4. METHODOLOGICAL FRAMEWORK FOR WATER EROSION RISK ASSESSMENT IN SOUTH AFRICA

Methodological framework

With the increase in human impacts on the environment, especially in terms of agricultural intensification and climate change, there is a need to accurately assess the distributed character of the erosion process and allow evaluation of at least the dominant contributing factors (Rubio and Bochet, 1998; Symeonakis Drake, 2004; Casalí *et al*., 2009). Advances in remote sensing, simulation models and GIS technology enable the processing of large amounts of data for application at a regional scale (De Jong *et al*., 1999; Wu and Wang, 2007). However, assessment at the regional scale is problematic due to spatial variability of the factors controlling erosion, the lack of input and validation data, as well as measurement variability (Zhang *et al*., 2002; De Vente and Poesen, 2005; Lenhart *et al*., 2005). Gullying and sediment movement are often ignored because of their variability at a regional scale (Boardman, 2006; Parsons, 2012).

Due to the fact that there are limitations to understanding each erosion process and scale at which assessment techniques can be applied (Drake *et al*., 1999), this study implemented a multi-process and multi-scale approach in Section 3. The approach includes assessment of (*i*) sheet-rill erosion at a national scale based on the principles and components defined in the (Revised) Universal Soil Loss Equation (R)USLE), (*ii*) gully erosion in a large catchment located in the Eastern Cape Province by integrating eleven important factors into a GIS, and (*iii*) sediment migration for a research catchment near Wartburg in KwaZulu-Natal by means of the Soil and Water Assessment Tool (SWAT). For each of these Case Studies, information is presented in the form of a methodological framework (Figure 1) encompassing different techniques and data to describe the main contributing factors and areas at risk. Figure 1 outlines the most feasible erosion assessment techniques and input datasets for which there is sufficient spatial information, emphasizing simplicity required for application at a regional scale with proper incorporation of the most important factors. The framework should not be interpreted as a single assessment technique but rather as an approach that guides the selection of appropriate techniques and datasets according to the complexity of the erosion processes and scale dependency. Several authors state that the selection of assessment techniques should be determined by the objective of the study, the scale, the dominant erosion processes and factors, as well as the availability of data (Boardman, 2006;

Vrieling, 2006; Van Zyl, 2007). In order to provide a comprehensive overview of the erosion risk, the framework illustrates that three hierarchical levels need to be implemented.

Hierarchical levels with increasing technique and data requirements

Three hierarchical levels for erosion risk assessment in SA, with increasing technique and data requirements, are illustrated in Figure 1. The first level allows for assessment of the spatial distribution of erosion risk and contributing factors at a national scale, emphasizing the sheet-rill aspects of the erosion process (Case Study *i*). This level should be followed by a second level that allows for assessment of the spatial distribution of gully erosion and contributing factors at a large catchment scale (Case Study *ii*). These levels provide no information about where material moves to or about connectivity between source and sink. A third level thus allows for assessment of sediment migration and associated connectivity aspects at a smaller/research catchment scale, including the influence of identified source and sink zones (Case Study *iii*).

The studies of Kirkby *et al*. (1996) and Drake *et al*. (1999) also suggested a hierarchical approach with three levels, although using different techniques at different scales compared to this study. Kirkby *et al*. (1996) assessed slope-scale water redistribution (first level), infiltration and vegetation interactions (second level), and soil aggregation (third level) in southeast Spain. Drake *et al*. (1999) conducted global scale modelling (first level), catchment scale modelling for the Walia catchment in Mali (second level), and proposed local scale assessment (third level) for areas that are identified as having accelerating erosion. Similar to the above-mentioned studies, nevertheless, the assessment techniques and data requirements used in this study increase with progression through the first to third level.

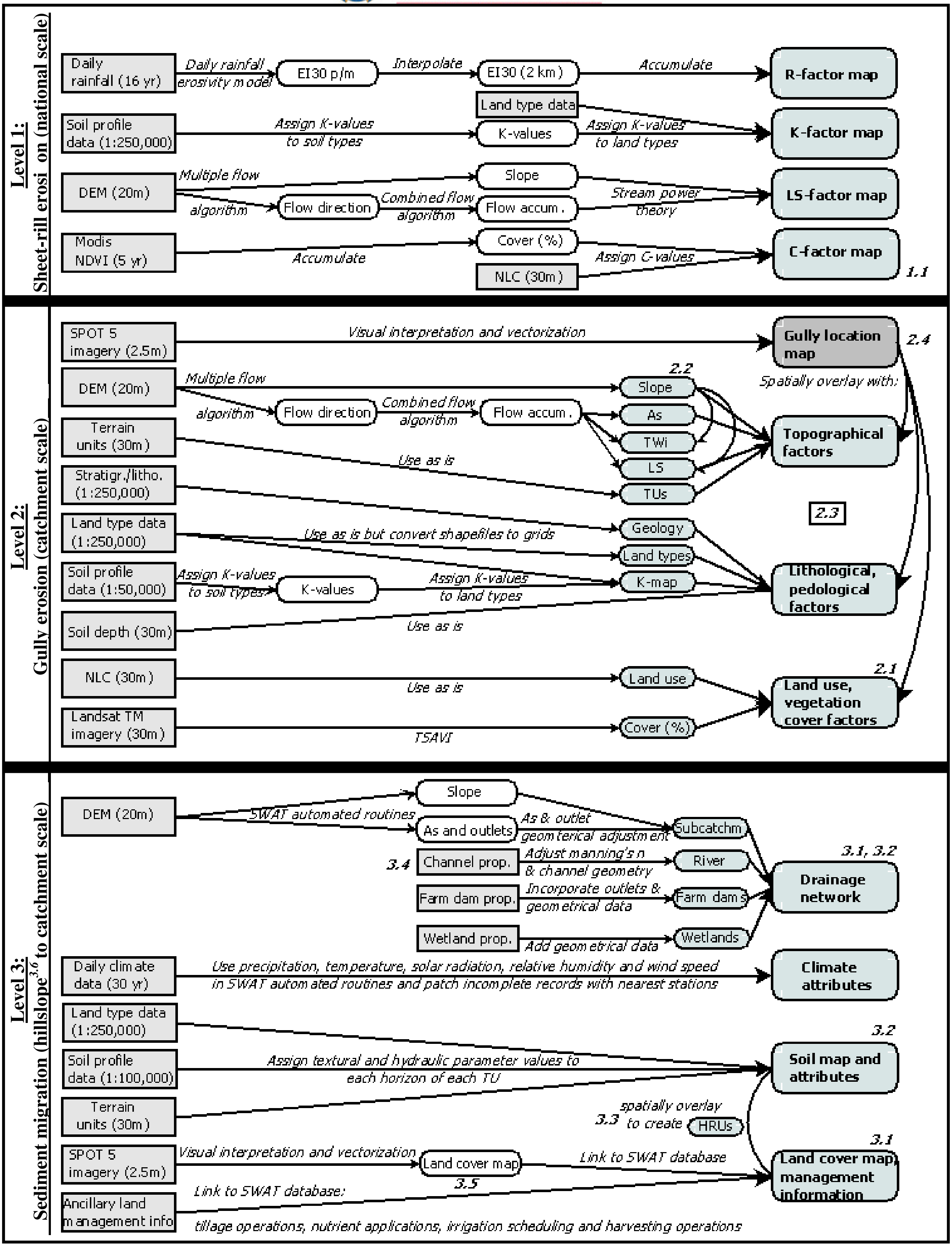

Figure 1: **Methodological framework for soil erosion risk assessment in South Africa (abbreviations and additional footnotes on following page).**

Figure 1 abbreviations:

As - upslope contributing area; C – Vegetation cover factor; DEM – digital elevation model; EI30 – Rainfall erosivity index; Flow accum. – flow accumulation; HRUs – hydrological response units; LS – topography factor or sediment transport capacity index; K – soil erodibility factor; MODIS - Moderate Resolution Imaging Spectroradiometer; NLC – National land cover; prop. – properties; R – rainfall erosivity factor; SPOT 5 - *Syste`me Pour l'Observation de la Terre*; Stratigr./Litho. – stratigraphic/lithologic; SWAT – Soil and Water Assessment Tool; TSAVI - Transformed Soil Adjusted Vegetation Index; TUs – terrain units; TWi - Topographic wetness index; Yr – year.

Figure 1 footnotes:

1.1 Combining the R-K- and LS-factors, and excluding the C-factor, provides the potential water erosion map of SA and represents the inherent susceptibility of the soil to erosion, irrespective of vegetation cover.
2.1 After quantifying the influence of factors in gully development, the identification of vegetated gully-free areas susceptible to gully development can be achieved by means of overlay analysis.
2.2 Each gully factor layer was categorized into 5 expert-based rankings or classes that, according to observations, uniquely influence gully development; due to the spatially thematic configuration of the gully factor layers it was decided to determine the proportion that each of the 5 classes are affected by gully erosion.
2.3 Although gully initiation occurs when certain rainfall and subsequent runoff thresholds are exceeded, this factor was not integrated in this analysis because threshold data were not available and the rainfall itself does not vary substantially in the central gullied part of the catchment.
2.4 Gully erosion rates can be modelled for representative test gullies and the results averaged over the areas of active gully erosion.
3.1 In order to create a final catchment overview of sediment migration downstream and associated connectivity aspects, the current study performed four scenarios: removal and expansion of the identified sediment source (cabbage plot) were performed to establish the extent that sediment outputs create input for downstream sub-catchments; whereas removal of the sediment sinks (9 farm dams and 5 wetlands) were performed to establish their impact on connectivity downstream.
3.2 Calibration should be achieved by adjusting the most sensitive model parameters. For example, the hydrological component can be calibrated by modifying the curve number and base-flow coefficients, whereas the erosion component can be calibrated by adjusting the soil erodibility and support management factors. Model performance can be improved by sequentially optimizing the widely used coefficient of efficiency of Nash and Sutcliffe (1970), as well as the coefficient of determination (r^2). As a measure of goodness-of-fit between simulated and observed loads, a simple per cent deviation method of Martinec and Rango (1989) can be used.
3.3 The overlay of land cover and soil maps creates hydrological response units (HRUs); portions of a sub-catchment that possess unique land use and soil attributes. Discretisation should be done to keep the number of HRUs down to a reasonable number, while considering the diversity and sensitivity of land cover and soil combinations.
3.4 Flow paths should represent all the relevant tributaries of the main river, whereas the unit links or sub-catchment outlets should spatially overlay with the flow monitoring points for calibration of model simulations with field measurements. In addition, channel erosion parameters can only be set to default representing non-erosive channels to eliminate channel erosion in simulations when all or most sediment is generated from agricultural fields.
3.5 The plant growth component of SWAT is a simplified version of the EPIC plant growth model (Sharpley and Williams, 1990), where phenological plant development is based on daily accumulated heat units developed by Monteith (1977) and biomass is inhibited by temperature, water or nutrient stress.
3.6. Although the importance of plot and hillslope scales is acknowledged (see for example Kakembo *et al*., 2012), it is not considered in the methodological framework.

In terms of remote sensing techniques, more sophisticated and/or time-consuming procedures such as pre-processing and specialized software are generally required to separate erosion features such as gullies from bare soil than automated procedures such as vegetation indices and classification techniques to create vegetal attributes. For example, automated techniques such as object-based modelling (i.e. eCognition® software and Erdas Imagine® Objectives Feature Extraction Model) cannot express individual gullies with the required accuracy over large areas due to their spectral complexity (Taruvinga, 2008; Pirie, 2009; Mararakanye and Le Roux, 2011). The imagery itself should have a pixel resolution smaller than the size of the erosion feature (Ludwig *et al*., 2007). Fortunately, with the development in sensor technology, space-borne data with improved spatial, spectral and temporal resolution is now available such as SPOT 5, IKONOS, Quickbird, WorldView and GeoEye (Smith and Pain, 2009). SPOT 5 satellite imagery was utilized in Case Study *ii* because the panchromatic sharpened images at 2.5 m resolution provide high resolution air photo-like quality for gully mapping (Taruvinga, 2008) and were acquired from government agencies for the whole of SA.

In terms of modelling techniques, more complex models are required to simulate sediment migration and associated connectivity aspects at the catchment scale than assessment of the spatial distribution of the erosion risk and contributing factors at a national scale. The main reason is that sediment migration is the integrated result of all erosion processes operating in a catchment (Vanmaercke *et al*., 2011; Parsons, 2012). Semi-distributed or semi-lumped models are often preferred above lumped models and fully-distributed or physically-based models, since the application of the former do not take connectivity aspects into account whereas the latter lead to additional errors and uncertainty resulting from more parameters and input data requirements in large catchments (Lenhart *et al*., 2005; Medeiros *et al*., 2010). The foundational strength of semi-distributed models such as SWAT is that it partitions the catchment of interest into homogeneous morphological units while considering most significant connectivity aspects, including factors controlling upland sediment generation, channel transport and deposition into sinks (Gassman *et al*., 2007). The combination of these models within a GIS framework is commonly utilized for erosion risk assessment (Flügel *et al*., 2003; Gao, 2008). GIS serves, not only as an output display platform, but also as a simulation interface and input data source. In addition to assessment techniques, Figure 1 also indicates regional datasets which are available for different erosion processes and contributing factors.

Similar to assessment techniques, data requirements increase with progression from the first to third level. More data are needed to simulate sediment migration at the catchment scale than erosion risk assessment and contributing factors at a national scale. According to Lenhart *et al*. (2005), this is the main reason sediment migration modelling has been restricted to applications in relatively small catchments for which high-quality data are available. A major limitation in the use of continuous time models such as SWAT in developing countries is the lack of recorded flow and sediment data for calibration and validation (Van Zyl, 2007; Boardman, 2006). Although higher accuracies are usually obtained when using high instead of low quality input data (De Vente *et al*., 2009) in many cases data with high spatial, spectral and temporal resolution do not exist for large areas (Van Rompaey *et al*., 2003). Besides, De Vente *et al*. (2009) found that differences in regional scale patterns are relatively small when using different input datasets. Furthermore, it is not feasible to collect input data required for existing models which exceeded data collection methods and compromises between data requirements and practical considerations are necessary (Collins and Walling, 2004).

Comparison between scales

In order to make the framework illustrated in Figure 1 more descriptive, important differences in technique and data requirements between national and catchment scale as well as the requirements for different processes, are highlighted for them. Here, the term catchment scale refers to both the large catchment and smaller research catchment utilized in Case studies *ii* and *iii* respectively. Figure 1 illustrates that assessment of the soil erosion risk at a national scale requires at least four main types of spatial input datasets including long term daily rainfall, soil data, digital elevation models and vegetation cover. These datasets are interfaced into a GIS and fed into appropriate and available algorithms to create soil erosion factor maps including rainfall erosivity, soil erodibility, topography and cover management factor maps. The product of these factor maps then provides the soil erosion risk map, also referred to as the Water Erosion Prediction Map of SA in Case Study *i* of Section 3.

At a catchment scale, more detailed processes need to be considered including gully erosion process (Van Zyl, 2007). Figure 1 further show that gully erosion mapping requires imagery with high spatial resolution, followed by the use of nine spatial input datasets to assess factor dominance. In order to assess factor dominance, the input datasets are integrated in a GIS to create eleven gully factor maps including topographical variables, parent material-soil associations and land use-cover interactions. Input data and assessment technique requirements for gully assessment at the catchment scale essentially double compared to national scale risk assessment. The main reason is assessment at a national scale does not purposefully target specific erosion processes but ‘merges’ them in a simplified empirical model, also referred to as a semi-quantitative model (De Vente and Poesen, 2005). Although the RUSLE model applied in this study emphasises the sheet-rill aspects of the erosion cycle by design, field observations indicate that most areas modelled as eroded on the risk map are recorded as having combinations of sheet-rill and gully erosion. In contrast, gully erosion risk assessment is explicitly aimed at separating gullies from other erosion processes, thereby accounting for the complexity associated with gully processes and contributing factors. Proper gully erosion risk assessment at a catchment scale generally involves more complex mapping and modelling techniques than soil erosion risk assessment at a national scale. Therefore, accurate gully erosion risk assessment at national scale would require spatial input data that are not currently available, as well as techniques that will not be feasible (too time-consuming). In addition to gully erosion, catchment scale assessment ideally/usually requires estimation of the migration of sediment from source to sinks (Parsons, 2012).

In addition to the input datasets required in levels 1 and 2, modelling the migration of sediment (level 3) at the catchment scale requires more quantitative hydrological data including water balance in the soil profile, hydrological structures and land management operations. Although this study used the SWAT model, these datasets could be utilized in any model that includes both a hydrological module and sediment module such as ACRU. As mentioned above, more complex models are required to simulate sediment migration and associated connectivity aspects at the catchment scale than assessment of the spatial distribution of the erosion risk and contributing factors at a national scale. The main reason is that sediment migration is the integrated result of all erosion processes operating in a catchment (Vanmaercke *et al.*, 2011; Parsons, 2012). Subsequently, assessment of sediment migration in catchments with gullies should not only include techniques and data described in level 3, but also the techniques and data described in level 2 or more.

Since data and technique requirements increase with progression through the first to third level, it is possible to apply the data and techniques of level 1 (national scale) at level 2 and 3 (catchment scale), but not the other way around simply due to the lack of data at a national scale and/or for most non-research catchments. Clearly, soil erosion risk assessment is very much data dependent, especially in developing countries such as SA. The following section briefly describes some important considerations and scale issues of the main factors controlling both sediment generation and migration at a regional scale.

Important considerations and scale issues

Since no study can incorporate the knowledge of all aspects of erosion, Gao (2008) states that 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. Soil erosion risk assessment techniques should be adapted and modified to combine sufficient simplicity for application at a regional scale with proper incorporation of the most important contributing factors (Gobin *et al*., 2003). However, contributing factors can only be assessed at a regional scale if they and their scale issues are understood in a geographical context (Molenaar, 1996). This section describes some important considerations and scale issues of the dominant factors in order to guide and facilitate standardization of future regional assessment efforts in SA. The scale issues referred to here relate to changes in the methods or resolution used for data collection in the three Case Studies of Section 3 and not to those concerning upscaling or downscaling of erosion processes. The main factors contributing to sediment generation and migration at a regional scale include rainfall, parent material-soil associations, topographic-drainage-network variables, and land use-cover interactions.

Rainfall

Sediment generation and transport largely depends on rainfall duration and intensity (Bracken and Croke, 2007). Unfortunately, rainfall intensity data are usually incomplete and/or have short recorded periods at a regional scale particularly in developing countries. The best alternative is to use daily rainfall data in empirical relationships between rainfall intensity data and daily rainfall amount. Care needs to be taken to insure that the rainfall erosivity algorithms used are not solely a function of rainfall amount. Irrespective of the rainfall amount, winter rainfall produced by frontal activity is less erosive compared to thunderstorms associated with convection during summer in SA. Case Study *iii* in Section 3 clearly illustrate a summer dominant erosion pattern in the Mkabela catchment which is mainly caused by intensive summer rainfall events, where the infiltration capacity of the soil is exceeded. Laker (2004) also states that the episodic nature of rainfall in SA can be a strong control on soil loss rates. Extreme events and seasons produce the most erosion and runoff when break-of-season rains following long periods of drought (see also Hamblin, 2001). Vegetation cover is severely denuded during prolonged droughts, leaving the bare soil exposed to torrential rains that often follow (Snyman, 1999).

Selection of an erosivity algorithm should thus consider the climatic variations and conditions of intended use. The period of interest must accommodate natural climatic variations and include a variety of climatic conditions (above-normal rainfall and drought). For example, Case Study *i* in Section 3 used the daily rainfall erosivity algorithm developed by Yu and Rosewell (1996a and 1996b) in Australia for two main reasons (Le Roux *et al*., 2008). First, Australia has a climate that, similar to SA, ranges spatially between winter rainfall areas in the southwest to a summer rainfall with tropical influences over the northern parts. Second, large areas over the interior of both countries are classified as semi-arid while coastal regions in the east receive high rainfall amounts. It is further recommended to assess the impact of rainfall with relation to vegetation cover on soil erosion (see Lu *et al*., 2003). Laker (2004) stresses that some areas in SA with high rainfall are inversely related to soil loss due to good vegetation cover and stable soils from advanced pedogenesis.

Parent material-soil associations

Several authors state the importance of soil as an erosion factor in SA (e.g. Beckedahl, 1998; Rienks *et al*., 2000; Laker, 2004; Le Roux and Sumner, 2012). Although the physical, as well as chemical, soil properties and their interactions that affect soil erodibility are many and varied, most models focus on topsoil properties such as texture and structure. Coarse textured soils with a strong structure (fine granular) render the soil resistant to detachment and have low erodibility values, whereas fine textured soils with low-density aggregates (blocky, platy or massive structure) are carried more easily by overland flow and have high erodibility values. Some properties that influence soil erodibility in SA, however, do not feature in (R)USLE type models. Therefore, in all three Case Studies a modified version of the Soil Loss Estimator of Southern Africa (SLEMSA) model was used as a guide to the assignment of (R)USLE soil erodibility factors to the land types of SA (Land Type Survey Staff, 1972-2006). SLEMSA was chosen because it was developed for use in southern Africa and particularly for the manner in which topsoil and subsoil structure are incorporated (see Appendix A).

Nevertheless, some of the most important hydraulic (available water capacity and saturated hydraulic conductivity) and chemical (organic matter content, free iron oxides, Mg:Ca ratios, sodium exchangeability and clay mineralogy) parameters could not be quantified or modelled in any of the three Case Studies due to the limited range of descriptive soil information available at a regional scale. Soil dispersibility is probably the most important soil property that could not be analyzed by the Case Studies because differences are too large between soil types. For example, relationships between sodium exchangeability and crusting are region specific and threshold values can only be drawn if they are determined separately for different groups of soils with similar clay mineralogy and/or geology (see D'Huyvetter, 1985; Bloem and Laker, 1992; Bühmann *et al*., 1996).

Several authors state the importance of parent material in terms of soil erodibility (e.g. Dardis *et al*., 1988; Watson and Ramokgopa, 1997; Le Roux *et al*., 2008). However, eroded soils do not always, or simply, correlate spatially with weak underlying geology. As mentioned in Case Study *ii*, one would expect to find higher proportions of gullies in transported/unconsolidated alluvium and weak sedimentary mudrock that usually give rise to deep erodible soils (Laker, 2004). The most probable reason for latter discrepancy is that quantification of factor dominance is complicated by the relatively large spatial extent of stratigraphic polygons (aggregated geological types) as described by the Council for Geoscience (2007); not because of the lack of geological variability as indicated in several other studies (Verbist *et al*., 2010). Another reason that gullied soils do not always, or simply, correlate spatially with weak underlying geology is that gully development is enhanced by other factors.

Topographic-drainage-network variables

The three Case Studies in Section 3 indicate that topographic factors and/or drainage networks should be constructed in order to represent the movement of runoff and sediment downslope from hydrologically active areas to stream channels and further downstream. Most studies agree that topographical parameters should be determined from fine resolution digital elevation models (DEMs) (e.g. <30 m) resulting in computed topographic surfaces with less variance and uncertainty than coarse resolution DEMs (>30 m) (see e.g. Mitasova *et al*., 1996; Gertner *et al*., 2002; De Vente *et al*., 2009). The main reason that resolution is important is tied to the spatial variability of topographic factors, influencing processes at a fine spatial scale. Coarse DEMs tend to have a "smoothing" effect on computed topographic surfaces. High altitude areas are lower whereas low altitude areas are higher and short steep slopes tend to disappear, reducing the resultant slope estimate and insinuating a higher connectivity (Zhang *et al*., 2002; Verstraeten, 2006; De Vente *et al*., 2009). The finest resolution DEM used in all three Case Studies available in SA at a national scale is a DEM interpolated from contour data by GISCOE (2001) with a grid cell size of 20 m. However, when using this DEM users should be cautious of artificial pits/sinks, especially in flat areas, because the DEM is not hydrologically corrected such as the improved but still coarse Shuttle Radar Topography Mission (SRTM) DEM at 90 m resolution (Weepener *et al*., 2011).

Automated procedures are required to determine topographical variables for complex terrain at a regional scale. Extraction of stream networks or flow path lines in the Case Studies in Section 3 are therefore conducted by algorithms that accumulate the contributing area upslope of each pixel through a network of cell-to-cell drainage paths (Band and Moore, 1995; Gallant and Wilson, 2000). Combined flow algorithms are recommended since they simulate more realistic flow networks by combining multiple and single flow procedures to represent flow dispersion in upland areas, as well as channel convergence further downslope respectively (Freeman, 1991; Wilson and Gallant, 2000). In addition to the flow algorithms, a variety of models exist that connect sediment sources with the river channel and further downstream (Lenhart *et al*., 2005).

Case Study *iii* used the SWAT model, a semi-distributed or semi-lumped model that partition the catchment of interest into homogeneous morphological units allowing to certain extents the spatial variation to be accounted for (see also Lenhart *et al*., 2005; Gassman *et al*., 2007). Semi-distributed or semi-lumped models are often preferred above fully-distributed or physically-based models, since the application of the latter in large catchments lead to additional errors and uncertainty resulting from more parameters and input data requirements (Medeiros *et al*., 2010). When using semi-distributed models, however, care is needed in selecting unit sizes so that spatially aggregated areas adequately represent the spatial variability in the catchment. Importantly, the flow paths should represent all the relevant tributaries of the main river, whereas the unit links or sub-catchment outlets should spatially overlay with the flow monitoring points for calibration of model simulations with field measurements. According to observations in the field, channels should be subdivided into segments with unique geometric (slope, length and width) and roughness (e.g. Manning's roughness coefficient) properties.

In addition, stream channel processes and hydrological structures need to be characterised, allowing deposition of excess sediment depending on the carrying capacity and/or sediment storages where connectivity is reduced (Chen and Mackay, 2004). Case Study *iii* illustrates that farm dams within the Mkabela catchment are particularly efficient storages where flow speed is reduced and sediment deposited. Several other studies indicate that the effect of sediment sinks become dominant over sediment sources with increasing spatial scale (Kirkby *et al*., 1996; De Vente and Poesen, 2005; De Vente *et al*., 2007; Lesschen *et al*., 2009). It is therefore not surprising that, within the Mkabela catchment, changes in sediment production upstream have no significant changes on the sediment yield at the catchment outlet (see also Walling, 1999; Prosser *et al*., 2001). The reduction in connectivity with increasing spatial scale or catchment area (> ~10 km^2) is a globally recognized trend although this varies regionally (De Vente *et al*., 2007). Sediment yield can increase or decrease at any catchment area due to the spatial variability of the factors influencing soil erosion and sediment yield, such as land use-cover interactions (De Vente *et al*., 2007).

The advantages in applying widely-used approaches in the Case Studies in Section 3 were offset by a few disadvantages. The specifications or input values including slope exponents, flow accumulation/slope-length threshold values and maximum cross grading area used for the calculation of slope-length, were based on values recommended in other sources of literature (Freeman, 1991; Renard *et al*., 1994; Wilson and Gallant, 2000; Schäuble, 2003). However, optimum values depend on local conditions and the use of reference parameter values over large areas may lead to errors. (R)USLE based studies tend to overestimate erosion rates in areas with steep terrain, for example along the escarpment in SA (Le Roux *et al*., 2008), especially since (R)USLE was developed in the US where topographic features are considered to be a dominant factor (Laker, 2004). Collectively, the factors discussed above highlight areas that are intrinsically susceptible to erosion and sediment yield. The last parameter discussed below is important in highlighting areas where erosion is extrinsically triggered or accelerated by land use and human-induced reduction of the vegetation cover.

Land use-cover interactions

It is generally agreed that land use and vegetation cover interactions are dominant above all factors. Vegetation indexes such as the Normalised Difference Vegetation Index (NDVI) are an important source of information for vegetation cover at a regional scale (Gobin *et al*., 2003). However, NDVI data are sometimes inaccurate due to the effect of soil reflectance and the sensitivity to vitality of the vegetation. In Case Study *i*, the fractional vegetation cover estimated for Fynbos in the Western Cape is probably too low, leading to over-estimated soil-erosion values. This problem occurs during vegetation senescence when vegetation indices decrease even when cover remains the same, but senescent vegetation offers the same protection to soil as green vegetation and it is also important to detect relatively dry vegetation (see e.g. French *et al*., 2000; Odindi and Kakembo, 2009). It is therefore recommended to use imagery that depicts conditions for which differentiation is easily obtained between green vegetation and bare soil, as opposed to dry vegetation which is more difficult to detect. It is also recommended to use soil adjusted vegetation indices such as the Transformed Soil Adjusted Vegetation Index (TSAVI). Case Study *ii* used TSAVI because it leads to a significant reduction of the soil effects for areas of sparse vegetation or bare soil and delivers reliable results for arid and semi-arid grassveld landscapes in SA (see also Flügel *et al*., 2003; Hochschild *et al*., 2003). Nevertheless, soil adjusted indices have difficulty in accounting for spatially variable soil types, especially at a regional scale.

Apart from the canopy cover, ground cover is not always represented in remotely sensed data. For example, in Case Study *i* the fractional vegetation cover for savanna in northern

Limpopo and Northern Cape remain questionable due to the dense tree canopy concealing the poor ground cover when monitored by satellite. Field observations indicate that arid area ground cover is frequently less than its projected vegetation crown cover, which is not always protective against erosion. Soil is especially susceptible to erosion when the ground cover is at its lowest and rainfall erosivity at its highest. Although it is recommended to use multi-temporal satellite imagery to account for the interaction between vegetation growth and rainfall (see Lu and Yu, 2002; Lu *et al*., 2003), multi-temporal analysis is beyond the scope of this research.

In terms of spatial scale, results depend on the grid-cell resolution since land use and vegetation parameters are carried out in a grid-based system (Zhang *et al*., 2002). Zhang *et al*. (2002) illustrate how grid-cell resolution affects predicted erosion. Coarse resolution grids reduce predicted erosion due to bare soil areas being incorrectly imbedded in vegetated areas. This explains why more vegetation is illustrated in discontinuous gullies than continuous gullies (Case Study *ii* in Section 3). The Landsat TM image used to calculate the TSAVI and subsequent cover grid have a coarse resolution of 30 m^2 and therefore, small gullies with narrow patches of bare soil are incorrectly imbedded in vegetated areas (see also Taruvinga, 2008). Since discontinuous gullies are frequently less than 30 m^2 in size, the proportion of vegetation cover inside these gullies could be overestimated, while the proportion of bare soil could be underestimated. In addition to spatial resolution, Case Study *iii* indicates that the location and organization of land cover pixels is also important, especially in terms of sediment transport and connectivity between sources and sinks (see also Van Rompaey *et al*., 1999; Van Oost *et al*., 2000; Kakembo *et al*., 2012). However, a major weakness of SWAT is that it does not consider the processes of deposition during transport from hillslopes/HRUs to channel (Lenhart *et al*., 2005). The cabbage plot sediment is not spatially identified within the sub-catchment it is located and all the sediment generated from the cabbage plot reaches the channel, whether connected to the channel or not. Chen and Mackay (2004) suggest the use of smaller sub-catchments instead of HRUs, but this approach is not applicable in relatively large catchments such as simulated in Case Study *iii*. In such catchments, discretisation should be done to keep the number of sub-catchments and HRUs down to a reasonable number, while considering the diversity and sensitivity of land cover and soil combinations. It is imperative that the spatial resolution and organization adequately represent the spatial variability in the catchment and that all the significant land cover and soil combinations affecting sediment yield are integrated.

In addition to spatial resolution, the imagery itself needs to consist of an adequate spectral resolution. When using remotely sensed images for detecting erosion features amongst vegetation and bare soil, it is important to consider which imagery will provide the most appropriate information. For example, the spatial resolution (2.5 m panchromatic band) of SPOT 5 imagery used in Case Study *ii* were adequate to manually vectorize gullies in a large catchment, but automated mapping techniques could not express individual gullies with the required accuracy due to the imagery's limited spectral resolution of only 3 bands. The spectral reflectance between gullies varies significantly and depends on vegetation cover inside gullies, as well as several soil properties such as the soil organic matter and soil moisture contents. In order to account for the spectral variability of South African landscapes at a regional scale, sophisticated and time-consuming strategies such as spectral unmixing are required for endmember selection that are outside the scope of text (see e.g. Haboudane *et al.*, 2002).

Lastly, land use and management information are also important including tillage operations, nutrient applications, irrigation scheduling, harvesting operations and support practices. Of all the erosion factors, however, this factor or set of parameters are the least reliable due to the lack of data on crop rotation systems and timing of agricultural operations at a regional scale (Renard *et al.*, 1994). The most practical way to incorporate this information is to link a land cover map to an existing model structure and database consisting of several plant growth parameters where phenological plant development is based on daily accumulated heat units. In Case Study *iii*, for example, the land cover map was digitized from SPOT 5 imagery acquired in 2006 and linked to the plant growth component of the SWAT model. SWAT utilizes a simplified version of the EPIC plant growth model (Sharpley and Williams, 1990), where phenological plant development is based on daily accumulated heat units developed by Monteith (1977) and biomass is inhibited by temperature, water or nutrient stress. Despite a lack of reliability and associated uncertainties of such data and the subsequent modelled outputs, these parameters are specifically useful to determine the relative impact of different land use and management scenarios, as well as for comparative purposes with possible future scenarios under land use and climate change.

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5. CONCLUSIONS AND RECOMMENDATIONS

With the increase in human impacts on the environment, especially in terms of agricultural intensification and climate change, there is a need to assess and continually monitor the erosion process and contributing factors (Rubio and Bochet, 1998; Symeonakis Drake, 2004; Casalí *et al*., 2009). SOILOSS (Lu *et al*., 2003), BASINS (US EPA) and PESERA (Kirkby *et al*., 2004) are standardized approaches that assess the soil erosion problem according to conditions in Australia, the U.S.A. and Europe respectively. In most other countries, however, especially in developing countries such as South Africa (SA), there is still an absence of standardized methodological frameworks that deliver comparable results across large areas as a baseline for regional scale monitoring. Although a fair number of attempts have been made to assess the soil erosion risk in SA (described in Section 2), there is hitherto no practical methodological framework to provide a consistent baseline for regional scale monitoring under South African conditions.

Since there are limitations to understanding each erosion process and scale at which assessment techniques can be applied (Drake *et al*., 1999), this study implemented a multi-process and -scale approach using different techniques and data in order to assess different soil erosion processes and contributing factors. These include assessment of (*i*) sheet-rill erosion at a national scale, (*ii*) gully erosion in a large catchment and (*iii*) sediment migration for a smaller research catchment. More specifically, the first Case Study presented in Section 3 based sheet-rill erosion prediction on the principles and components defined in the (Revised) Universal Soil Loss Equation (R)USLE (Renard *et al*., 1994). These results are followed by a description of the limitations and challenges that must be overcome in soil-erosion assessment on a national scale. The second Case Study presented in Section 3 assessed gully factor dominance in a large catchment located in the Eastern Cape Province by integrating eleven important factors into a GIS that could be readily derived for the whole area. The study also highlights gully factors likely to emerge as dominant between continuous gullies and discontinuous gullies. The third Case Study utilized the frequently applied Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1998) to assess sediment migration and associated connectivity aspects in a catchment (Mkabela near Wartburg, South Africa) with identified source and sink zones. Insight is also provided into the applicability of SWAT in connectivity studies, explicitly describing how model assumptions affect outputs in context of connectivity between sources and sinks. The following conclusions can be drawn from the study.

Results presented in the Case Studies of Section 3 re-enforce that soil erosion is a major soil degradation problem in South Africa. Case Study *i* illustrates that approximately 50% (61 million ha) of national land has a moderate to severe erosion potential (>12 t/ha·yr), whereas approximately 20% (26 million ha) of land is classified as having a moderate to severe actual erosion risk. The Eastern Cape Province makes the largest (28%) contribution to soil loss with approximately one third (16 million ha, 37%) of the province classified as moderate to extremely high. Case Study *ii* identifies severe gully erosion, affecting an area of approximately 5 273 ha in the large catchment (the Tsitsa valley) of the Eastern Cape Province. Case Study *iii* illustrates that a cabbage plot in the upper reaches of the research catchment near Wartburg is a significant sediment source, but is counterbalanced by sinks including the river channel and farm dams downstream.

The factor-based nature of this multi-process and -scale approach allowed scrutiny of the role of the main factors in contributing to the erosion risk. In terms of sediment generation (sheet-rill and gully in Case Studies *i* and *ii*), it appears that the combination of poor vegetation cover and susceptible parent material-soil associations are the overriding factors in South Africa, and not the topography and rainfall as frequently determined in the USA and Europe (e.g. Vanmaercke *et al*., 2011). Several studies in other parts of the world found similar results that parent material-soil associations and land use-cover interactions control erosion risk at a regional scale. For example, Tamene *et al*. (2006) determined that the major controlling factors in a mountainous dryland region of northern Ethiopia include surface lithology and land cover. Topography, sometimes together with soil type and rainfall, seems to play a more important role at a local scale (Lane *et al*., 1997; Verstraeten, 2006; Bracken and Croke, 2007) but their assessment and influence should not be ignored due to high levels of accuracy required for policy and management purposes. In terms of sediment migration, Case Study *iii* compares well with the global trend that sediment sinks becomes dominant over sediment sources with increasing spatial scale (see Kirkby *et al*., 1996; De Vente and Poesen, 2005; De Vente *et al*., 2007; Lesschen *et al*., 2009). Hydrological structures such as farm dams can be particularly efficient storages where connectivity is reduced and sediment deposited (Mishra *et al*., 2007). Nevertheless, it is recognised that the reduction in connectivity with increasing spatial scale or catchment area varies regionally (De Vente *et al*., 2007). According to De Vente and Poesen (2005), not all processes and contributing factors are equally important in different regions. Hence, 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).

Section 4 presents the methodological framework illustrating the most feasible erosion assessment techniques and input datasets for which sufficient spatial information exists, and emphasizes simplicity required for application at a regional scale with proper incorporation of the most important factors. In order to provide a comprehensive overview of erosion risk, the framework illustrates that a multi-process and -scale approach with three hierarchical levels needs to be implemented (see simplified version of the framework in Figure 1). The first level allows for the assessment of the spatial distribution of erosion risk and contributing factors at a national scale, emphasizing the sheet-rill aspects of the erosion process. This level should be followed by a second level that allows assessment of the spatial distribution of gully erosion and contributing factors at a large catchment scale. These levels provide no information about where material moves to or about connectivity between source and sink. A third level allows for assessment of sediment migration and associated connectivity aspects at a smaller/research catchment scale, including the influence of identified source and sink zones. As mentioned above, Kirkby *et al.* (1996) and Drake *et al.* (1999) also applied/suggested a hierarchical approach with three levels, but using different techniques in different areas at finer or coarser scales than applied in this study.

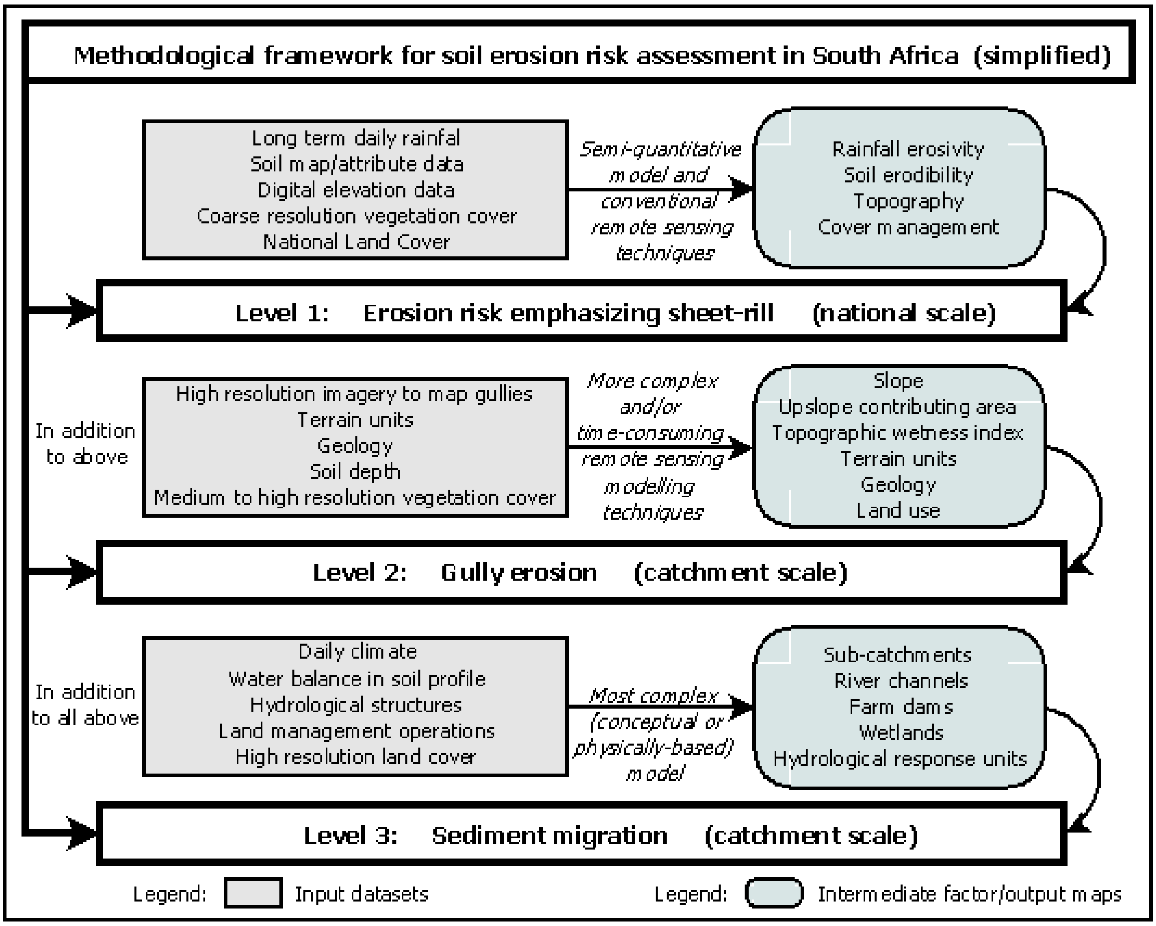

Figure 1: Methodological framework for soil erosion risk assessment in South Africa (simplified).

Assessment techniques and data requirements increase with progression through the first to third level. In terms of remote sensing techniques, more sophisticated and/or time-consuming procedures such as pre-processing and specialized software are required to separate erosion features such as gullies from bare soil than automated procedures such as vegetation indices and classification techniques to create vegetal attributes. In terms of modelling techniques, more complex models are required to simulate sediment migration and associated connectivity aspects at the catchment scale than assessment of the spatial distribution of the erosion risk and contributing factors at a national scale. Similar to the assessment techniques, data requirements increase with progression through the first to third level; more data are generally needed to simulate sediment migration at the catchment scale than erosion risk assessment and contributing factors at a national scale. Since data and technique requirements increase with progression through the first to third level, it is possible to apply the data and techniques of level 1 (national scale) at level 2 and 3 (catchment scale), but not the other way around simply due to the lack of data at a national scale. Clearly, soil erosion risk assessment is very much data dependent, especially in developing countries such as South Africa.

Further refinement of soil erosion risk assessment will be possible given additional research, including the following. It is recommended to consider all sediment yielding processes and assess the sediment supply from each. In addition to water erosion, Symeonakis and Drake (2004) state that the effects of wind need to be considered, especially in windy plains with fine sandy soils such as in some areas in the Kalahari and Karoo. According to Van Zyl (2007), the ability to account for sediment supply from gullies will be an important feature in catchments with gullies as the predominant source of sediment. Gully erosion rates can be modelled for representative test gullies and the results averaged over the areas of active gully erosion (Flügel *et al.*, 2003). Furthermore, the effect of socio-economic drivers of erosion risk needs to be investigated. Boardman (2006) states that farmers are too often not considered in studies but the way farmers perceive their role influences their attitude to erosion and conservation.

Multi-temporal analysis should be used to investigate the effect of land use history and vegetation conditions (e.g. Kakembo *et al.*, 2009; Kakembo *et al.*, 2012) and can also be used to account for the interaction between vegetation growth and rainfall (Lu and Yu, 2002; Lu *et al.*, 2003). Another example where multi-temporal analysis is required is to distinguish between active and passive erosion features. Active gully erosion features are of major importance, because large active gullies usually deliver the main quantity of sediments in a catchment, whereas, stable gullies have little or no sediment delivery. Parsons (2012) stresses that adequate consideration should be given to the time taken for sediment to travel via the various pathways to the catchment outlet, specifically the rates of sediment movement of different sizes and from different sources.

It is also recommended to quantify the individual factor dominance of the main factors contributing to each erosion process. Although the factor-based nature of this multi-process and -scale approach allowed scrutiny of the role of the main factors in contributing to the erosion risk, this study did not quantify factor dominance contributing to each erosion process. Factor dominance was only quantified in Case Study *ii* for gully erosion in a large catchment by integrating the factors into a GIS. According to Wu and Wang (2007), contributing factors may differ between different regions and their individual degrees of risk and corresponding comparative weights may call for re-evaluation.

It is further recommended to increase efforts of continuous long-term monitoring of discharge and sediment load in South Africa, including reservoir sedimentation and trap efficiencies. There is a need for datasets comprising spatially distributed data of recorded flow and sedimentation, especially for calibration and validation (see also Van Zyl, 2007; Boardman, 2006). Calibration and verification of results should preferably consider the spatial distribution and absolute values if possible including flow characteristics, sediment generation at source areas, as well as sediment transport and deposition exhibited in sinks. Sediment fingerprinting best represents the direct approach to sediment sourcing and offer considerable potential for meeting this requirement (Collins and Walling, 2004). However, tradeoffs are necessary between the extra effort and increase in accuracy of results (De Vente and Poesen, 2005).

Despite the lack of reliability and associated uncertainties of data and subsequent modelled outputs, the methodological framework presented here provides descriptions of the contributing factors for standardized definition of the soil erosion risk in South Africa. In conclusion, the framework outlines the techniques that should be used and the data that are available to identify areas at risk. The framework should not be interpreted as a single assessment technique but rather as an approach that guides the selection of appropriate techniques and datasets according to the complexity of the erosion processes and scale dependency. A set of guidelines (important considerations and scale issues) are provided in order to allow evaluation of at least the dominant factors that contribute to different processes. In addition, in future it will be useful to determine the relative impact of different land use and management scenarios, as well as for comparative purposes with possible scenarios under climate change. It is often argued that climate change will increase future erosion rates, especially where increased rainfall intensity and/or extreme event frequency are predicted (Boardman, 2006). However, Boardman (2006) stresses that certain land use changes causing a reduction in the vegetation cover are likely to have greater impact on the erosion risk than any likely climate change. Therefore, the vegetated erosion-free areas susceptible to erosion that were identified in this study are important in policy terms. Results indicate those areas which are inherently susceptible to erosion, but which are presently protected by vegetation. Appropriate strategies need to be designed for these susceptible areas in order to protect the current vegetation cover.

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