A knowledge gap analysis on multi-scale predictive ability for agriculturally derived sediments under South African conditions

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Abstract Agriculture has been implicated as a major source of sediments in South Africa. The aim of the knowledge gap analysis was to understand the production and delivery components of agriculturally derived sediments under South African conditions and to assess the predictive ability to address the fate of these sediments from field to catchment scales. An overview is given of important erosion processes and erosion modelling applied in South Africa at the field and catchment scale. A limitation of the sediment models is that gully erosion is not simulated; therefore, the models should be complemented with gully erosion predictions if gullies are an important sediment source. Field-scale models inadequately predict sediment production localised at hydrologically sensitive areas as a result of saturation excess flow and/or throughflow. The discussion on erosion modelling reveals that more complex models have had limited application in South Africa because they require large and detailed data sets, and may have parameters that are difficult to measure or to estimate. A modelling framework is discussed which allows linking of sediment models requiring readily available data, gully erosion models/maps and the use of other techniques to assess the fate of agriculturally derived sediments from field to catchment scale.

Keywords Agriculture; modelling; scale; sediment; South Africa

Introduction
Non-point source pollution plays a major role in the degradation of water quality and it is increasingly accepted that it is infeasible to properly manage water quality without addressing the contribution from non-point sources (Rossouw and Görgens, 2005). After hydrology, understanding sediment production and delivery from agricultural land is essential for non-point source assessment (Pegram and Görgens, 2001). Most of the land area in South Africa is utilised for agricultural activities, which have been implicated as a major source of sediments. It is thus necessary to assess the contribution that different agricultural activities make towards sediments, to devise the means through which sediments can be controlled, and to assess the effect that control measures at the source will have in reducing sediments (Rossouw and Görgens, 2005). The aim of the knowledge gap analysis was to understand the production and delivery components of agriculturally derived sediments and to assess the predictive ability to address the fate of these sediments from field to catchment scale under South African conditions.

Scale and erosion processes
Soil erosion occurs at a range of spatial and temporal scales. Specific erosion processes exhibit one or more preferred scales (Kirkby et al., 1996).

Field scale
Erosion processes at the field scale relate to the detachment of soil particles at interrill and rill areas and gullies, and the delivery of the detached soil particles from interrill and...
rill areas and gullies to ephemeral streams. Processes determining the spatial extent of sediment production and major sediment delivery pathways at the field scale are also important (Van Zyl, 2005).

**Interrill and rill erosion.** Interrill (sheet) erosion encompasses the detachment and transport of soil particles by raindrop impact (rainsplash erosion) and transport by shallow overland flow. Rills are initiated at a critical distance downslope where the critical shear velocity of runoff in concentrated flow paths exceeds the shear strength of the soil (Morgan, 1995). Interrill and rill erosion is most significant on grazing lands in South Africa, occurring in a wide band from the southwest to the northeast, and on cropland in the northern and eastern parts of the country (Garland et al., 1999).

**Gully erosion.** Gullies develop in hillslope hollows and on footslopes by a complex of processes which may include: scour by concentrated runoff, undercutting and slumping of the gully head, gully expansion through sapping, undermining and collapse of the headwall and side walls, and gully stabilisation (Bocco, 1991). Active gullies are likely to be the major sediment sources and the main sediment pathways in headwater catchments (Wasson, 1998). According to the literature study conducted by Garland et al. (1999), gully formation processes in South Africa are largely confined to headward erosion and width expansion, and tend to form on the footslopes with gradients less than $10^8$, typically on unconsolidated colluvial or alluvial materials, shales and dispersive clays. Soil and lithological characteristics exercise much control on the occurrence of gullies, and many gullies are located on erodible soil on Beaufort mudstones and Dwyka Tillite. Many surface gully systems are the result of subsurface erosion with subsequent collapse of the ground surface (Beckedahl, 1998).

**Spatial distribution of sediment production and delivery.** The spatial distribution of hydrological response units and the connectivity thereof along a hillslope determines the occurrence and extension of rills and gullies, as well as the dominant sediment delivery pathways to the stream network. The identification of hydrologically active areas limits the scope of controlling sediment production and delivery to only those areas (Walter et al., 2000). Studies at the Weatherly catchment in northern Eastern Cape province and the Zululand catchment in northern KwaZulu-Natal province in South Africa reveal that runoff generation can be associated mainly with saturation excess and exfiltration of throughflow (Kelbe et al., 1992; Lorentz et al., 2003).

**Catchment scale**

The erosion processes at the small catchment ($< 10 \text{ km}^2$) scale are sediment production and delivery from stream channel erosion in addition to those at the field scale. The transport (routing) of sediment through the river system is an important process in larger catchments. Flood plain scour may occur in large catchments with alluvial deposits downstream (Wasson, 1998; Van Zyl, 2005).

**Stream channel erosion.** Stream bank and bed scour induced by stream flow most often closely resembles rill erosion, which is often followed by bank collapse due to side-slope instability. The transport processes in streams interact strongly with the runoff and sediment load from hillslopes. Streams can be major sediment sinks during periods of excessive erosion at the hillslopes, whereas previously stored sediment may erode after the supply of sediment from the hillslopes is reduced (Lenzi et al., 1999).
Sediment delivery and transport. The delivery of sediment to rivers and instream sediment transport are important processes at the large catchment scale (Wasson, 1998). The sediment source is not always known in a large catchment due to the complex nature of sediment delivery to the rivers and sediment transport through the river system. A reduction in sediment yield may take decades after reduction in agriculturally derived sediment due to the remobilisation of sediment deposited in the river from previously high sediment inputs (Walling, 1994). According to Rooseboom (1992), sediment availability rather than transporting capacity proves to be the limiting factor in determining sediment yields in most southern African rivers.

Simulation of processes
Van Zyl (2005) theoretically evaluated 15 models for simulating important sediment production and delivery processes under South African conditions and identified the following limitations.

Almost all the field and small catchment scale models apply a simple routine to estimate shallow subsurface redistribution of water and may not be able to effectively simulate saturation excess overland flow and/or throughflow. Consequently, the models may not have the capability to identify the hydrologically active areas, and thus the spatial extent of major sediment production and delivery areas and areas susceptible to gully initiation and development. According to Van Zyl and Lorentz (2003), partial area overland flow conditions due to a rising water table at footslopes and valley bottoms and/or throughflow are to be expected in several regions in South Africa where the terrain is steep and the hydraulic transition between soil horizons is abrupt.

All the models simulate interrill and rill erosion, and some process models simulate ephemeral stream channel erosion. However, gully erosion as a model routine is rarely incorporated to include headcut and sidewall mass failure processes from which most of the sediment may be supplied from a gully. None of the models has the capability to predict the location of gullies or the amount of sediment produced and delivered from gully initiation and growth. These are severe limitations if the models are to be applied in catchments where gullies are the dominant source of sediment.

Scale and erosion modelling
Catchment scale
The aim of erosion modelling at the catchment scale is to identify and prioritise the sediment source areas, activities and processes of concern that require control.

Sediment yield maps. Rooseboom et al. (1992) produced a revised sediment yield map of southern Africa, which was based on records of sediment loads of reservoirs and rivers. The ability to differentiate between production, delivery and transport, as well as different non-point source areas is limited, and the map lacks the capacity to predict the effect of land management change.

Hillslope erosion potential. Erosion potential is estimated with a geographic information system (GIS) approach using soil loss models and satellite imagery to predict the quantity of eroded soil at the interrill and rill areas available for delivery. The universal soil loss equation (USLE, Wischmeier and Smith, 1978) was applied to predict soil loss in the Mgeni River catchment (Kienzle et al., 1997) and the Olifants River catchment (Moolman et al., 1999). Soil loss predictions underestimate the quantity of sediment produced in gullied catchments (Wasson, 1998).
Hillslope erosion hazard. Prediction of erosion hazard extends erosion potential predictions by incorporating the estimation of the delivery of the eroded soil from interrill and rill areas. Sediment yield can be estimated from empirically derived delivery factors (loading functions) or can be simulated by a model.

Loading functions estimate sediment yield by multiplying the predicted erosion potential with a sediment delivery ratio (SDR) to account for the deposition of the eroded soil during its movement from the source areas (Pegram and Görgens, 2001). The SDR concept was applied in combination with the USLE for the Amatole System (Pegram, 1999), the soil loss estimation model for Southern Africa (SLEMSA; Elwell, 1978) for the Mgeni and Sabie River catchments (Donald, 1997), and the revised USLE (RUSLE; Renard et al., 1993) for the Henley catchment (Hagos, 2004) to estimate the sediment yield. According to Walling (1994), considerable uncertainty surrounds the methods for calculating sediment delivery ratios, and the failure to produce a generally applicable prediction equation for SDR is due to the complexity of sediment delivery processes and their interaction with catchment characteristics.

Simple process models use simplified deterministic representations of the processes governing nonpoint source production and delivery. These models consist of a hydrological module, an empirical sediment module, and a contaminant module that uses loading functions (Pegram and Görgens, 2001). Detailed process models describe the physical processes governing non-point source production and delivery. Process models incorporate a detailed contaminant process with relatively complex hydrological and sediment modules. Unfortunately, these models tend to be very data intensive and as such are limited to areas for which there has been intensive data collection. Although a number of operational models have been developed over the past three decades, only a few have been applied in South Africa and thus have some local expertise (Pegram and Görgens, 2001). The locally developed Agricultural Catchments Research Unit (ACRU; Schulze, 1995) which draws on the modified USLE (MUSLE; Williams and Berndt, 1977) approach was applied for the Mgeni River catchment (Kienzle et al., 1997), and the De Hoek and Henley catchments (Howe, 1998). The Negev model (Negev, 1967) has been applied in a limited number of case studies as part of the Hydrological Simulation Program Fortran (HSPF; Bricknell et al., 1993) model in South Africa (Pegram and Görgens, 2001).

Gully erosion hazard. Hillslope erosion hazard predictions should be complemented with a gully erosion hazard prediction for catchments with active gullies, since sediment models simulate only interrill and rill erosion. Gully density maps are produced by plotting the gullies from aerial photomaps and then generalising the information to produce a map of gully density (Morgan, 1995).

Field scale
The aim of erosion modelling at the field scale is to evaluate alternative management interventions in order to select the most suitable agricultural practices and/or erosion control measures for the prioritised sediment source area or activity.

Hillslope erosion. The detailed process models applied at the field scale have the capability to estimate the spatial and temporal distributions of the sediment production and depositional areas from hillslopes, farming fields and field-sized catchments. Various agricultural practices and erosion control measures for an agricultural system can be simulated in great detail. The disadvantages of field-scale models is that they require increased computer use and computation time, are data intensive and contain parameters that are difficult to measure or to estimate, and as such are limited to areas for which
there has been intensive data collection. Therefore, these models have had limited application in South Africa (Lane et al., 1992; Morgan, 1995). Platford (1985) applied the Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS; Knisel, 1980) model to predict soil losses from sugarcane lands. The Water Erosion Prediction Project (WEPP; Nearing et al., 1989) and a research version of ACRU were applied for the Zululand catchment with informal rural subsistence farming and for the Weatherly catchment under grassland with a wetland (Van Zyl and Lorentz, 2003). ACRU was also applied for small catchments at La Mercy under sugarcane production (Schmidt et al., 1998).

Gully erosion. The location where gully heads of ephemeral gullies might be initiated in the landscape can be estimated from the threshold concept. The critical flow necessary to exceed the erodibility threshold of the soil is determined from digital elevation models and a model calculating the average shear stress by predicting the drainage area needed for each point in a catchment to exceed the threshold. However, the threshold concept cannot predict the location of gullies which develop from processes other than the hydraulics of overland flow (Bocco, 1991). A recent approach was developed by Sidorchuk to model the two stages of gully development: an initial stage of rapid gully growth and changes in gully morphology, and the final morphometric characteristics during the second phase of gully stabilisation (Sidorchuk, 1999). This model was applied within the Mkomazi River catchment in the KwaZulu-Natal province of South Africa (Flügel et al., 2003).

Integrated catchment and field scale
The integration of the field and catchment scales for erosion modelling allows one to assess the effect which the selected agricultural practices and/or erosion control measures at the sediment sources will have in reducing sediment in a catchment. There are a number of scaling problems in the context of erosion model integration which relate to the dominant processes and factors at the various scales and model conceptualisations (Kirkby et al., 1996).

Comprehensive model. The HSPF model (Bricknell et al., 1993) is a comprehensive package that can simulate the catchment hydrological, sediment, and nutrient and pesticide-related processes from pervious and/or impervious surfaces, and in-stream hydraulic and sediment–chemical interactions for urban and/or rural catchments. The result of this simulation is a time history of water quantity and quality at any point in a catchment. Two approaches can be used in predicting sediments: the Negev sediment generation model, which is a simple process model, or the detailed process Agricultural Runoff Management Model. The drawback of HSPF is its data-intensive nature, both for input as well as for calibration, and an experienced analyst with an understanding of the model and the catchment is needed. Many of the parameters are not physically based, and thus the model needs to be calibrated with local data, which limits its use in data-poor situations. HSPF has been applied in South Africa (Pegram and Görgens, 2001), but does not draw from the USLE approach for which parameters are available for South African conditions.

Modelling framework. An alternative approach to a comprehensive model is a modelling framework which allows models to be linked formally or where the outputs from submodels can be used without the models necessarily being formally connected. It will also be possible to identify qualitative associations between processes and landscape...
characteristics before more intensive predictions are made. The framework can serve as an example of linking sediment models with gully erosion with the use of aerial photographs (Hatton et al., 1998). Van Zyl (2005) recommended that such a modelling framework should have a simple core process catchment-scale model which is linked with an instream sediment routing model. A field-scale model that considers more detailed processes in order to identify hydrologically active areas for sediment production and delivery and potential gully initiation can be nested within the catchment-scale model through a catchment routing framework. The ability of the modelling framework to accommodate sediment supply from gullies, as predicted by gully erosion models/mapping, in addition to that supplied from the catchment or field-scale model, will be an important feature in catchments with gullies as the predominant sources of sediment.

The concept of this modelling framework was applied in the Namoi basin in Australia (Jakeman et al., 1999), and by Flügel et al. (2003) within the Mkomazi River catchment in South Africa. Erosion response units (ERUs) that are characterised by specific erosion dynamics and characteristics were delineated in the Mkomazi River catchment from a classification of erosion features and type of erosion by analysing aerial photographs, orthophotos and information collected during a field mapping campaign. The delineated ERUs were used to identify areas affected by gully erosion and further as modelling entities for simulating sediment production and delivery. The amount of sediment produced from gullies was calculated for a representative gully by a model developed by Sidorchuk (1999). The results were regionalised to the subcatchment in which the gully occurred, and were combined with the predicted amount of sediment produced from interrill and rill erosion. The amounts of sediments predicted for interrill and rill erosion and gully erosion for the individual ERUs have been transported down the river system. These examples show that it is possible to estimate the amount of sediments from gully erosion in addition to interrill and rill erosion, which is not considered with sediment models.

Conclusions
The purpose and requirements of erosion modelling are determined by the objective of the study, the dominant erosion processes, and the availability of data and expertise required for the prediction. The modelling and information requirements will increase with progression through the levels of assessment from the identification of problem areas and problematic land uses, prioritisation of sources and management strategies, and the selection of best management practices. The need for models with more advanced routines/submodels to predict partial area overland flow conditions as a result of saturation excess and interflow; and the occurrence of active gullies in a catchment, will also increase the modelling and information requirements. A minimum information requirement approach should be followed where the simplest model is applied that satisfies the study objectives whilst ensuring that the dominant erosion processes and factors are accounted for. A modelling framework is recommended which allows linking of sediment models requiring readily available data, gully erosion models/mapping and the use of other techniques to assess the fate of agriculturally derived sediments from field to catchment scales.

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