Loss of topsoil is one of the major soil degradation problems confronting agriculture throughout South Africa and receives special attention by policy-makers. For effective prevention and remediation, the spatial extent of the problem has to be established and monitored. Recent developments in the application of remote sensing and GIS to the study of soil erosion offer considerable potential in this regard. This paper outlines key technologies available for monitoring, and highlights the problems to be solved at a regional scale. The status of the technologies used in South Africa are reviewed and the more recent studies related to soil erosion presented in a comparative context. Spatial, temporal and measurement variability are major constraints in erosion assessment. Previous erosion studies conducted in South Africa at the regional scale have disregarded important erosion factors and have overvalued less important ones. Different processes and interactions are likely to emerge as dominant when crossing scale boundaries. Such considerations highlight the need to establish a methodological framework to guide and standardize future regional soil loss monitoring efforts.

Introduction

Soil erosion is a major problem confronting land resources throughout the Republic of South Africa (SA). Previous research indicates that over 70% of the country's surface has been affected by varying intensities and types of soil erosion (Pretorius, 1998; Garland *et al.*, 2000). Although erosion is a natural process, it is accelerated by human activities such as clearing vegetation or overgrazing (Snyman, 1999). Land degradation caused by soil erosion not only involves the loss of fertile topsoil and reduction of soil productivity, but also leads to sedimentation of reservoirs and increases suspended sediment concentrations in streams with consequent effects on ecosystem health (Flügel *et al.*, 2003).

Erosion is a process of detachment and transportation of soil materials by wind or water (Morgan, 1995). Since water is the dominant agent causing erosion in SA (Laker, 2004), it is the focus of this review. Water erosion can occur through rainsplash, in unconcentrated flow as sheet erosion, or in concentrated flow as rill and/or gully erosion (SARCCUS, 1981). Outcomes depend on the combined and interactive effects of erosion factors, namely, rainfall erosivity, soil erodibility, slope steepness and slope length, crop management, and support practice (Wischmeier and Smith, 1978). Assessment of erosion thus requires knowledge of how these parameters change across different scales of space and time. More detail on the factors governing erosion, specifically in a South African context, is provided by Laker (2004), Mulibana (2001), D'Huyvetter (1985) and Garland *et al*. (2000).

Remediation and prevention require that the spatial extent of erosion be established. Many observations of soil erosion have been carried out in SA (Rowntree, 1988; Stern, 1990; Snyman, 1999), but the derived statistical relationships from individual erosion measurements are confined to local conditions and do not provide a sufficiently broad range of input data for regional soil loss monitoring (Vrieling, 2006). Although erosion control measures need to be implemented at the field or hillslope scale, allocation of scarce conservation resources and development of policies demands regional scale assessment (Vrieling, 2006). Geographic Information Systems (GIS) and remote sensing techniques, as well as soil erosion models applied within a spatial context, play an important role at the regional scale. We review available technologies with international standing for this purpose, and the techniques and approaches used in SA. More recent techniques and products related to soil erosion at a national scale receive special attention. The review is followed by a discussion of the major assessment-related deficits and recommendations for future research.

Technologies available for monitoring

A wide variety of techniques are available for assessing soil erosion risk across a wide range of scales (Morgan, 1995; Garen *et al*., 1999; Jetten *et al*., 1999; Smith, 1999; Merrit *et al*., 2003; Aksoy and Kavvas, 2005; King *et al*., 2005; Stroosnijder, 2005; Vrieling, 2006). Slope-scale measurements include field rainfall simulation studies and the use of delineated runoff plots (McPhee *et al*., 1983; Snyman and Van Rensburg, 1986; Stern, 1990; Russell, 1995; Rapp, 1998), which provide valuable data on erosion rates of different crop covers and soil types. Although essential for calibration and verification of soil loss models, such field experiments only apply to one or a few hillslopes and cannot be directly extrapolated to evaluate and monitor erosion for a whole catchment (Sivapalan, 2003). Thus methods designed to analyze and interpret broader spatial scales are becoming increasingly important (EEA, 2003). The advent of recent developments in the application of GIS and remote sensing technology offer considerable potential for meeting these requirements.

Remote sensing

Remote sensing techniques using aerial photographs and satellite remote sensing data have greatly increased the capacity to record and monitor land degradation at the regional level

(Kumar *et al*., 1996). Important sensor development has taken place through airborne systems including photogrammetric methods using stereo images (Kakembo, 1997; Flügel *et al*., 2003), synthetic aperture radar interferometry (Hochschild and Herold, 2001), airborne laser altimetry (Ritchie, 2000) and hyperspectral remote sensing (Vrieling, 2006). Although airborne systems and methodologies are useful in the direct identification of erosion, they are not feasible for monitoring erosion at a national scale for which satellite imagery is better adapted.

Five types of satellite-based observations can be undertaken (Stroosnijder, 2005; Vrieling, 2006). Firstly, large eroded surfaces can be visually interpreted, based on deviating spectral properties (Kumar *et al*., 1996). Secondly, modifications of the former technique involve automatic extraction, including unsupervised and supervised classification, using principal component analysis and the maximum likelihood technique amongst others (Floras and Sgouras, 1999; Servenay and Prat, 2003). Highest accuracy can be achieved using a combination of images from different sensors, e.g., Landsat Thematic Mapper (TM) and Japanese Earth Resources Satellite synthetic aperture radar (SAR) data (Metternicht and Zinck, 1998). Thirdly, direct correlation between erosion and spectral reflectance values sometimes permits the detection of erosion and its intensity. Assuming a relation between vegetation cover and erosion, an empirical relation between erosion and reflection can be used (Price, 1993). The fourth category includes visual interpretation and detection of off-site impacts, such as sediment deposition (Jain *et al*., 2002) as well as dissolved sediment (Ritchie and Cooper, 1991). The fifth application uses repeat pass SAR interferometry that allows assessment of the change in erosion (Massonet and Feigl, 1998).

Until recently, detection of erosion features with satellite data was difficult due to inadequate resolution (Hochschild *et al*., 2003). Usually higher resolution data (e.g. *Syste`me Pour l'Observation de la Terre*; SPOT) are better for classifying eroded areas, whereas a larger number of spectral bands (e.g. Landsat TM) results in a better classification of vegetational attributes (Dwivedi *et al*., 1997). With advances in sensor technology, space-borne data with improved spectral, spatial and temporal resolution is now available. Although not yet reported in the literature, new high resolution satellite imagery such as SPOT 5, IKONOS and Quickbird are very promising for identifying erosion features, such as individual gullies (Lindemann and Pretorius, 1995). However, automatic retrieval of individual features is not currently available due to the heterogeneity of the object itself as well as the environment (King *et al*., 2005). Most remote sensing studies of soil erosion thus concentrate on the assessment of erosion risk factors, notably, vegetal attributes and, to a lesser extent, soil erodibility, topography and conservation practices (Garen *et al*., 1999; Vrieling, 2006).

Spatial modelling/analysis

Differentiation between classes of models usually rests on the level of complexity used to represent the soil erosion processes and on the spatial and temporal resolution of the model. Models fall into three main categories: empirical, conceptual and physically-based models (Merritt *et al*., 2003). Table 1 summarises selected models in terms of their classification and scale of application. The best known and widely implemented empirical models for estimating soil loss at the regional scale are USLE developed in the 1970s by the United States Department of Agriculture (USDA), and its upgraded version RUSLE. Although developed for application to small hillslopes, (R)USLE and its derivatives have been incorporated into many regional scale erosion studies across the globe. The European Environment Agency (EEA, 1995), the USDA (NRI, 2001), and the National Land and Water Resources Audit of Australia (Rosewell, 1993; Lu *et al*., 2003), have presented some of the most sophisticated work, namely, CORINE, USLE, and SOILOSS respectively. Conceptual models better represent reality by incorporating the underlying transfer mechanisms of sediment and runoff generation in their structure, representing flow paths in a catchment as a series of storages (Merritt *et al*., 2003). Physically-based models have a much more sophisticated model structure being based on the solution of fundamental physical equations describing streamflow and sediment on a hillslope or in a catchment.

Other categories include continuous simulation models (e.g. SWAT, AGNPS, ACRU), event-based models (e.g. KINEROS, LISEM), lumped models (e.g. RUSLE, SLEMSA) and distributed models (e.g. KINEROS). The first simulates long time periods with a time step of 1 h – 1 day; the second uses a small time step (< 1 min) to simulate a single event; the third employs single values of input parameters with no spatial variability while the last incorporates spatially distributed parameters by taking explicit account of spatial variability.

Table 1: Examples of land degradation approaches and soil erosion models.

Acronym and (model type)	**Name**	**Developed by**	**Aim**	**Time step and partition**
ACRU (Conceptual)	Agricultural Catchment Research Model	Univ. of Natal – Dept. of Agricultural Engineering (Schulze, 1995)	Sub-catchment modelling	Daily Sub-catchment
AGNPS (Conceptual)	Agricultural Non-Point Source Pollution	US Dept. of Agriculture – Agricultural Research Service (Young, 1989)	Estimate runoff water quality from agricultural catchments	Daily Event Cell
CORINE (Empirical and Expert)	Coordination of information on the environment	European Environmental Agency (EEA, 1995)	Soil erosion risk modelling by USLE factor/indicator mapping to target poly actions at a continental scale	Annual Continental, 1:1 million
EUROSEM (Physical)	European Soil Erosion Model	European Union (Morgan *et al.*, 1998)	Compute sediment transport, erosion and deposition throughout a storm	Event Break point Channel Hillslope
GLASOD (Expert)	Global assessment of human-induced soil degradation	International Soil Reference and Information Centre (ISRIC) (Oldeman *et al.*, 1991)	Actual soil erosion based on distributed point data obtained from experts in several countries across the world.	Current risk Global
KINEROS (Physical)	Kinematic Runoff and Erosion model	US Dept. of Agriculture – Agricultural Research Service (Woolhiser *et al.*, 1990)	Event-oriented, physically-based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds.	Event Field
LISEM (Physical)	Limburg Soil Erosion Model	Department of Physical Geography at Utrecht University and Soil Physics Division at Winard Staring Centre (De Roo and Jetten, 1999)	Spatially distributed physics-based hydrological and soil erosion model, based on EUROSEM	Event Catchments up to 100 km^2
MEDALUS (Physical)	Mediterranean Desertification and Land Use	European Commission (Kosmas *et al.*, 1999)	To understand and mitigate the effects of desertification in southern Europe	Event, daily Field, catchment
(R)USLE (Empirical)	(Revised) Universal soil loss Equation	US Dept. of Agriculture (Wischmeier and Smith, 1978; Renard *et al.*, 1994)	Lumped empirical models that estimates annual rill and interill erosion based on main soil erosion factors	Annual Hillslope
SLEMSA (Empirical)	Soil loss estimation method for Southern Africa	Department of Agricultural Technical Services (Elwell, 1976)	Lumped empirical model that estimates interill erosion based on main soil erosion factors	Annual Hillslope
SOILOSS (Empirical)	Soiloss: Australian version of the RUSLE	Soil Conservation Service of New South Wales (Rosewell, 1993)	A computer programme that calibrates and modifies RUSLE factors according to Australian conditions	Monthly, Annual Continental Regional
SWAT (Conceptual)	Soil and Water Assessment Tool	US Dept. of Agriculture – Agricultural Research Service (Arnold *et al.*, 1994)	Prediction of the effects of management decisions on water sediment yields for ungauged rural basins	Daily Event Sub-catchment
WEPP (Physical)	Water Erosion Prediction Project	US Dept. of Agriculture – Agricultural Research Service (Nearing *et al.*, 1989)	Soil and water conservation planning and assessment	Breakpoint Continuous Channel Hillslope

The data requirements of models dramatically increase with the introduction of spatial (distributed) and temporal (event-based and continuous time step) complexity. For example, distributed and continuous simulation models require large quantities of spatial and temporal data for weather and land use. Several authors state that the description of water fluxes over and through the soil is the foundation of an erosion model (Garen *et al.*, 1999; Jetten *et al.*, 1999; Aksoy and Kavvas, 2005). Additional information, in particular changes in soil structure resulting from agricultural activities, greatly improves the quality of results. However, complex models tend to be restricted to research catchments and are prohibitive in terms of the time required for implementation on a regional basis as required by government policies. According to Prosser *et al.* (2001), this is the main reason why empirical models are frequently preferred to more complex models, especially at a regional scale. They can be implemented in areas with limited data and are particularly useful as a first step in identifying sources of sediment.

Furthermore, input errors may increase with increasing model complexity. This prevents the application of American models, such as WEPP and KINEROS, or EU-funded models such as EUROSEM and MEDALUS. According to Garen *et al.* (1999) it is not expected that physically-based models such as WEPP will find use in state and field offices of the Natural Resources Conservation Service (NRCS); formerly the Soil Conservation Service. Instead, the empirical and conceptual models, namely RUSLE, SWAT and AGNPS, were adopted by the NRCS for modelling at the regional scale. A user interface, as developed for the AGNPS and SWAT models, streamlines access to key databases and facilitates the preparation of input data sets in the USA. Techniques involving GIS and algorithms for digital terrain analysis are readily available and are currently improving the hydrologic process description in models. Such algorithms are currently used to identify catchment boundaries, determine stream networks and establish overland flow paths as described by Taudem (Tarboton, 2005), HydroTools (Schäuble, 2003) and Tapes (Wilson and Gallant, 2000).

Soil erosion modelling suffers from a range of problems including data variability, over-parameterization, unrealistic input requirements, unsuitability of model assumptions or misleading parameter values in local context and lack of verification data. Recent assessments of the quality of erosion models showed that, in general, the spatial patterns of erosion are poorly predicted (Jetten *et al.*, 2003; Merritt *et al.*, 2003). Furthermore, models can rarely be relied upon to give accurate predictions of absolute amounts of erosion. Without adequate input data and calibration, models can only be expected to give a relative ranking of the effects of land management (Garen *et al.*, 1999). Input data preparation is a laborious task and the mechanics of operating the models is sometimes complicated (Jetten *et al.*, 2003). A large part of the effort goes into the construction of the input data set, often derived from a few basic variables that are available as raw data. Despite these limitations, soil erosion models have been modified and applied to regional scales for scenario analysis, and to make objective comparisons that are important for targeting of research and soil conservation efforts in SA.

Background of erosion assessment in South Africa at a national scale

The Department of Agriculture (DoA) and the Water Research Commission (WRC) funded a number of regional-based research projects in SA. Starting in 1991, national studies are summarised in terms of their methodology and scale of application (Table 2). GLASOD was one of the first major regional scale degradation studies conducted by recognized experts in several countries across the globe (Oldeman *et al*., 1991), including SA (Laker, 2004). Experts divided soil erosion areas into relatively uniform units based on the most important erosion processes. From this a relative ranking of soil erosion risk per area was obtained and a soil erosion risk map was produced at a continental scale.

Thereafter, the use of remote sensing in monitoring soil erosion on a national scale was investigated in 1993. The Bare Soil Index (BSI) was developed with Landsat TM data, making it possible to detect the status of eroded areas on a national scale (Pretorius and Bezuidenhout, 1994). The BSI proved to be reliable in identifying rural settlements and overgrazed and eroded areas in the Mpumalanga and Eastern Cape provinces. Review of the results indicated, however, that the BSI did not differentiate ploughed fields and sandstone outcrops from eroded areas. Furthermore, due to the limited resolution of Landsat TM data (30m), single gullies and limited rill and sheet erosion could not be delineated.

Most regional-based studies concentrated on the assessment of erosion controlling factors, including, rainfall erosivity, soil erodibility, slope length and steepness, vegetal attributes and conservation practices. These are the well-known USLE erosion factors. USLE (McPhee and Smithen, 1984; Crosby *et al*., 1986; Smith *et al*., 1995; Smith *et al*., 2000), RUSLE (Haarhoff *et al*., 1994; Smith *et al*., 1995; Pretorius and Smith, 1998; Smith *et al*., 2000) and SLEMSA (Schulze, 1979; Hudson, 1987; Smith *et al*., 2000) have been the most widely applied models in SA. Production of the Erosion Susceptibility Map (ESM) was the first national level attempt to integrate the main erosion risk factors within a GIS framework (Pretorius, 1995). The ESM at a scale of 1:2.5 million was created by integrating spatial data on sediment yield, provided by Rooseboom *et al*. (1992) and Verster (1992), with remotely sensed vegetation data, namely, normalized difference vegetation index from the National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer (NOAA – AVHRR) sensor. A second attempt to integrate the main erosion contributing factors at a national level followed in 1998 with the production of the Predicted Water Erosion Map (PWEM) of SA (Pretorius, 1998). Improvements on ESM involved, inter alia, the inclusion of long-term rainfall erosivity data obtained from the iso-erodent map of Smithen and Schulze (Smithen and Schulze, 1982). Also at a scale of 1:2.5 million, PWEM indicates that a very large percentage of the Limpopo (60%) and Eastern Cape (56%) provinces are under severe threat of erosion, whereas the Gauteng and North-West provinces seem to be the least threatened by water erosion. The methodology of ESM and PWEM, however, was based on a considerable simplification of USLE; by combining soil and slope factors with sediment yield data obtained from Rooseboom *et al*. (1992) and Verster (1992). Since PWEM is only suitable for the prioritization of problem areas on a broad scale, due to the coarse resolution (1.1 km) of NOAA images, research continues at a provincial scale.

Mapping and monitoring of natural resources of the Mpumalanga (Wessels *et al*., 2001a) and Gauteng (Wessels *et al*., 2001b) provinces was completed in 2001 and for the O. R. Tambo and Umkhanyakude ISRDS Nodes, located in northern Eastern Cape and KwaZulu-Natal, in 2004 (Ströhmenger, 2004). Improvements to ESM and PWEM include individual attention to the soil erodibility and topography input factors. Soil erodibility index values were utilized by using SLEMSA. In the absence of soil analytical and experimental data, two alternative sources of soil information were used: soil maps (1:50 000 and 1:250 000) (Soil Survey Staff, 1973–1987) and the Land Type Inventory database (1:50 000) (Land Type Survey Staff, 1972–2006). Topography factors were facilitated by the application of digital elevation models and the unit stream power theory developed by Moore and Burch (1986). Results indicate that areas with high erosion potential occur mostly in subsistence farming areas associated with steep slopes and highly erodible soils. However, some units displayed by the erosion hazard maps gave the wrong impression of current soil loss damage. Erosion rates seem to be over-predicted in some of the subsistence farming areas with steep slopes, as well as in mountainous terrain with long and steep slopes.

The most recent national scale overview was compiled by the South African National Biodiversity Institute (Garland *et al*., 2000). A national soil degradation review was compiled using information obtained from 34 workshops throughout SA during 1997 and 1998. Results were presented as a series of maps illustrating the type and severity of soil degradation of different land use types for each magisterial district of SA. The approach is limited by being lumped for each magisterial district, and due to its dependence on apparently subjective judgments.

Table 2: Summary of erosion assessment projects in South Africa at a national scale (from 1991).

Acronym	Name	Location
GLASOD	Global assessment of human-induced soil degradation	Global (Oldeman *et al.*, 1991) Southern Africa (Laker, 1993)
SDPM	Sediment Delivery Potential Map	Southern Africa (Rooseboom *et al.*, 1992; Verster, 1992)
BSI	Bare Soil Index	National (Pretorius and Bezuidenhout, 1994)
ESM	Erosion Susceptibility Map	National (Pretorius, 1995)
PWEM	Predicted Water Erosion Map	National (Pretorius, 1998)
NRA ISRDS nodes	Natural Resources Auditing Integrated Sustainable Rural Development Strategy nodes	Mpumalanga (Wessels *et al.*, 2001a) Gauteng (Wessels *et al.*, 2001b) OR Tambo and Umkhanyakude (Ströhmenger, 2004)
SANBI land degradation review	South African National Biodiversity Institute land degradation review	National (Garland *et al.*, 2000)
–	Potential and actual water erosion prediction maps for SA	National (Le Roux *et al.*, 2006)
SPS of DoA	Soil Protection Strategy of the Department of Agriculture (Lindemann and Pretorius, 2005)	Tertiary catchments in Limpopo, KwaZulu-Natal and Eastern Cape
–	Sedimentation and Sediment Yield Maps for SA conducted by Stellenbosch University - Department of Civil Engineering and ARC-ISCW	National
NPS Pollution Project	Non Point Source Pollution Project	Mkabela and Berg River research catchments (see Le Roux and Germishuyse, 2007)

ISCW is currently involved in several regional-based erosion studies funded by DoA and WRC (see Table 2). These include: potential and actual water erosion maps of SA, currently being validated (Le Roux *et al*., 2006); remote sensing (SPOT 5) and modelling (SWAT and RUSLE) of the erosion status of three priority tertiary catchment areas, located in the Eastern Cape, KwaZulu-Natal and Limpopo provinces, identified by the Soil Protection Strategy of the DoA (Lindemann and Pretorius, 2005); sedimentation and sediment yield maps for SA to improve the sediment yield maps of Rooseboom *et al*. (1992) and modelling of runoff and sediment transport processes at field to catchment scale to improve understanding of the requirements and processes accounted for by models with international standing, such as SWAT and KINEROS (see Le Roux and Germishuyse, 2007). The following section discusses how the South African studies compare with the international technologies available for monitoring.

Discussion

Spatial pattern prediction of soil erosion is generally not very accurate due to spatial and temporal variability (Jetten *et al*., 2003). Although soil erosion has been regarded as an important phenomenon in SA since the turn of the century, one of the weaknesses of South

African soil erosion research is the limited information on where the worst problems are located (Mpumalanga DACE, 2002). Errors are assumed to be high in certain areas because of the unknown input factors, especially the vegetation cover factor for various land use practices. More research is needed to assess the confidence limits for the erosion estimates generated for SA at a national scale.

According to Vrieling (2006), it is striking that many studies across the globe have minimally addressed the issue of validation. Studies merely relate the actual range of quantitative erosion rates to measured or predicted values from literature, and are satisfied when values correlate. This is probably because, other than visual comparison of maps, there are very few pattern comparison techniques (Jetten *et al*., 2003). According to the EEA (2003), proper validation obtained from applying an erosion model at a national scale is hardly possible. Widespread and long-continued soil loss measurements or observations are limited to selected test areas. In SA, limited plot-scale measurements of erosion (e.g. Cedara Agricultural Research Station in KwaZulu-Natal since 1983) (Russell *et al*., 1995) allow limited regional validation and calibration of USLE factors. Empirical models still need to be appropriately adapted and validated over a long-term and wide range of conditions in SA.

Soil erosion encompasses a vast array of processes, which makes its assessment difficult to encapsulate in a few simple measures. Erosion occurs over a large variety of timescales such as a single storm to many decades. Furthermore, soil loss occurs over many spatial scales including the site of impact from a single raindrop to large fields and catchments. Therefore, measurements undertaken at one set of scales cannot be compared with measurements at another. In this context, a major limitation of soil erosion assessment is that different processes and interactions are likely to dominate when crossing scale boundaries. Soil erosion processes and parameters important at one scale are frequently not important or predictive at another scale (Wilson and Gallant, 2000). The scale problem is coupled with the availability of a wide variety of approaches and techniques that causes measurement variability. Erosion research methodologies became much diversified during the 1980s and 1990s (Laker, 2004), but the methods used and the results produced are far from comparable to each other. Individual studies have inconsistencies in their definitions and measurement procedures, and usually cover short or irregular research periods. Although monitoring implies multi-temporal sampling, most of the studies mentioned above were confined to the use of field surveys and single date imagery to test the potential of using earth observation remote sensing and GIS as monitoring tools. In this context, there exists no methodological framework or “blueprint” to assess the spatial distribution of soil erosion types at different regional scales in SA.

Regional erosion studies cannot integrate all the erosion factors, but have to incorporate the most important processes. Unfortunately, previous erosion studies conducted in SA at the regional scale disregard important erosion factors. For example, Laker (2004) states that important factors of soil erodibility, such as the parent material, degree of soil weathering and stability against dispersion and crusting, are currently excluded in modelling. Various authors state that geology is probably the most dominant factor controlling the inherent erodibilities of soils in SA (e.g. D'Huyvetter, 1985; Dardis *et al*., 1988; Rowntree, 1998; Laker, 2004). Clay dispersibility is also a key factor and significant research is being conducted to gain an understanding on how it influences erodibility of soils in SA (Stern *et al*., 1991; Bühmann *et al*., 1996). However, erodibility of South African soils and how it affects soil erosion in the country, especially within a spatial context, is as yet poorly understood and needs further investigation.

Several regional studies indicate that the soil erosion risk of SA seems to follow topography poorly and is probably overestimated in some areas with steep terrain (Wessels *et al*., 2001a; Ströhmenger, 2004). Although several studies across the globe demonstrate that soil erosion is very sensitive to the topographical factor of RUSLE (Risse *et al*., 1993; Mitasova *et al*., 1996; Biesemans *et al*., 2000), additional work is still needed to test and validate the suitability of topography indices in SA and how it affects soil erosion in the country.

Another noteworthy regional limitation is that not all erosion types occurring in SA are taken into account. Most erosion prediction models emphasize the interrill and rill aspects of the erosion cycle, but few models predict gully erosion (Bull and Kirkby, 1997; Van Zyl, 2004). This is probably due to the temporal and spatial complexity at which the phenomenon occurs, which is difficult to model; e.g. the importance of paths and cattle tracks in creating gullies (Garland *et al*., 2000; Boardman *et al*., 2003; Hochschild *et al*., 2003). Fortunately, more detailed maps derived from satellite imagery are now available for measuring and monitoring gullies, as well as sheet and rill erosion, on a national scale.

Conclusions and recommendations

South Africa is predisposed to soil erosion due to poor farming practices together with erodible soils. When considered across all land use types, it is clear that soil degradation is perceived as more of a problem in the KwaZulu-Natal, Limpopo and Eastern Cape provinces, and less of a problem in the Free State, Western Cape and Northern Cape. However, our ability to develop cost-effective land management strategies is still limited by sources of error in spatial data, ranging from natural variability to issues of accuracy and precision in mapping techniques. In addition, the spatial problem is coupled with a wide variety of mapping techniques that are equally valid but give different results.

Methodological problems, discussed previously, point to the need to establish a proper framework to guide and standardize future regional soil loss modelling and mapping efforts. Such a framework should outline the different erosion processes and interactions likely to dominate at different scales. In this context, regional modelling should combine the simplicity required for application on a regional scale with a proper incorporation of the most important processes. At the regional scale, it appears that the inherent erodibility of the soil and parent material are the overriding erosion risk factors in SA, and not the slope gradient as determined in the USA.

Furthermore, the framework needs to describe the most feasible erosion assessment techniques, as well as input datasets, for application at different scales. For example, it may be feasible to use qualitative approaches where no model is available that was developed or tested in the region under study. Due to the complexity of erosion processes, regional differences and scale dependency, it cannot be expected that a single standardized operational erosion assessment system will be useful. According to Laker (2004), one should rather adopt a dynamic “evaluation tree” approach which would lead the user through a ranking of factors (e.g. parent material, clay mineralogy) in a specific area.

Finally, further refinement of national erosion assessment will be possible given additional research, including:

- Long-term monitoring of soil erosion (e.g. using field measurement and time-series imagery);
- The production of more accurate erodibility maps at a national scale;
- Monthly erosivity estimations in combination with monthly vegetation data in order to capture seasonal variations in soil erosion;
- Spatial modelling techniques to predict gully erosion extent at national scale;
- The use of high resolution imagery (SPOT 5) to extract erosion features at a national scale;
- Careful calibration and validation of prediction models and model components, especially when applied to large geographical areas.

The advent of new techniques and approaches of erosion assessment and recent developments in the application of GIS and remote sensing techniques offer considerable potential for meeting these requirements.

Acknowledgements

Numerous colleagues at the Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) have assisted the research efforts. A special word of gratitude to Dr. T.L. Morgenthal and Mrs. E.C. van den Berg for providing data and assistance during the preliminary stages of this review (needed for the 2006 SAEON land degradation presentation). The paper benefited greatly from the comments of Prof. K. Rowntree at Rhodes University. A word of gratitude to Mrs. R. van Dyk for providing literature and documents cited in this paper.

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