EFFECTS OF SOIL CARBON AND AMBIENT CARBON DIOXIDE CONCENTRATIONS ON HYDROLOGICAL PROCESSES – A MODELLING STUDY

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DISCLAIMER

As the candidate's Supervisor(s), I (we) agree/do not agree to the submission of this thesis.

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M. Scholes

COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE DECLARATION 1: PLAGIARISM

I, Stefanie Schütte………, declare that

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COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE DECLARATION 2: PUBLICATIONS

The details of contribution to publications is outlines below:

1. Publication: Peer-reviewed journal article *(published*).
Schulze RE and Schütte, S. '*Mapping soil organic carbon at a terrain unit resolution across South Africa'*.

This publication is based on:

- Chapter 2: Developing soil carbon maps for South Africa at terrain unit scale; as well as on
- 2. Publication (see below).

The overview of literature, and most technical work and the writing of the paper was done by Schütte, S (corresponding author). Schulze, RE provided technical and editorial support.

2. Publication: Report to the South African Department of Environmental Affairs *(published)*.
Schütte, S, Schulze, RE, and Paterson, G. 2019. *'Identification and Mapping of Soils Rich in Organic Carbon in South Africa as a Climate Change Mitigation Option'*. Report, 107 pages. Pretoria, South Africa. https://www.environment.gov.za/sites/default/files/reports/identificationandmapping_soilsrich_organiccarboninsouthafrica.pdf

The overview of literature, the technical work, except the matching of the taxonomic to the binomial soil classification system, and part of the report writing was done by Schütte, S. The technical work regarding matching of the taxonomic to the binomial soil classification system, as well as technical support and the writing of part of the report was done by Schulze, R.E. Paterson, G. provided technical and review support. The report was undertaken for the Department of Environment Affairs, Pretoria, South Africa with funding through the Deutsche Gesellschaft für Internationale

Zusammenarbeit (GIZ) Climate Support Programme [GIZ Contract No: 83258289], which is part of the International Climate Initiative (IKI). From the onset it was agreed that S. Schütte would use part of the work for her PhD.

3. Publication: Peer-reviewed journal article *(submitted).*
Schütte, S, Schulze, RE and Scholes, M. '*Impacts of soil carbon on hydrological processes – A literature review, with an emphasis on South Africa'.*

This publication is based on Chapter 3: Impacts of soil carbon on hydrological responses – A literature review.

The overview of literature was compiled by Schütte, S. Technical support and review was provided by Schulze, R.E. and Scholes, M.

4. Publication: Peer-reviewed journal article *(under review).*
Schütte, S, Schulze, RE and Scholes, M. '*Impacts of soil carbon on hydrological processes – A sensitivity study across diverse climatic zones in South Africa'.*

This publication is based on Chapter 4: A sensitivity study of impacts of soil carbon on hydrological responses.

The technical work and the writing of the paper was done by Schütte, S. Technical support and review was provided by Schulze, R.E. and Scholes, M.

5. Publication: Peer-reviewed journal article (*under review*).
Schütte, S, Schulze, RE and Scholes, M. *'The value of including changes in transpiration, due to elevated atmospheric* CO_2 *levels, in the ACRU hydrological model for South Africa'.*

This publication is based on Chapter 5: Impact of reduced transpiration due to elevated atmospheric CO_2 concentrations on hydrological responses.

The overview of literature, the technical work and the writing of the paper was done by Schütte, S. Technical support and review was provided by Schulze, R.E. and Scholes, M.

S.Schütte

Signed: Stefanie Schütte

DEDICATION

All glory be to God, who guided my life, up to this point and beyond. Without God nothing of this would have been possible.

I want to dedicate this work to my family. To my husband Carl and our children Aidan and Philip. To my Mom, Erika Agyemang, who saw me start this journey, but not complete it. To my Father, Kurt Dietenmaier, who would have been so proud of his daughter. To my Father-in-Law, Rolf Schütte, who supported me through most of this journey, before passing recently as well. I know you all see this from above. And to the whole rest of my family in South Africa, Germany, the US and Denmark.

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Thank you to my co-supervisor Prof Mary Scholes. You are such a role model as a strong woman in Science. Ours was mainly a long distance relationship. You were always supportive, efficient and fast. The few times that we met personally I was in awe of your ability to analyse and extract the important issues, to the point.

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To Prof Simon Langan and colleagues at the International Institute for Applied Systems Analysis (IIASA), Austria and to the colleagues at the Potsdam Institute of Climate Impact Research (PIC), Berlin, Germany, for fruitful discussions during my visit in September 2017.

ABSTRACT

Impacts of changes of carbon concentrations on hydrological responses were reviewed, in order to facilitate the integration facets of the carbon cycle with those of the hydrological cycle at local scales to enable better assessments of impacts of carbon concentration changes on hydrological responses in South Africa (SA). Carbon related impacts on the hydrological cycle were found and two effects, namely the impacts of soil organic carbon (SOC), as well as the impacts of elevated ambient carbon dioxide levels (eCO_2) are discussed in detail.

SOC in SA first had to be mapped at finer spatial detail than available previously. Several existing datasets were used, enhanced and combined to produce detailed soil carbon maps for South Africa at a resolution of terrain units.

Impacts of SOC content on the soil's water retention constants, and hence on plant available water, were explored. Suitable identified pedo-transfer equations were used to calculate impacts of changes in SOC content on soil water content at saturation, drained upper limit and at permanent wilting point. These altered soil-related parameters were used as inputs into scenarios simulated with the process-based agro-hydrological ACRU model. The study locations were Quinary catchments in different climatic zones within South Africa. Increased SOC content in the topsoil horizon resulted in increased transpiration, reduced runoff, especially in its stormflow component, and to a reduction of extreme runoff events. The magnitudes of these changes depended on other climate-, soil- or location-specific factors. Depending on the study locations, when changing SOC from 1% to 4%, for example, changes in hydrological responses ranged from no significant change to a 14 mm increase in mean annual transpiration, and a runoff reduction of up to 24 mm in a 1:10 wet year.

Impacts of elevated ambient carbon dioxide levels (eCO_2) on photosynthesis and stomatal conductance, and therefore on transpiration rates, were identified. A direct quantification for SA was considered premature. However, the sensitivities of hydrological response to eCO_2-induced reductions in maximum transpiration through the soil-plant-atmosphere continuum were simulated, using an additional functionality added to the ACRU model. An assumed 30% reduction in maximum transpiration, for example, resulted in a reduction in mean annual actual transpiration of 14% across the Quinary catchments covering SA and an increase of accumulated runoff of 18%, while a 20% reduction in maximum transpiration increased runoff by 11%. Effects of elevated CO_2 concentrations on hydrological responses should thus not be ignored in hydrological climate change studies, as is currently the case.

Given the above, it is believed that through this research, the impacts of changes in the carbon cycle on the hydrological cycle are now better understood than before, especially in the case of hydrological responses within South Africa.

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1. INTRODUCTION

1.1 Introduction

In a changing world it is important to understand the impacts of changes of one natural cycle on other natural cycles. The two natural cycles of interest here are the carbon and hydrological cycles. The carbon cycle has been heavily influenced by humans. One change is in soil organic carbon (SOC) content, with agricultural practices often depleting soil carbon stocks (du Preez et al., 2011a; 2011b; Swanepoel et al., 2015). Soil carbon stocks have the potential of increasing with suitable management, thus also providing a climate change mitigation measure (Minasny et al., 2017). Another change in the carbon cycle has been the anthropogenically driven increase of atmospheric carbon dioxide, leading to elevated carbon dioxide levels (eCO_2) compared to pre-industrial levels (Lacis et al., 2010; Quéré et al., 2018). There are links between the carbon cycle and the hydrological cycle (Falkowski et al., 2000; Lal, 2004a; Mu and Zhao, 2011; Wu et al., 2012; Lin et al., 2015; Wehr et al., 2017), with both, changes in- the SOC content and eCO_2 affecting hydrological responses. The impacts of changes in the carbon cycle on the hydrological cycle are shown in a simplified form in Figure 1-1.

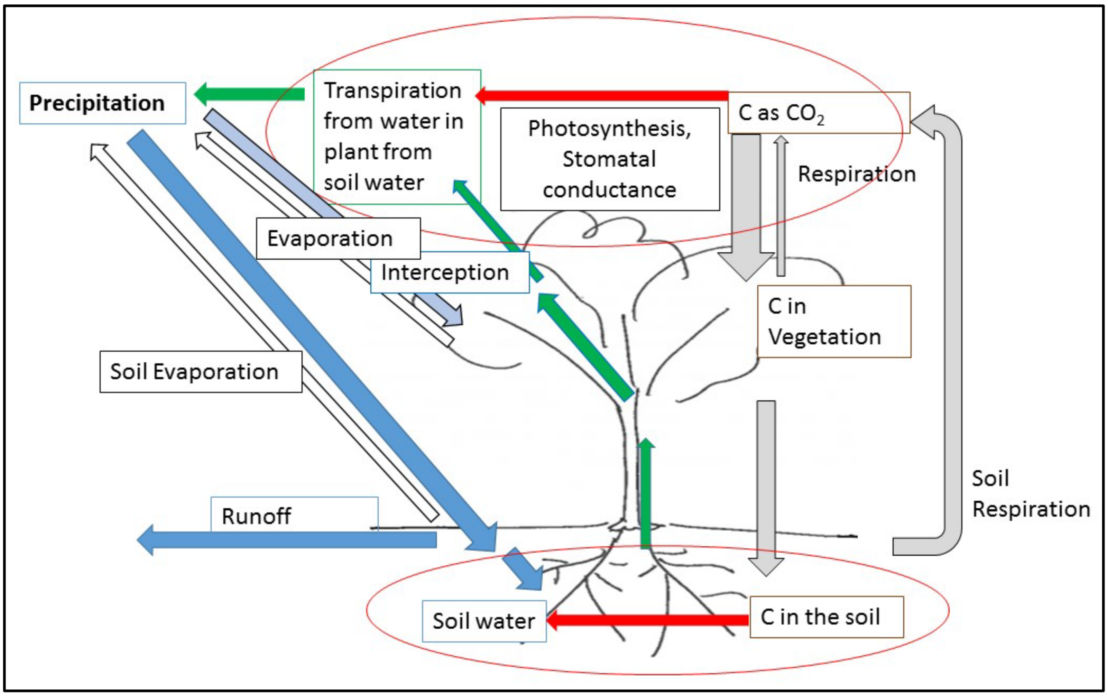

Figure 1-1 Linking the simplified carbon cycle to the simplified hydrological cycle with the links between soil carbon and soil water, as well as between carbon (C) as carbon dioxide (CO_2) and transpiration highlighted in red

Changes in SOC impact soil water properties (Kay et al., 1997; Rawls et al., 2003; Lal, 2004a; 2004b; Olness and Archer, 2005; Saxton and Rawls, 2006; Resurreccion et al., 2011; da Costa et al., 2017; Ankenbauer and Loheide, 2017), and thus runoff, and its components of stormflow and baseflow. Using suitable pedo-transfer functions, these changes in soil water properties can be quantified (Rawls et al., 2003; 2004). These altered soil water properties can then be used for modelling hydrological responses with, for example, the process-based, daily time-step agro-hydrological ACRU model (Schulze et al., 1995 and updates).

eCO_2 impacts photosynthesis and leaf and canopy conductance (e.g. Drake et al., 1997; Cox et al., 2000; Baldocchi et al., 2001; Naumburg et al., 2003; Long et al., 2004; Ainsworth and Long, 2005; Ainsworth and Rogers, 2007; Leakey et al., 2009; Wehr et al., 2017), linking to the transpiration component of the hydrological cycle. While it is found to be premature to try to quantitatively link eCO_2 to maximum transpiration for South Africa (SA), what can be quantified are the sensitivities of eCO_2 induced reductions in maximum transpiration on hydrological responses.

An overview of the thesis structure is shown in Figure 1-2. In SA, soil carbon has often been observed to be declining (Dominy et al., 2001; du Preez et al., 2011a;b; Department of Environmental Affairs, 2017). To be able to model soil carbon impacts on hydrological responses, it is first necessary to develop and provide a fine scale inventory of soil carbon in SA. This provides the background necessary to be able to model impacts on other natural cycles. In Chapter 2, a new methodology to achieve high spatial resolution mapping of soil organic carbon in SA is presented and applied. In Chapter 3 a literature overview is provided, in which impacts of changes in SOC content in general, and more specifically in SA, are explored. In Chapter 4 impacts of changes in SOC on hydrological responses in selected climatically diverse areas within South Africa are modelled. In Chapter 5 impacts of eCO_2 on hydrological responses are explored and sensitivities of eCO_2 induced reductions in maximum transpiration on hydrological responses are modelled and thus quantified and, finally, in Chapter 6 conclusions are drawn and recommendations made.

1.2 Research Statement

This thesis focusses on researching impacts of altered carbon concentrations in the soil and the atmosphere on plant physiological water use and on soil water properties in South Africa, so as to be able to model these impacts on hydrological responses in order for hydrological projections to be improved.

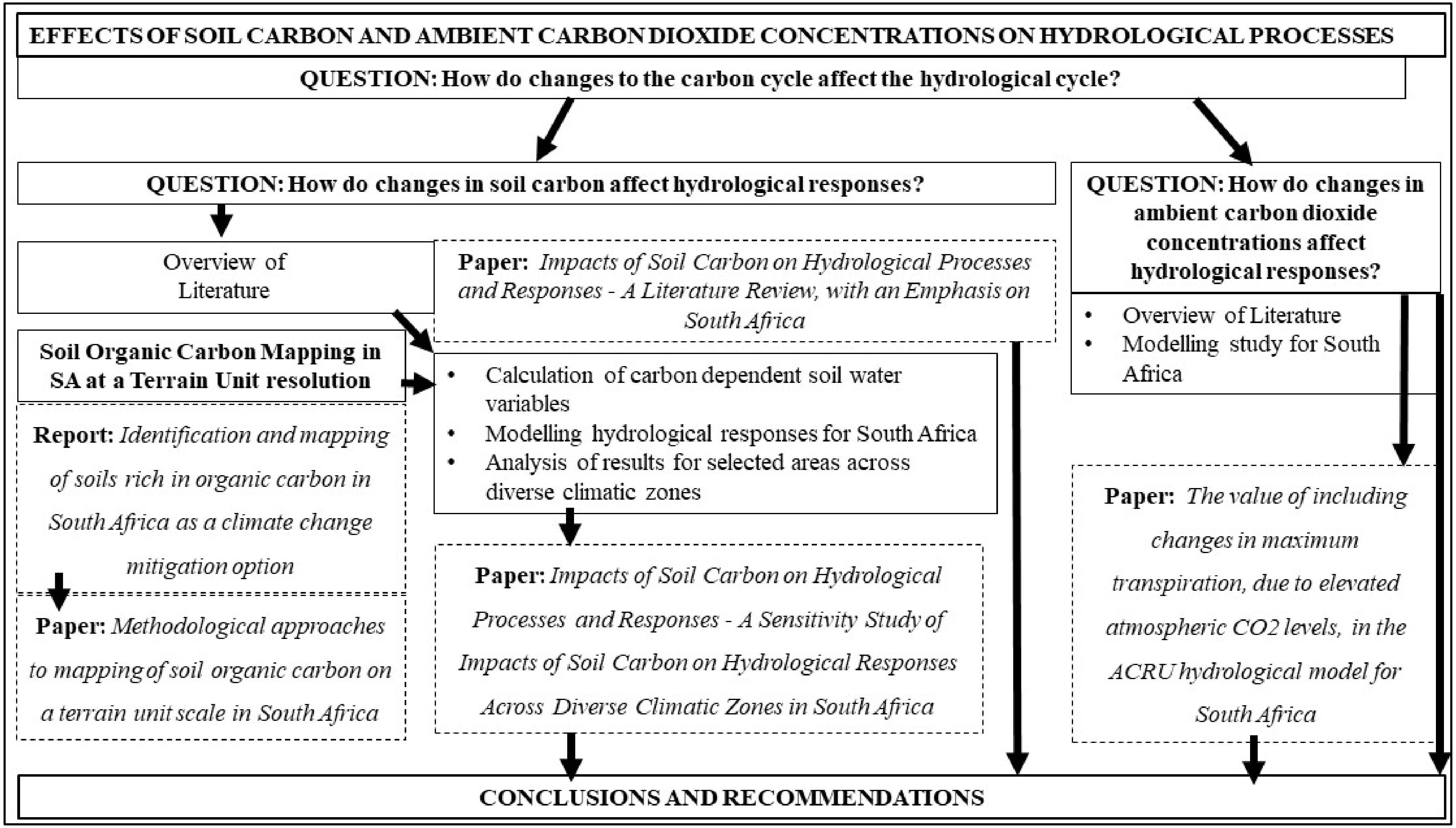

Figure 1-2 Thesis overview

1.3 Significance of the Proposed Research

Carbon concentrations in the atmosphere and in the soil are changing and the impacts of these need to be better understood in order to reduce the knowledge gap on how changes to the carbon cycle impact on the hydrological cycle. While global models which integrate both the carbon and the hydrological cycles exist, these are not normally used by hydrologists at local scales when assessing hydrological responses.

The geographical focus of this study is on South Africa. In the absence of detailed measurements of hydrological responses in South Africa such as transpiration and runoff, these have to be simulated with event- and process-based hydrological models. Changing spatial and temporal carbon related factors need to be accommodated in these models to facilitate improved simulations of hydrological impacts of land use and land management, as well as of climate change, for planning into the future.

1.4 Research Questions

The research questions are as follows:

a) How are increases or decreases of soil carbon concentrations projected to directly or indirectly change hydrological stores and fluxes such as field capacity, the permanent wilting point and hence soil water storage, transpiration and the runoff components of stormflows and baseflows?

b) How are increases in ambient carbon dioxide concentrations in the atmosphere, via plant physiological processes, projected to influence changes in hydrological stores and fluxes such as transpiration and the runoff components of stormflows and baseflows?

c) How can the above changes in soil carbon content and atmospheric carbon dioxide concentrations be modelled realistically by developing and including appropriate routines and feedbacks into the process-based daily time-step agro-hydrological ACRU model?

d) How do these modelled changes in hydrological responses vary spatially across South Africa and over time?

e) Are these changes in hydrological responses significant?

1.5 Research Activities and Outcomes

The research steps are listed below:

- Identify impacts of changed soil carbon concentration on soil water storage parameters;
- Identify impacts of increased carbon dioxide concentrations in the atmosphere on plant physiological water use;
- Develop or find algorithms describing the above for South African conditions;
- Include these algorithms as a suite of routines within the ACRU hydrological model; and
- Model and assess impacts on South African hydrological responses of transpiration, soil water content and runoff, distinguishing between different climatic zones and also between impacts on stormflows, baseflows and extreme (flood) events.

1.6 Objectives

To be able to address the above-mentioned research questions, the required objectives are outlined in this section.

The first objective is to identify, by way of a detailed literature review as well as through discussions with experts, and with an emphasis on South African conditions, the factors by which carbon in the soil can influence relevant soil hydrological processes. These processes have been identified, either directly or indirectly, as those impacting on soil field capacity, wilting point and soil porosity.

The second objective is to identify, again by way of a detailed literature review as well as through discussions with experts, and again with an emphasis on South African conditions, the factors by which carbon in the atmosphere in the form of CO_2 concentrations can influence hydrologically relevant plant related processes.

The third objective is to evaluate how these carbon – hydrology interactions can be modelled, and relevant models and modelling studies will be examined.

The fourth objective is to either find, or to develop algorithms at an appropriate level of complexity that capture the above relationships and, if required program these into the ACRU Model.

The fifth objective is to model hydrological responses with the new carbon-linked routines, assuming conditions of natural vegetation, to be able to isolate impacts on hydrological responses. This objective is unpacked further as follows:

- For the soil carbon impacts, selected areas within South Africa will be studied. The soil carbon contents will first be mapped in detail, by combining and enhancing several detailed soil databases.
- Results of modelled changes in hydrological responses will be analysed and interpreted.
- For the carbon dioxide related changes, this is to be achieved by using the existing South African Quinary Catchments Database, where South Africa, as well as Lesotho and Eswatini have been delineated into 5 838 relatively homogeneous agro-hydrological response units (Schulze and Horan, 2010), with standardized climate, soil, and plant related inputs.

The sixth objective is to analyse the results of modelled changes in hydrological responses, to interpret these and to publish results.

1.7 Issues that Fall Outside the Scope of this Research

There are a number of related issues that, however, fall outside of the scope of this thesis.

- Increased carbon dioxide concentrations, together with other greenhouse gases, lead to an enhanced greenhouse effect and, consequently, to climate change. These processes, *per se*, are not part of this study.
- Neither changes in soil respiration, nor carbon sequestration due to increased CO_2 concentrations, nor impacts of land use changes on hydrological responses will be addressed in this study.
- The impact of hydrology on carbon losses, e.g. as a result of soil erosion and the export of carbon via rivers, will not be a focus of this study.
- Impacts of fire-related issues on soil carbon content will also not be addressed in this study.
- Furthermore, impacts of SOC on soil erosion properties are not part of this study.

2. DEVELOPING SOIL CARBON MAPS FOR SOUTH AFRICA AT TERRAIN UNIT SCALE

Journal article published at Geoderma:

MAPPING SOIL ORGANIC CARBON AT A TERRAIN UNIT RESOLUTION ACROSS SOUTH AFRICA

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Abstract

The objective of this paper is to map soil organic carbon content (%) across South Africa in detail and at high spatial resolution. Several existing datasets, namely the Soil Profile Database, the Terrain Unit Database and the Binomial Soil Series Database were used, but had to be enhanced to be able to combine some information to produce detailed soil carbon maps for South Africa at a resolution of terrain units. A distinction was made between soil samples taken under assumed pristine conditions with a natural vegetation cover and those samples that had been modified by agricultural activities. The results were maps of areas with soil organic carbon content across South Africa at a spatial detail not previously achieved. The methodology did not allow for SOC mapping of stony or rocky soil, so these areas were omitted, but these are likely to be low in SOC. The results show that generally a higher SOC content is found in topsoil horizons than in subsoil horizons, in areas of natural vegetation versus those with agricultural land uses and in the higher rainfall areas compared to drier areas.

Keywords

Soil organic carbon mapping; Terrain units; South Africa; Carbon content

2.1. Introduction

Carbon concentrations in the soil are highly variable and can change either slowly or more rapidly over time, and both negatively and positively, due to a number of factors which include land use practices (du Preez et al., 2011a; b) and climatic interactions (Paustian et al., 2016). The main process by which carbon is incorporated into soil is through plant decomposition and conversion into soil organic carbon (SOC; Bot and Benites, 2005). SOC has also been identified as beneficial to soil water storage properties and plant production (Ankenbauer and Loheide, 2017; Shaxson, 2006). Maintaining high levels of SOC in existing soil and promoting practices that increase, rather than reduce, SOC thus has multiple benefits.

Soil organic matter (SOM) is an important component of the soil, with carbon being the main ingredient. SOM provides an indication of the level of the SOC content in the soil. The chemical composition of soil organic matter generally comprises 54.0% carbon, 5.2% hydrogen, 4.7% nitrogen, 35.7% oxygen and 0.4% sulphur (Schulten and Leinweber, 2000). Small amounts of carbon in the soil can derive from non-organic sources, but this is not a focus here, and in this paper soil carbon implies SOC, even if not stated explicitly.

SOC has been mapped in many countries (e.g. Grimm et al., 2008; Somarathna et al., 2016; Song et al., 2016). The mapping methodologies of mapping SOC concentrations and stocks vary, and include remote sensing (e.g. Mulder et al., 2011), various modelling approaches such as using geostatical techniques and regression analysis, machine learning (Keskin et al., 2019), as well as field-based methods. There is, however, no 'best' mapping method and the method selection has to be undertaken for every scenario of data availability (Yigini et al., 2018; Grimm et al., 2007).

2.1.1. South African soil carbon studies

Soil carbon forms the largest part of the terrestrial carbon pool in South Africa (Department of Environmental Affairs, 2017) and worldwide. The estimated average South African total ecosystem organic carbon stock, which is the sum of SOC and total biomass organic carbon is 6 396 gC/m2, with a gross primary production of 373 gC/m2 and a net primary production of 186 gC/m2 (Department of Environmental Affairs, 2017). The bulk of this carbon is stored in the soil. South African soil carbon levels are generally low when compared to levels in the Northern Hemisphere (Kucharik et al., 2000) and they have been reviewed by du Preez et al (2011a; 2011b). Since 2010 some South African carbon sink and carbon pool related studies have been published (Department of Environmental Affairs, 2015; 2017; Knowles et al., 2015). Because of their relative area coverage across South Africa, the grasslands and savanna biomes contribute most to South Africa's terrestrial carbon stocks, although per square metre the storage of forest biomes exceeds that of grasslands and savannas (Department of Environmental Affairs 2017: 5). Grasslands, while containing less above-ground carbon storage, make up for this by contributing more below-ground storage of up to 100t/ha of carbon (Department of Environmental Affairs 2017: 5).

Since 2008, there have been a number of studies on soil carbon in South Africa. Stronkhorst and Venter (2008) used 4 837 measured values of C in the topsoil and compiled a map of SOC content (%; Figure 2-1). Soil organic carbon stocks (g/m2) up to one metre soil depth (representing soil columns) were subsequently estimated by the Department of Environmental Affairs (2015), with results shown in Figure 2-2. Data were extrapolated, with the driest, hottest third of the country's SOCs only being approximated owing to a lack of data. SOCs for soil depths of 0–300 mm were assumed to be from the topsoil and for depths from 300–1 000 mm were assumed to be from the subsoil. SOC in the topsoil was reduced by a land use factor for cropping, compared to values from natural vegetation. Generally, a positive correlation was found between soil carbon and rainfall (Department of Environmental Affairs, 2017; Stronkhorst and Venter, 2008).

Wiese et al. (2016) developed vertical distribution functions for several soil profiles in South Africa, to calculate soil carbon distribution from an observation point near the soil surface to up to 1 m depth, and these could be useful in future studies.

2.1.2 Agricultural activities

Agricultural activities often reduce soil carbon concentrations. Swanepoel et al. (2015) found that SOM in dryland (i.e. rainfed) agricultural fields in southern Africa has declined by 25% in semi-arid areas, by 53% in sub-humid areas and by 46% in humid areas. Regarding this significant decrease in SOC, findings show a higher SOC loss during the first five years of cultivation and equilibrium conditions being reached after ~ 35 years of cultivation. Concerns lie in both release of elevated levels of GHGs to the atmosphere, and in loss of soil quality, which influences the production potential of soil in a region that is already food insecure. Du Preez et al. (2011b) found that in South Africa continual cultivation reduces the soil carbon content, particularly in the topsoil, by around 45% on average, but varying from 30% to 75%.

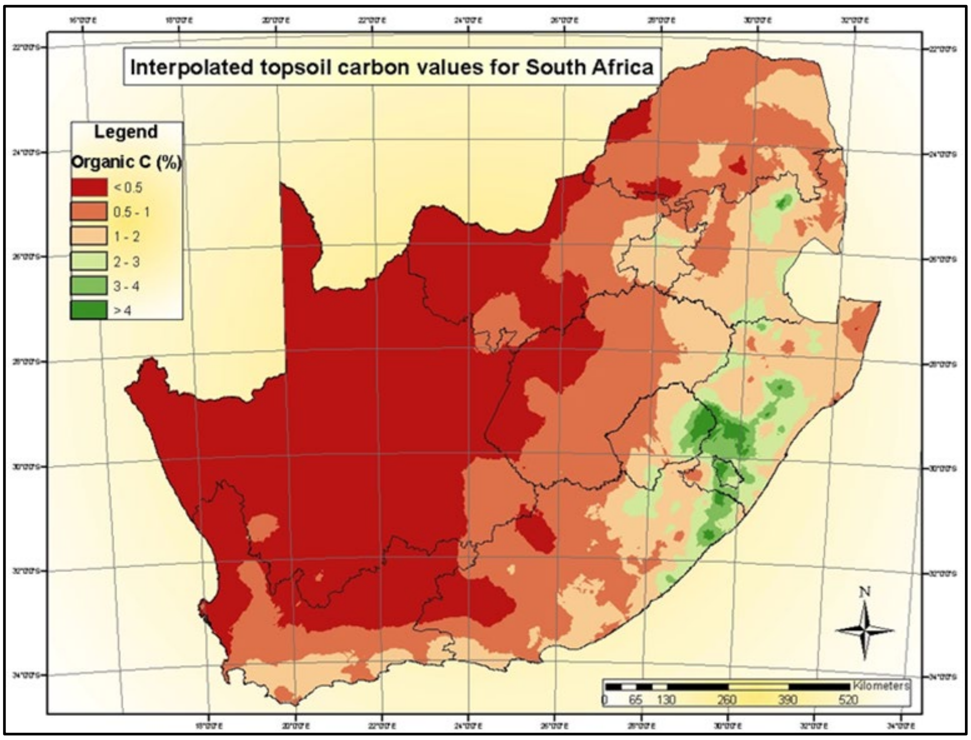

Figure 2-1 Distribution of soil organic carbon content (% by mass) across South Africa, Eswatini and Lesotho for the topsoil horizon only, based on 4 837 measured values (Stronkhorst and Venter, 2008)

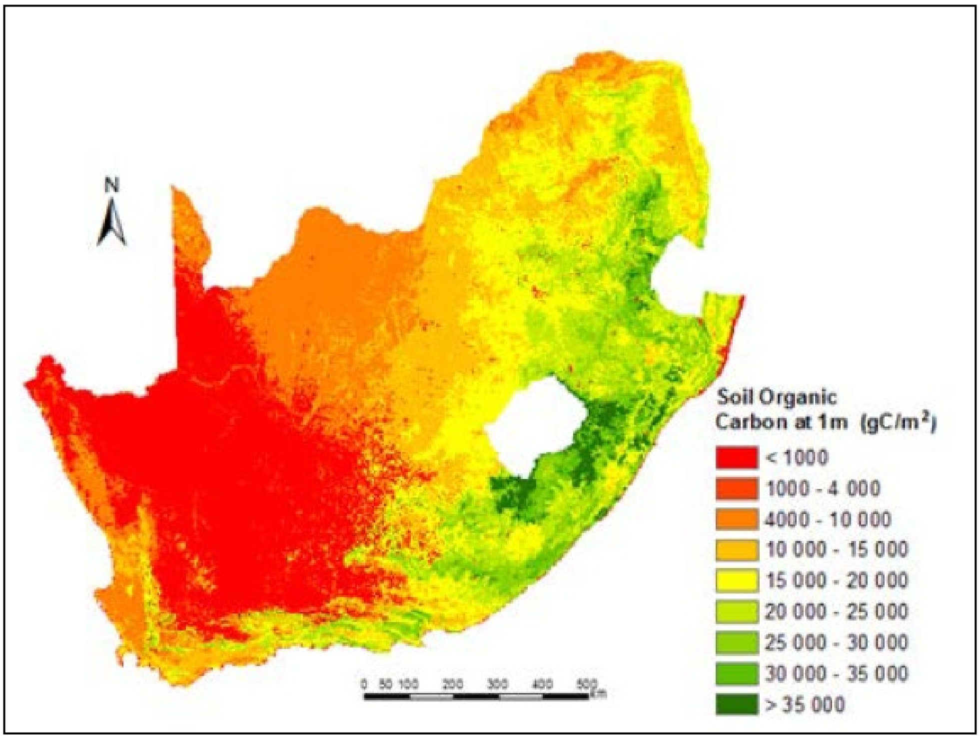

Figure 2-2 Soil organic carbon stocks (g/m2) up to 1m soil depth across South Africa (Department of Environmental Affairs, 2015)

Carbon facilitates the improvement of soil by aggregating soil particles. This requires a regular supply of carbon, for example through the retention of residual plant matter, cover crops, mulching or by working organic matter into the soil; as well as by soil biological activity which, similarly, requires a regular supply of carbon, low mechanical disturbance (for example less tilling) and reduced exposure to UV light (for example through mulching and less tilling).

2.1.3 Soil mapping in South Africa: From Land Types to terrain units

Historically, soils in South Africa were distinguished using the South African Binomial Soil Classification (Macvicar et al., 1977), in which 501 soil series within 41 soil forms were described. Soil series are a subdivision of soil forms which have been used to narrow down soil properties and define diagnostic horizons (Macvicar et al., 1977). From here on this is termed the Soil Series Database. The number of soil forms later increased (Soil Classification Working Group, 1991) and is evolving further (Turner, 2013; Van Huyststeen et al., 2014). Many of the soil series descriptions are key to SOC determinations.

Soil mapping in South Africa commonly is at the level of so-called ‘Land Types’, with original field mapping at a spatial scale of 1:50 000 and eventual production mapping by the Agricultural Research Council’s Institute for Soil, Climate and Water at 1:250 000 (ARC–ISCW, undated). A Land Type is defined as ‘a homogeneous, unique combination of terrain type, soil pattern and macroclimate zone’ with approximately one observation per 300 ha over the whole of South Africa. A review of Land Type mapping procedures can be found in Paterson et al. (2015). The over 6 000 mapped Land Types were each made up of a number of soil series, with the areas and percentages of each soil series given in the documentation on each Land Type. A refinement, but not widely utilised, was a division of a Land Type into up to five terrain unit (TU) categories, based on a refined 90 m digital elevation model. These categories are the crest, which is convex shaped, the scarp, which is akin to a cliff, the midslope, which is concave in shape, the footslope and the valley bottom. This division of the over 6 000 Land Types yielded 27 491 spatially defined TUs across South Africa, in what is from now on is called the Terrain Unit Database (Beukes, pers. com). In respect of SOC mapping, the Terrain Unit Database (TUD) lists all soil series found within a particular TU (up to a maximum of 15) and the proportion of each. Where the TU was dominated by stones and rocks, however, no soil series information was given. In addition to the proportion of each TU making up a Land Type, the profile depth of each soil series within a TU, and other attributes unrelated to SOC mapping, are given in the TUD.

The Soil Profile Database (SPD) accompanying the Land Type maps (ARC-ISCW, undated) contains information from sample locations, usually with several samples per location at various depths, obtained over many decades of fieldwork from the 1920s to the present (Paterson et al., 2015). This database includes information on SOC content, as well as fractions of the textural components of clay, sand and silt and often a broadly classified land use.

2.2. Objectives

The objective of this paper is to map, in detail and at a high resolution, soil organic carbon content as percentages across South Africa at a spatial detail not previously achieved. These maps can be used to choose areas to apply appropriate management regimes and possible interventions to protect soil rich in SOC. These important soil types can later be identified, for example by the South African Department of Environmental Affairs, to curb unnecessary carbon releases from these soils.

2.3. Methods

The methodology chosen was based on utilising available South African resources. Several existing databases were used, namely the SPD, the TUD and the Soil Series Database. These databases had to be manipulated and converged to be able to combine some information from each, in order to be able to produce detailed maps of SOC for South Africa at the spatial resolution of TUs. An overview of the methodology is first provided (also see Figure 2-3). Our work was to upscale the SOC point information from the SPD to all areas covering South Africa at a detailed spatial scale. Median SOC contents per soil series, per soil horizon and per land use cluster were first calculated. The median SOC contents were then used with information in the TUD in order to map SOC in detail across South Africa, both under assumed pristine conditions with a natural vegetation cover and for soils that had been modified by agricultural activities.

The calculations were undertaken using Excel, as well as utilising the programming language R. Geographical/spatial mapping was undertaken using ArcGIS 10.4.

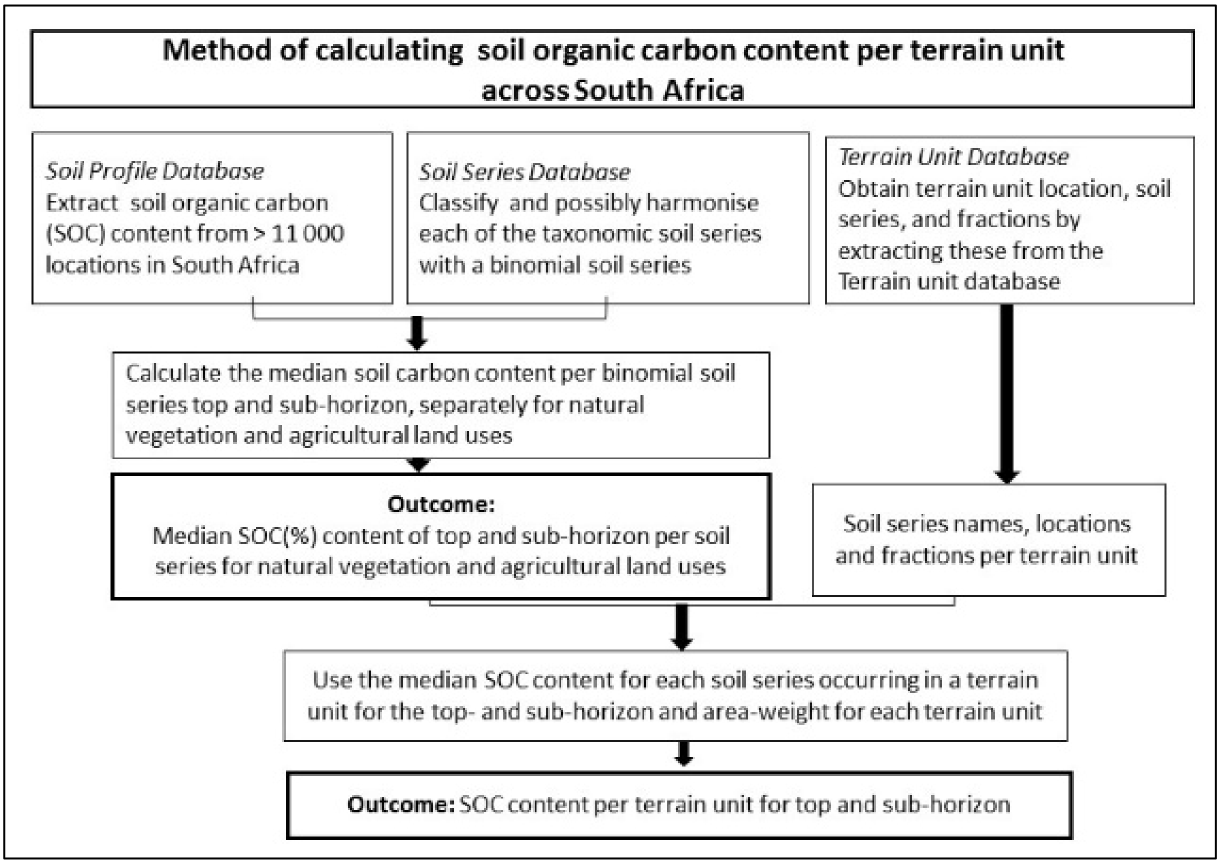

Figure 2-3 An overview over the methodology of calculating soil organic carbon content per TU by combining several databases

2.3.1 Utilising the Soil Profile Database

The information in the SPD was first evaluated. Owing to the impact of land use on SOC, a distinction was made between natural vegetation and agricultural land. The land cover groupings in the SPD were, therefore, evaluated. The original groupings were simplified, with similar land covers grouped together as far as possible into the natural vegetation and agricultural land categories (see Appendices, Table 8-1). Unspecified land uses were assumed to be under natural vegetation. A total of 11 099 locations' soil profiles were analysed, and from the descriptions available 8 772 were assumed to be under natural vegetation and 2 031 soil profiles under agricultural land uses, with the remaining 296 undisclosed.

The locations of the soil profiles were, in many cases, sampled for different soil horizons, giving a total of 19 131 point-sampled soil carbon data. Where there was more than one subsoil, the carbon values were depth weighted.

Following quality checks, the locations of the 11 099 sample points used in subsequent analyses were mapped, with the distribution of sample points shown in Figure 2-4. Note that there are more soil carbon sample points in the wetter east and south of the country where more intensive agriculture is practised. Secondly, an uneven distribution seems to be a remnant of provincial or regional projects, or lack thereof (Paterson et al., 2015).

The soil profiles were further analysed by soil classification system. The SPD contains data derived in the field using both the 1977 Binomial Soil Classification (MacVicar et al., 1977) and the later Taxonomic Soil Classification of South Africa (Soil Classification Working Group, 1991; Figure 2-4).

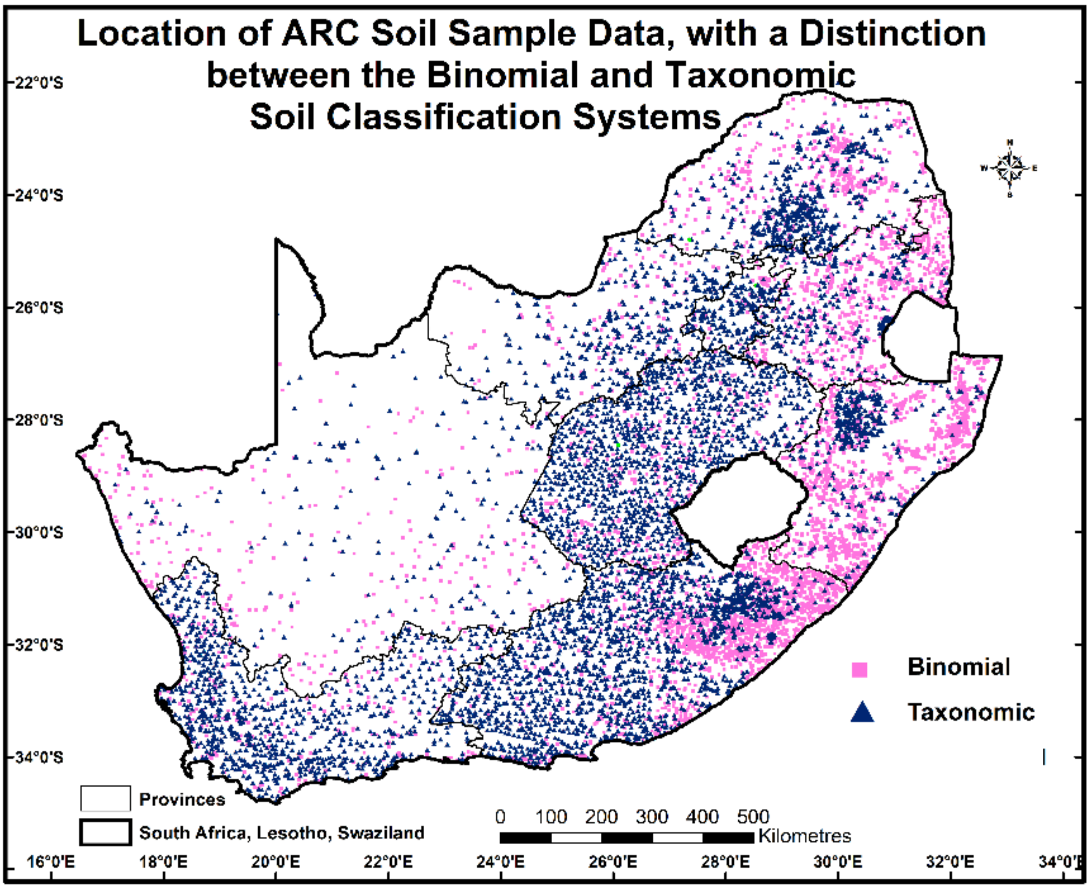

Figure 2-4 Locations of the 11 099 sample points within South Africa from which soil carbon data were used in this study, with a distinction made between samples classified by the Binomial system (pink) and the Taxonomic system (blue)

2.3.2 Reconciling and matching soil forms and families of the Taxonomic soil classification with those of the Binomial soil classification

With the TUD including soils information from the Binomial Soil Classification only, the use of the two soil classification systems in the SPD presented a challenge. So as not to lose the carbon information from the SPD from the soil series with the Taxonomic Soil Classification system, "equivalent" characteristics had to be determined and reconciled. An initial matching was made at the primary level of soil forms. Then, within each soil form, the individual soil families of the taxonomic soil classification system where matched to one of the 501 potentially possible equivalent soil series of the Binomial Classification system. While the binomial soil series were predominantly classified by clay content, the taxonomic soil series were not. The SPD profiles defined with the taxonomic soil classification system, however, also included a soil texture breakdown, and hence the clay content for the specified soil family. Each Taxonomic soil family was then further sub-divided into the same clay classes, between 0-55% clay, used in the Binomial Soil Classification. The sub-divisions were 0-6%, 6-15%, 15-35%, 35-55% and > 55% clay. A binomial soil series was then assigned, based on the clay classes. In addition, any dystrophic, mesotrophic or eutrophic characteristics of the TSC soil families were used for the reconciliation. Depending on the soil form, either the topsoil horizon or the subsoil horizon was used for decisions making. For more details see Schütte et al. (2019). The results of the matching are shown in Appendices (Table 8-2). While every care was taken to ensure that the Binomial soil series equivalents of the Taxonomic system were interpreted as correctly/representatively as possible, it must be stressed that this was a manual task. This correlation might therefore be subject to improvement in the future.

2.3.3 Determination of soil carbon content per soil series, but distinguishing between soils under natural conditions and those subjected to agricultural practices

The organic matter content of a mature natural soil is determined by specific combinations of soil forming factors, which include climate, topography, vegetation and organisms, parent material and time (e.g. Jenny, 1941). However, this equilibrium is disturbed by human interventions such as land use change or cultivation. Care should thus be taken when estimating and mapping soil organic carbon to distinguish clearly between SOC under natural conditions as opposed to those following agricultural practices. The quality-controlled SPD used in this study was therefore split into those samples assumed to have been taken under conditions of natural vegetation and those assumed to have been taken under agriculture. For all 501 soil series median SOC content was calculated from the SPD, separately for natural vegetation soil carbon samples and for those with agricultural practices. For results see the

Appendices (Table 8-3) and for more detail see Schütte et al. (2019). Owing to the difference in the number of soil series at the various locations and hence the number of carbon values per soil series and per land use, there is a difference in confidence and uncertainty in those calculated median SOC values.

2.3.4 Soil organic carbon content (%) per terrain unit in South African soils

From the median SOC per soil series, and separately for the top- and subsoil horizon, the SOC content for each of the 27 491 terrain units (TUs) covering South Africa was calculated by area-weighting the SOCs of each of the soil series making up a TU (see Results section). Areas which had been annotated as being high in stone content could not be evaluated as no soil series were specified in the TUD, and these areas are shown in the Results section as "no soil information given". It is hypothesised, however, that those areas are low in SOC.

2.4. Results

After first making a distinction between those samples of SOC collected at locations under natural vegetation and those under agricultural land uses, the median values of SOC% were calculated for each of the 501 soil series of the Binomial soil classification system of South Africa, using the procedures described above. Thereafter the SOC% for each of the 27 491 TUs covering South Africa was calculated by area-weighting the SOCs of each of the soil series making up a TU, according to the respective thicknesses of the topsoil horizon and the subsoil horizon of each soil series in that TU.

2.4.1 SOC% under conditions of natural vegetation

The percentages of soil organic carbon for topsoils under natural vegetation, based on medians of the sample values per soil series as calculated by procedures explained above, were then mapped at a spatial resolution of TUs, with results shown in Figure 2-5. The difference between higher topsoil SOCs in the more humid east, in places averaging up to 3.5% per TU, and the lower SOCs of the arid west with generally < 1.0% SOC per TU, is clearly visible in Figure 2-5 (top). The level of spatial detail possible when mapping at the resolution of TUs is also illustrated in Figure 2-5 (bottom) in which the SOC results are scaled to an area around the city of Durban in the province of KwaZulu-Natal. The reduction of SOC in the subsoil is very evident for natural vegetation conditions when results of the topsoil from Figure 2-5 are compared with those of the subsoil (not shown), to the extent that Figure 2-6 shows ratios of

SOC% between the top- to subsoil to be in the order of 2 and more in the east and around 1.5 in the west.

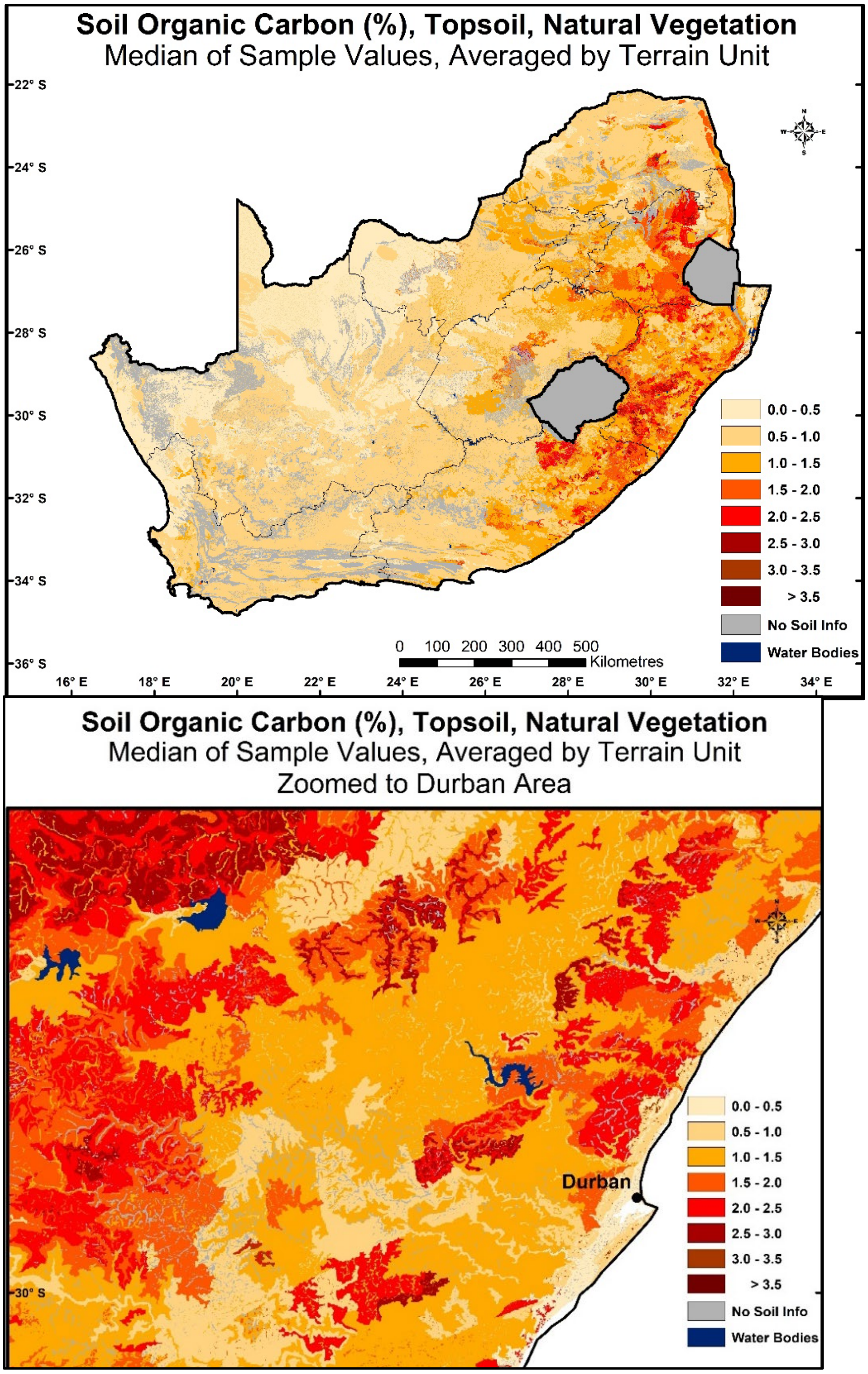

Figure 2-5 Median soil organic carbon content (%) in the topsoil mapped at a spatial resolution of terrain units across South Africa under conditions of natural vegetation (top) and the area around Durban in the province of KwaZulu-Natal (bottom) magnified

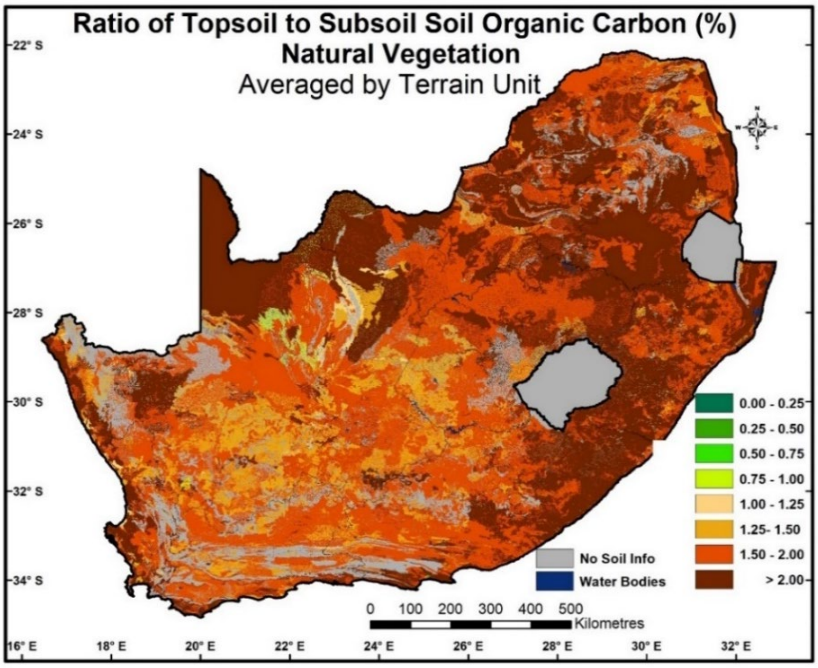

Figure 2-6 Ratio of topsoil to subsoil percentage soil organic carbon across South Africa under conditions of natural vegetation, mapped at a spatial resolution of terrain units

2.4.2 SOC% under conditions of agricultural land uses

The loss of SOC% when natural vegetation is converted to agricultural practices becomes obvious when the topsoil and ratio SOC% maps in Figure 2-7 are compared with the corresponding maps in Figure 2-5. A similar loss was found for the subsoil (not shown). Again, as in the case of natural vegetation, ratios of top- to subsoil SOCs frequently exceed a factor of 2, but for agricultural land uses the ratios (where there is enough information) remain high even in the more arid west. It is hypothesized that this might possibly be because certain agricultural areas are under irrigation, which increase SOC, but irrigated areas were not specified in the databases used.

2.4.3 Comparisons of soil organic carbon content (%) between natural vegetation and agricultural land uses

When the SOC contents (%) between natural vegetation and agricultural land uses are compared as ratios, then Figure 2-8 shows that for the topsoil in the more humid east, where most of South Africa’s intensive agriculture is practised, SOC losses resulting from agricultural land uses are of the order of 50%, corroborating earlier findings by Swanpoel et al. (2016). However, in the more arid west the ratios for the topsoil are around unity and even > 1 in places, suggesting that SOC losses there occur on a much reduced scale. As stated above, this might also be because these areas might be irrigated and thus provide more plant matter and thus a higher SOC content. It must, however, also be reiterated that the values here are at a much lower confidence level than in the moister east due to a low sample density in this area.

For the subsoil horizon (not shown), patterns of SOC loss under agriculture are similar to those for the topsoil in the wetter east, but with the SOC losses continuing through to the drier west.

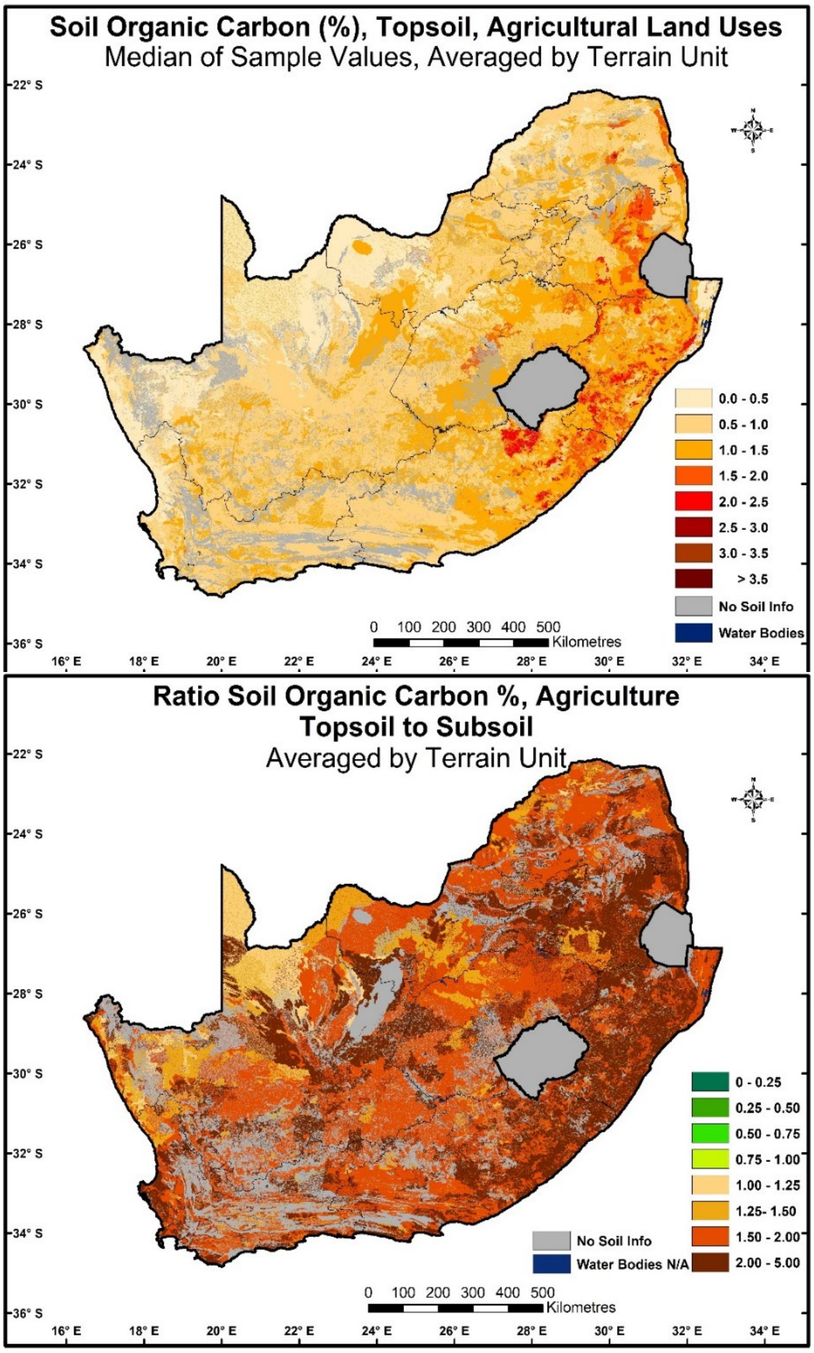

Figure 2-7 Median soil organic carbon content (% by mass) in the topsoil (top) and (bottom) ratios of topsoil to subsoil soil organic carbon across South Africa under agricultural land uses, mapped at a spatial resolution of terrain units

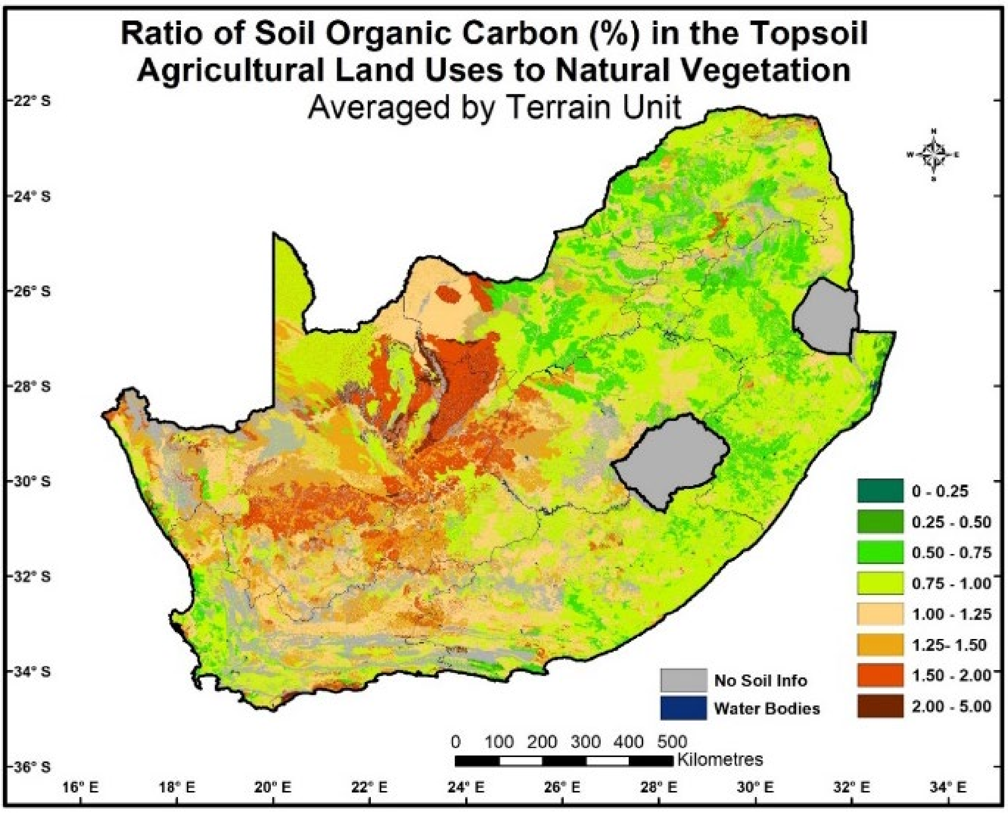

Figure 2-8 Ratios between agricultural land uses and natural vegetation of percentages of soil organic carbon in the topsoils across South Africa, mapped at a spatial resolution of terrain units

2.5. Summary and discussion

In this paper we have outlined some background on SOC, with specific reference to South Africa. We have, furthermore, provided background information on the more than 27 000 terrain units which were identified across SA from a 90 m Digital Elevation Model, and linked to the soils 'Land Type' information. These TUs were used as the spatial resolution for mapping SOCs contents. We used the TU information which was linked to the soil series from the Binomial Soil Classification which had been associated with each terrain unit, in order to map SOC across SA. The methodologies were described which were developed for enhancing the ARC's SPD, derived from two different soil classification systems which first had to be reconciled, to enable mapping of SOC content and densities across SA at the spatial resolution of TUs. Detailed mapped results for SOC contents were presented at TU level under land cover conditions of natural vegetation and agricultural land uses, for the topsoil as well as the subsoil horizons in both cases. In many respects, this was undertaken at a spatial resolution and with innovative techniques hitherto not attempted in SA.

The results show the spatial differences in SOC content across SA, with usually lower content in the more arid west, compared to the moister east, but with large spatial variation. It also shows the higher SOC content in the topsoil compared to the subsoil, although if the subsoil is deep, this might be different for carbon stocks.

When comparing results from previous mapping exercises with results from this project, the overall soil carbon contents in the topsoil horizon (Figures 2-1 and 2-6, left) appear fairly similar, but we have provided much more detail compared to Stronkhorst and Venter (2008). In future research, the results from the large number of soil profiles could be explored with other modelling methods, e.g. regression analysis and/or geostatistical techniques, and the results of SOC content could then be compared with the results of this study.

As was shown in this research, agricultural activities in general lead to a reduction in SOC in the topsoil horizon, which corresponds to other studies (e.g. Swanepoel et al., 2016). This, however, was not the case everywhere. It might well be that irrigation of otherwise dry areas, as well as certain conservation agricultural practices can increase, rather than decrease the SOC content. It is therefore recommended that emphasis be placed on agricultural methods that do not lead to a reduction in SOC and rather build up SOC. This could be achieved with conservation agriculture practices such as the construction of contour banks, no-till practices and retention of mulch, as well as introducing policies, for example in sugarcane and commercial forestry, to reduce post-harvest burning practices, or by planting perennial rather than annual crops.

In this research only a broad distinction was made between natural vegetation and agricultural land uses in a generic sense. It would be prudent to, for example, further subdivide agricultural practices by separating forestry plantations from other agricultural land uses, as the former might well increase carbon stocks. Furthermore, SOC in irrigated areas could be assessed separately. However, this was beyond the scope of this research and the information available. Additionally, a relativity large proportion of the South African soils have a high stone content within the first metre of soil depth, and this was not accounted for in this methodology.

While the SOC results presented are at a level of detail hitherto not achieved in SA, it must also be mentioned in closing that there remain certain aspects of uncertainty in the results. There are, for example, difference numbers of samples of any specific soil series from which their median carbon content was determined, with the samples often having a range of carbon values. This range and their differences could be further investigated to obtain an indication of confidence in results. Furthermore, it was assumed that the information in the databases provided was accurate, with some uncertainties arising from this assumption as well.

2.6. Conclusions

The results have provided detailed maps of soil carbon in South Africa. These results can potentially make a significant input to the Electronic National Carbon Sinks Atlas which has been developed by the South African State Department of Environmental Affairs. The maps could also be used when desktop studies for specific areas are required.

Several aspects are recommended for future work. Uncertainty assessments are recommended. While every step in the methodology was considered to be based on solid reasoning, there remain areas where further validation would be prudent. Matching the Binomial and Taxonomic Soil Classification systems of SA was a key aspect of this research project. The matching process was a tedious and manual one and should be further validated in future research work, to identify and correct possible misinterpretations. Secondly, scrutiny of soil carbon content (Appendices, Table 8-3) has identified a number of soil series other than those from the organic soil form (Champagne) and the humic soil forms (Kranskop, Magwa, Inanda and Nomanci) with high (> 2%) percentages of organic carbon. These other soil series should be re-assessed to check whether the high SOCs are valid, or whether they may be artefacts of assumptions in the cases where only a few or no samples were available and values from soils with similar properties had to be used. Thirdly, a cursory assessment of results indicates that the methodology developed may, in certain cases, have resulted in anomalously high or anomalously low SOC estimates. These will have to be scrutinised to check the validity of, and confidence into, the results. Furthermore, additional in-field assessments of those soils identified high in SOC should be undertaken, for purposes of considering whether to ring-fence these because they would be considered carbon sink areas.

Maps on SOCs shown in this paper under natural vegetation in contrast with those under agricultural land use practices were prepared assuming the entire area of SA to be under one or the other of these two land covers. This is, however, not the case in reality, as only a fraction of the country is still under natural vegetation and land converted to agricultural uses may be under either intensive or extensive use, under irrigation or under commercial forest plantations, or else the converted areas may be urban land or dams. Mapping should, therefore, be re-visited to account for all the above scenarios by considering actual land uses by using, for example, the South African national land cover maps (SANLC, 2018). Such an analysis would also show how many areas of potentially high SOCs have already been irreversibly converted to, say, urbanisation or dams.

It is recommended to at least further separate forestry plantations from other agricultural land uses, as the former might well increase carbon stocks. Also irrigated areas should be taken into account separately, which could also be determined from the land use maps.

Additionally, one will need to assess soil organic carbon contents of certain other soils, and in particular wetland soils, and possibly those experiencing lateral drainage, from the extensive SOC containing SPD, in intensive consultation with experienced soil scientists.

Lastly, more research into improving soil bulk density estimation in SA would facilitate the conversion of soil carbon content into carbon densities and thus soil carbon stocks.

3. IMPACTS OF SOIL CARBON ON HYDROLOGICAL RESPONSES – A LITERATURE REVIEW

IMPACTS OF SOIL CARBON ON HYDROLOGICAL PROCESSES AND RESPONSES – A LITERATURE REVIEW, WITH AN EMPHASIS ON SOUTH AFRICA

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Keywords

Soil carbon and hydrology links; soil water holding capacity quantification; drained upper limit; permanent wilting point, plant available water

Abstract

Hydrological processes can be simulated using hydrological models, with outputs of hydrological responses including transpiration, runoff and its components of stormflows and baseflows, as well as accumulated streamflows. Impacts of land use and/or climate change on hydrological responses can be assessed using scenario modelling. Required input variables are climate-, vegetation- and soil-related, and include the soil's water holding capacity. The water holding capacity can be impacted upon by changes in soil organic carbon (SOC), which has currently not been included in hydrological modelling in South Africa (SA). SOC content in SA varies spatially and has been declining over time in many locations. It can, however, be increased with suitable land management.

A review of the literature on links between SOC and hydrological processes within the soil-plant-atmosphere continuum, including soil water properties and hydrological responses, is provided. Suitable pedo-transfer equations are identified to calculate impacts of changes in SOC content on soil parameters of soil water content at saturation, at drained upper limit and

at permanent wilting point. Using these altered soils-related parameters with the ACRU model will thus allow the simulation of soil carbon impacts on hydrological responses.

This paper contributes towards a better understanding of the links between the carbon and hydrological cycles through an assessment of soil carbon impacts on soil water properties, providing a way forward for assessing soil carbon impacts on hydrological responses in SA.

3.1 Introduction

Knowledge of the links between soil carbon and hydrological responses will improve outputs from hydrological models. This paper sets out to contribute towards a better understanding and quantification of soil carbon impacts on hydrological responses in SA. Literature on the linkages between soil carbon and hydrology is reviewed, starting with a short recap of relevant hydrological concepts as well as some background on soil organic carbon (SOC). SOC is identified as a variable that can change the soil water holding capacity and hence its plant available water. To be able to quantify these impacts through the soil-plant-atmosphere continuum, certain soil-related inputs into the ACRU model (Schulze, 1995; Smithers and Schulze, 2004), a process-based daily time-step hydrological model frequently used in SA, are examined. These soil inputs are the soil water holding capacity at its drained upper limit (field capacity), at its permanent wilting point and at saturation, with the latter frequently referred to as the soil ‘porosity’. A short summary of the key findings from the literature are given, followed by a conclusion, in which knowledge gaps are highlighted and recommendations are suggested.

3.2 Background

3.2.1 Background of hydrological concepts and soil characteristics linkages to soil carbon

The hydrological cycle (Marshall, 2013; Rast et al., 2014) can, in simple terms, be explained as water that cycles, with one starting point being precipitation from clouds in the atmosphere falling onto land and water surfaces, from where it eventually returns to the atmosphere. A part of the water is returned directly to the atmosphere by either being evaporated from water surfaces or soil surfaces, or from vegetation and litter that had intercepted some of the precipitation. A part of the water that infiltrates into the soil is transpired back to the atmosphere through plant physiological processes, whereby soil water is taken up by plants through roots and transpired via plant stomata (Savenije, 1998; Falkenmark, 1999; Rast et al., 2014). Part of the water that reaches the soil (or other surfaces) becomes runoff, defined here as being made up of rapid response stormflows from the surface, or from near the surface, and slow response interflows and baseflows (Schulze and Maharaj, 2008). Both rapid and slow responses together feed rivers and water bodies.

Hydrological processes are relevant for the estimation of water quantity and for understanding pathways of water through the landscape (Falkenmark, 1999). Hydrological processes from the landscape can be described through various hydrological responses, including transpiration and evaporation back into the atmosphere, as well as drainage at varying rates into the soil and runoff from the landscape, with runoff consisting of the components of stormflows and baseflows, and, if a long series of daily runoff values is available, also through statistical design runoff magnitudes such as the 1:10 or 1:50 year events which usually manifest themselves as floods (Schulze and Maharaj, 2008). These hydrological responses can be simulated using models requiring climatic, soil, terrain and vegetation/land use information. Inputs of climatic data include precipitation, temperature, solar radiation and relative humidity. Vegetation information includes its active biomass, expressed either through a leaf area index or a crop water use coefficient which can vary throughout the year depending on seasonal growth/senescence patterns, its capacity to intercept rainfall as well as its rooting depth and distribution (Schulze, 1995). Inputs of soil information include soil thicknesses of top- and subsoil horizons and the respective horizon textures, as well as soil water contents at saturation, drained upper limit and permanent wilting point, which are described next.

Soil characteristics are important for conceptualising, assessing and modelling hydrological processes (Van Tol et al., 2017). Hydrologically important soil parameters include the soil water content at a given point in time within a time series and, as mentioned above already, the soil water content at saturation (also called porosity, PO), at its drained upper limit (DUL; also termed its field capacity) and at its permanent wilting point (PWP), with plant available water (PAW) being the water held between DUL and PWP for a given thickness of the soil (Bauer, 1974). Soil water content at saturation implies that water has filled the soil pore spaces to the extent that no air is present and any additional water runs off. Note that runoff can also occur if the rate of supply, i.e. the rainfall intensity, exceeds the soil infiltration rate. The soil DUL is the amount of water in the soil where drainage effectively ceases due to a balance between gravitational and soil water suction forces. The soil has drained any excess water and water and air contents in the soil are considered ideal for crop growth. PWP indicates the amount of water at which the soil has dried to the extent that any remaining water is no longer available to plants. Both DUL and PAW are conventionally measured as water volumes (m^3/m^3) at a suction of between -5 and -33 kPa for DUL and a -1500 kPa for PWP (Schulze, 1995). Soil porosity is the amount of pore space between soil particles (Shaxson, 2006). The soil parameters described above are important for plant growth, as well as for hydrological processes such as transpiration or drainage or runoff.

Focussing on South Africa, which is generally a water-scarce country, many plant physiological processes are limited by soil water availability (Wallace, 2000). The country's mean annual precipitation (MAP) is estimated at 497 mm (compared with a world average of 860 mm), with wide spatial variations of MAP ranging from 46 mm to 2004 mm (South African Weather Service, 2017). Atmospheric water demand is high, and is expressed as potential evaporation, which on an annual basis is generally much higher than precipitation, in places by a factor of over 10 (Schulze, 2011). The overall rainfall to runoff conversion in SA is low – on average being only 9% across the country (Whitmore, 1971), in contrast to the world average of 35%. By implication, therefore, the largest part of the precipitated water is transpired and evaporated, rather than being converted to runoff. Actual evapotranspiration in South Africa is controlled primarily through soil hydraulics. Hence, investigations into the changes in soil hydraulic characteristics is vital for this region.

Hydrological responses in SA are frequently simulated with the daily time-step and process-based ACRU hydrological model (Schulze, 1995; Smithers and Schulze, 2004).'This model has been continually enhanced and updated over the past 30 years and has been widely verified within SA and in many countries worldwide (Schulze, 1995; Jewitt and Schulze RE, 1999; Hope et al., 2004; Smithers and Schulze, 2004; Warburton et al., 2010).'Scenarios of land use and/or climate change impacts on hydrological responses can be simulated by varying model inputs of not only climate variables, but also of vegetative variables and/or soil variables. Changes in carbon concentrations, in the form of soil carbon, are seldom included in hydrological models. The hydrological cycle is, however, impacted upon by changes to the carbon cycle.

3.2.2 Some background to soil carbon linkages to hydrological processes

Typically, a soil contains 1-5% organic matter, while containing around 45% inorganic minerals and variably 20-30% water and 20-30% air, up to a combined maximum of the porosity. Texture, structure, density and porosity are physical soil properties. Soil structure is the aggregation of the particles into secondary structures, which are larger and relatively stable. The interaction of soil biology with sufficient SOM under suitable conditions in regard to water availability, temperature and pH, is required to maintain good soil structure (Shaxson, 2006). Soil porosity refers to the amount of open or pore space between soil particles. Root expansion and subsequent root decay favour porosity, as does the burrowing of soil-inhabiting fauna. Soil porosity is required for water, gases and roots in the soil and it impacts water infiltrability (Shaxson, 2006).

An important soil component is soil organic matter (SOM). Carbon is the main ingredient of SOM. SOM gives an indication of SOC content in the soil. Both terms will be used in this paper. The one can be calculated from the other by using a factor. It is understood that this can be an approximation only, with SOC content in SOM varying (Pribyl, 2010). SOM chemically contains around 54.0% carbon, 35.7% oxygen, 5.2% hydrogen and 4.7% nitrogen (Schulten et al., 2000). Some soil carbon can derive from non-organic sources. However, this is not a focus here, and in this paper soil carbon implies soil organic carbon, even if not explicitly stated. While most arable soil generally contain only 2%-5% (by mass) SOM, the effect on soil properties is disproportionally larger (Weil and Magdoff, 2004).

Carbon stocks, i.e. the carbon contained in soil and living terrestrial biomass, are approximately three times greater than atmospheric carbon stocks (Falkowski et al., 2000). Other biogeochemical cycles and carbon interact, with biotic sinks requiring other nutrients, for example, nitrogen. Carbon stocks on earth are impacted upon by several factors. One factor is climate change. Soil respiration is likely to be increased with elevated temperatures (Kirschbaum, 1995; Paustian et al., 2016). Increased atmospheric CO_2 levels could possibly lead to increasing soil carbon sequestration (Paustian et al., 2016). Another factor related to carbon stocks is land use change (Foley et al., 2005), with links between land use/management and soil carbon described elsewhere (Mchunu and Chaplot, 2012). This paper will not focus on these factors.

Soil carbon loss is facilitated through physical soil disturbance, which leads to a breakdown of soil aggregates. This allows increased exposure of SOM to direct solar radiation, which accelerates the breaking down of chemical bonds, and thus oxidation, of SOM (so-called stage-1 carbon loss from soil aggregates). This, in turn, predisposes soil to additional stage-2 carbon losses during surface runoff and erosion processes (Shaxson, 2006). Through these processes, carbon also might be displaced and deposited elsewhere (Mutema et al., 2017).

Management for the conservation and even increase of soil carbon is possible and is recommended as a mitigating factor for climate change (Paustian, 2016; Minasny et al., 2017). A correlation between higher topsoil carbon content with conservation measures (Jantke et al., 2016), as well as conservation agricultural practices (Hobbs et al., 2008) has been found. Adding biomass to the soil regularly (e.g. in the form of crop residues and/or mulch) creates positive feedback by maintaining soil organic content (Shaxson, 2006). Soil productivity is then created by the interaction of physical, biological, chemical and hydric constituents. Protecting soil surfaces and the soil integrity is thus required to maintain soil productivity. In many developing as well as developed countries, soil productivity has been reducing over time (Shaxson, 2006). SOM content can be influenced by management over time, while soil texture is a more static soil characteristic (Ankenbauer and Loheide, 2017).

3.2.3 Soil Carbon in South Africa

SOC in SA is low overall and is highly varied spatially (du Preez et al., 2011a). SOC has been reducing in many locations in SA over time (Dominy et al., 2001; du Preez et al., 2011a;b; Department of Environmental Affairs, 2017) and drivers have been identified as rangeland degradation (du Preez et al., 2011a), crop agriculture (Dominy et al., 2001; du Preez et al., 2011b), urban expansion and mining (Department of Environmental Affairs, 2017. Recommendations were that the prevention of land transformation was a priority if soil carbon was to be maintained, especially transformation from mature vegetation to annual crop agriculture (Department of Environmental Affairs, 2017). However, with an increase in population, the reality is that land transformation from natural vegetation is continuing in many places within the country (Hoffman, 2014; Jewitt et al., 2015). Increasing soil carbon can be a win-win situation and be both a climate change mitigation and adaptation strategy, thereby increasing resilience to climate change in SA (Department of Environmental Affairs, 2017). In SA, a positive correlation between rainfall and SOC has been found (Stronkhorst and Venter, 2008; Department of Environmental Affairs, 2017). SOC content in SA on a national scale has been estimated with varying details and methodologies used (Stronkhorst and Venter, 2008; Department of Environmental Affairs, 2015; Knowles et al., 2015; Department of Environmental Affairs, 2017; Schütte et al., 2019), which, in turn, can be used as input for further studies. Soil carbon also impacts on hydrological properties, and the interlinkages between soil carbon concentrations and hydrology will be explored in the next section.

3.3 Literature review: Interlinkages between soil carbon concentrations and hydrology

There are numerous links between the hydrological and the carbon cycle (Falkowski et al., 2000; Lal, 2004a, b; Mu and Zhao, 2011). Hydrological processes affect the carbon cycle, with examples including water erosion processes, which shift the spatial distribution of soil carbon, while carbon might also be exported via waterways elsewhere or even out to sea (Mutema et al., 2017). Other factors can also influence the carbon and/or water cycles. These include climate change, land use change and the earth's radiation balance through changes in albedo, the leaf area index, the Bowen ratio and the physiological capacity for carbon assimilation and to evaporate water (Betts et al., 1996). This review focusses on the links between soil carbon and hydrological processes.

3.3.1 Soil carbon and soil water properties: Water content, retention, infiltrability

Several studies have found a correlation of soil carbon content with soil water properties (Kay et al., 1997; Rawls et al., 2003; Lal, 2004a; Olness and Archer, 2005; Saxton and Rawls, 2006; Resurreccion et al., 2011; da Costa et al., 2017; Ankenbauer and Loheide, 2017). SOC levels are generally positively associated with soil porosity (e.g. Rawls et al., 2004; Xu et al., 2019) as well as with hydraulic conductivity (Rawls et al., 2004) and generally negatively associated with bulk density (Rawls et al., 2004).

Positive correlation with water retention and/or selected water potentials

Rawls et al. (2003) summarise twelve studies published between 1961 and 1995, with ten out of twelve finding a positive correlation of SOC with either water retention and/or water potentials at -33 kPa (i.e. the drained upper limit) and/or at -1500 kPa (PWP) water suctions. Later studies also show a positive correlation of SOC to water retention and water availability in different soil texture classes and lithologies in Brazil (da Costa et al., 2017). A significant greater long-term improvement of mean weekly water infiltration was found in no-till vs conventional tillage management on two soils under long term management and this was attributed to the increased SOC content (Franzluebbers, 2002). Ankenbauer and Loheide (2017) found a substantial positive correlation of SOC with soil water storage, particularly at the saturated soil water content, in their study area of a wet meadow ecosystem in Canada. Their results suggested that a loss of SOM decreased the reduction of the air entry pressure. This decreased the amount of moisture lost with incrementally increasing suction. This suggests gains or losses of SOM substantially affecting the soil water volume that could be retained and stored (Ankenbauer and Loheide, 2017). There are, however, some exceptions to this positive correlation.

Negative correlations

In fine-textured soil (high in clay content), adding organic carbon initially might show a reduction in water retention, before increasing with higher soil carbon levels (Kay et al., 1997; Rawls et al., 2003). This could, in some cases, be a result of a decrease in bulk densities and of measuring volumetric instead of gravimetric water content (Rawls et al., 2003).

No correlation

A few studies have found no change in soil water properties with regards to SOC. Lal (1978) and Danalatos et al. (1994), for example, did not find any effect of SOC on water retention. They attributed this to the generally low SOM content in their samples. Shaxson (2006), in a limited study in Lesotho, explained the lack in a change in soil water properties to missing soil biological activity which resulted in no decomposition of organic matter.

3.3.2 Soil carbon and soil texture

Most authors agree that in addition to soil texture, mineral content and management, it is also soil organic matter that affects water retention and availability (da Costa et al., 2017). Thus, while soil texture is generally a very important factor in water retention, organic carbon also has an impact (Ankenbauer and Loheide, 2017). A plausible hypothesis is that the effect of soil carbon on water retention depends on the proportions of textural soil components sand, clay and silt (Rawls et al., 2003; Saxton and Rawls, 2006). The importance of SOM in estimating water retention is thus affected by textural composition (Rawls et al., 2003), with this affect being of higher importance in coarse-textured soil than in fine-textured soil (Rawls et al., 2003; Saxton and Rawls, 2006; Ankenbauer and Loheide, 2017). Saxton and Rawls (2006) also found that water content at high tensions (when the soil was drier, approaching permanent wilting point) depended mainly on texture and less on aggregation and SOM. At higher water contents, however, the SOM effects were found to vary with soil texture, in particular with clay content, and the SOM effects were found to be similar to those of clay (Saxton and Rawls, 2006).

They concluded that SOM was a primary driver of variability in soil water retention characteristics, especially where clay content was low and where soil textures were relatively similar. SOM increments generally showed either no, or less, effect on the soil water content in fine-textured soil, or in soil already high in SOM (Ankenbauer and Loheide, 2017).

3.3.3 Soil carbon and plant available water

The increased soil water retention resulting from SOM retained and built-up by good soil husbandry provides benefits to plants, in addition to increasing total water holding capacity and this should, therefore, improve soil productivity (Lal, 2004a, b; Shaxson, 2006). Ankenbauer and Loheide (2017) found a substantial positive correlation of plant available water with soil organic content in their study area of a wet meadow ecosystem in Canada. Changes in soil water retention with SOM additions affect the duration and timing of plant water availability, factors which are especially valuable in current low carbon soil (Ankenbauer and Loheide, 2017). Olness and Archer (2005) found that a 1% increase in soil organic carbon resulted in a 2 to >5% increase in plant available water content, depending on the soil texture, using the US National Soil Inventory Database with more than 100 000 entries. While soil with finer particles retain more water, this does not necessarily translate into more water available to plants, with PAW having been found to increase with SOC content (da Costa et al., 2017).

3.3.4 Soil carbon and plant growth

Soil water is a key control of soil productivity and thus of plant growth and plant productivity (Shaxson, 2006). Increased SOC has been found to lead to an increase in plant transpiration (Ankenbauer and Loheide, 2017) and water stress-free days. This then leads to an increase in plant productivity and a reduction in (short-term) impacts of dry spells (Lal, 2004b; Shaxson, 2006; Ankenbauer and Loheide, 2017), leading to increases in crop yields.

3.3.5 Soil carbon water adsorption mechanism

The mechanism by which SOM influences water retention is not yet fully understood. While the SOM itself has a water retention effect, it is thought to also modify the water absorption sites in clay (Cristensen, 1996). SOM content is thought to affect soil structure and adsorption properties (Rawls et al., 2003), as well as soil aggregation and associated pore space distribution (Hudson, 1994). Alterations in the SOM contents with the same particle sizes are thought to modify the water retention capacity at low suctions (e.g. DUL) more than at higher suctions (e.g. PWP; Hudson, 1994). SOM affects the specific soil surface area, as well as the quantity of water that is absorbed by chemical bonds (Resurreccion et al., 2011).

3.3.6 Soil carbon and pedo-transfer functions

If all else were to remain the same, then the impact of SOC on soil water content should be quantifiable (Ankenbauer and Loheide, 2017). Quantifications of the relationship between SOC content and soil water retention have been reported by some authors as part of pedo-transfer functions. Pedo-transfer functions, i.e. the empirical relationships between parameters of soil models and more readily obtainable data on soil properties, were recently reviewed by Pachepsky et al. (2015) and Van Looy et al. (2017). There might be transferability issues when equations established from data in one country are transferred to another area (Nemes et al., 2009; Pachepsky et al., 2015), and ideally equations should be developed for the area and climate in question. However, pedo-transfer functions are an indispensable tool in large scale, data-poor environments (Pachepsky et al., 2015).

In this paper, we want to highlight pedo-transfer functions that included soil carbon concentrations in equations. Rawls et al. (2003) developed equations for water retention (by Volume, and expressed as a %) at 33 kPa (drained upper limit) and 1500 kPa (permanent wilting point) which included organic carbon content, sand, clay and silt content and taxonomical order, based on US soil databases, where measured texture, sand, silt and clay content, as well as water retentions were available. They used regression trees and group method data handling techniques to develop the equations. Predictive-to-observed fit of the equations on DUL and PWP were improved when soil carbon content was included as a variable in addition to clay and sand content (Rawls et al., 2003). While Rawls et al. (2003) published equations for the drained upper limit and wilting point which included SOC in 2003, soil porosity equations (soil water content at saturation) were published a year later in Rawls et al. (2004), which also again included the 2003 equations. Saxton and Rawls (2006) developed new equations, which faced some criticism as they were derived from a much less homogeneous database collected from reports and publications (Pachepsky, 2018, written pers. com), and some apparent errors from the underlying data were found by Nemes et al. (2009), where it appears that the organic matter component in the equation should have been replaced with organic carbon. It appears that the 2003 equations are preferable to use, compared to the 2006 equations (Pachepsky, 2018, written pers. com). Rawls et al. (2003; 2004) and Saxton and Rawls (2006) used a large soil dataset to attempt to quantify relationships between soil texture, SOM and soil hydraulic properties. Other pedo-transfer functions were developed to predict the SOC impacts on tropical soil in Brazil (Tomasella et al., 2000), while in two smaller studies in Canada one had limited variations in soil texture and other properties for a study area of a wet meadow ecosystem (Ankenbauer and Loheide, 2017), and in the other the topsoil consisted of coarse- and medium-textured calcareous illitic soil (Kay et al., 1997) and was thus limited as well.

3.3.7 Soil carbon and streamflow, stormflows and flooding

Soil carbon can affect stormflows, accumulated streamflows and, indirectly, flooding. Stormflows and erosion rates can be reduced by the surface cover and an increase in soil porosity, both influenced by input and output of organic material to the soil (Ankenbauer and Loheide, 2017). Improved water holding capacity can steady streamflows as well as reduce high return period extreme events (flooding), thereby increasing the soil resilience to erosion (Shaxson, 2006). No studies were found, however, that aimed at directly quantifying soil carbon impact on runoff, streamflows and flooding and this seems to be a knowledge gap.

3.3.8 Summary

In summary, soil carbon content, via soil water properties, links to hydrological responses as well as to plant productivity. The impacts depend, inter alia, on soil texture, as well as the initial SOC content, with organic matter additions being especially valuable in soil with lower carbon contents (Ankenbauer and Loheide, 2017), for example of less than 1%. SOC influences the soil drained upper limit and hence its plant available water, and thus by implication the plant's water use (transpiration), and it can reduce the impacts of dry spells on plant growth in the short term. Increased soil organic carbon (and soil surface cover) is postulated to lead to increased infiltration which, in turn, reduces runoff and its stormflow component and associated soil erosion, as well as steadying streamflows and reducing the effects of more extreme events such as high return extreme events often leading to flooding (Shaxson, 2006), thereby potentially increasing adaptation to climate extremes. A reduction in SOC concentrations, conversely, mainly through agricultural practices, can reduce soil water storage, thereby having the reverse effect.

3.4 Conclusion

Soil carbon concentrations affect soil water content and soil water retention and by implication, therefore, hydrological responses, thus linking the carbon and the hydrological cycles. These impacts differ depending on soil type, soil texture, SOC concentrations and climate. To the best of our knowledge, changes in carbon concentrations have not yet been included when modelling soil water and hydrological responses in SA. Pedo-transfer functions including SOC in addition to textural soil components can be used to calculate changes to DUL, WP and PAW. In the absence of suitable South African pedo-transfer functions that include SOC, the equations by Rawls et al. (2003) (see Section 4.3), might be suitable to calculate these variables for selected areas, which, in turn, can be used as input into hydrological models, such as ACRU, to simulate impacts of changes in soil carbon for South African conditions. With this in mind, research has been undertaken to quantify soil carbon impacts on soil water properties and hydrological responses in selected catchments in SA representing different climatic zones (see Chapter 4). More research is, however, recommended on the update of South African soil property databases, incorporating the new DUL, WP and PAW values. Furthermore, a better understanding of soil carbon water adsorption mechanisms would be beneficial to the research community in order to better understand SOM impacts on soil water holding capacity.

4. A SENSITIVITY STUDY OF IMPACTS OF SOIL CARBON ON HYDROLOGICAL RESPONSES

Journal article under review:

Impacts of Soil Carbon on Hydrological Processes and Responses – A Sensitivity Study across Diverse Climatic Zones in South Africa

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Keywords

Soil carbon, impact on hydrology, soil water holding capacity, South Africa

Abstract

Soil organic carbon (SOC) content and soil water holding capacities are a link between the carbon and hydrological cycle. A quantification of sensitivities of hydrological responses such as transpiration, runoff volumes, the stormflow component of runoff and extreme runoff events to SOC content under various climatic conditions in South Africa (SA) was undertaken. The soil water holding capacities of the drained upper limit (i.e. field capacity), permanent wilting point and saturation were calculated using SOC dependent pedo-transfer functions for different soil carbon scenarios and locations in SA. These variables, together with other pre-determined soil-, and location-related inputs, as well as 50 years of daily climate, were then used in a process-based hydrological model. Overall, it was found that increased SOC content in the topsoil horizon leads to an increase in transpiration, a reduction in runoff, especially in its stormflow component and to a reduction of extreme runoff events. The magnitude of these changes depends on other climate-, soil- or location-specific factors.

Total simulated transpiration was found to be increasing at most of the locations, with an absolute increase of up to 14 mm and a relative increase of up to 9% for a change in SOC from

1% to 4%. Transpiration increased more from the topsoil horizon, with a slight reduction in the subsoil horizon. The reason for the latter is hypothesized to be that more water is held in the topsoil horizon with higher SOC contents, with less draining to the subsoil horizon.

Small to significant reductions in stormflows were found, but this depends on the area and the climatic year. Changes from 1% to 4% SOC for a 1:10 wet year showed an absolute reduction of up to 24 mm and a relative reduction of up to a 27%. Reductions in extreme runoff events were found in most areas, but also with different magnitudes. Increases in soil carbon, for example from 1% SOC to 2% or 4% SOC should thus help to reduce some flood damage, thereby providing an important ecosystem service.

4.1 Introduction

Soil carbon content, together with other soil physical properties and especially soil texture, affect soil water holding capacities, and thereby influence the outputs of the hydrological cycle. An attempt was made to quantify sensitivities of hydrological responses such as transpiration, total runoff, its stormflow component, and extreme events to changes in soil organic carbon content at a number of diverse locations within South Africa. Relevant hydrological soil variables of soil water content at 'drained upper limit' (or field capacity, DUL), 'permanent wilting point' (WP) and 'porosity' (PO), *i.e.* at saturation, are calculated using pedo-transfer functions with various amounts of carbon representing different soil carbon scenarios. Several South African databases, one which includes soil sample data, one of area-based soils terrain units and one which includes catchments, climate, soil and hydrological inputs were used. The point values of DUL, WP, PO values calculated from the soil sample database were transformed into sub-catchment level values. These soil carbon scenarios were then used as inputs to a process-based hydrological model at sub-catchment resolution. Differences in hydrological responses between the scenarios were assessed for a number of climatically diverse areas within SA ranging from desert to sub-tropical climates.

4.2 Background Information

Soil carbon content impacts on the soil's water holding capacity, *i.e.* the volume of water that can be stored by the soil. The impact, however, depends on the type of soil, especially on soil's texture, on soil carbon content and on the amount of water in the soil at a given point in time (Rawls et al., 2003, 2004; Ankenbauer and Loheide, 2017). Pedo-transfer functions have been developed that use soil texture components (clay, sand and sometimes silt content) as well as soil organic carbon (SOC) as inputs to calculate the soil's water holding volumes at a suction of 33 kPa and 1500 kPa (Rawls et al., 2003). These suctions are indicators of that particular soil's drained upper limit (DUL) and permanent wilting point (WP), respectively. DUL (also termed field capacity) reflects the amount of water in the soil after the soil has drained any excess water. WP indicates the amount of water in the soil when the soil is so dry that any remaining water is not available to plants any longer. Plant available water (PAW) is the water held between DUL and WP (Bauer, 1974). Soil water content indicates the amount of water present in the soil at a given point in time, with the maximum soil water content being at saturation, which equals the soil's porosity (PO). It is assumed that the water holding volumes at a suction of 33 kPa and 1500 kPa are equivalent to the hydrological variables of DUL and WP. These variables are inputs into process-based hydrological models commonly used in South Africa.

To determine the sensitivity of the variables described above to changes in SOC, a range of carbon contents can be used to re-calculate values of the variables DUL, WP and PO. These variables, in turn, can then be used as inputs into a suitable model, e.g. the daily time-step and process-based ACRU Model (See Section 4.3.2; Schulze, 1995 and updates; Smithers and Schulze, 2004), to simulate impacts of changes in SOC on hydrological responses. Of interest here are transpiration, i.e. water use through plants (Schulze and Maharaj, 2008), the response of runoff, defined here as made up of rapid response stormflows from the surface or near the surface, and slower response interflows and baseflows, all feeding rivers as streamflow. Also of interest will be statistical design runoff magnitudes. Increased SOC was found by some authors to increase transpiration (Ankenbauer and Loheide, 2017) and by inference to decrease runoff and stormflows (Shaxson, 2006).

4.3 Methodology

An outline of the methodology is given and shown in in Figure 4-1, before the individual steps are explained in more detail. To be able to obtain sensitivities of hydrological responses to SOC concentrations, soil carbon scenarios are defined first, followed by the calculations of various DUL, WP and PO values in relation to the carbon scenarios. These values are, in turn, used as input variables into a hydrological model, while the other model inputs are kept constant for all carbon scenarios. The ACRU modelling system used is described briefly. Selected model output analyses are then described.

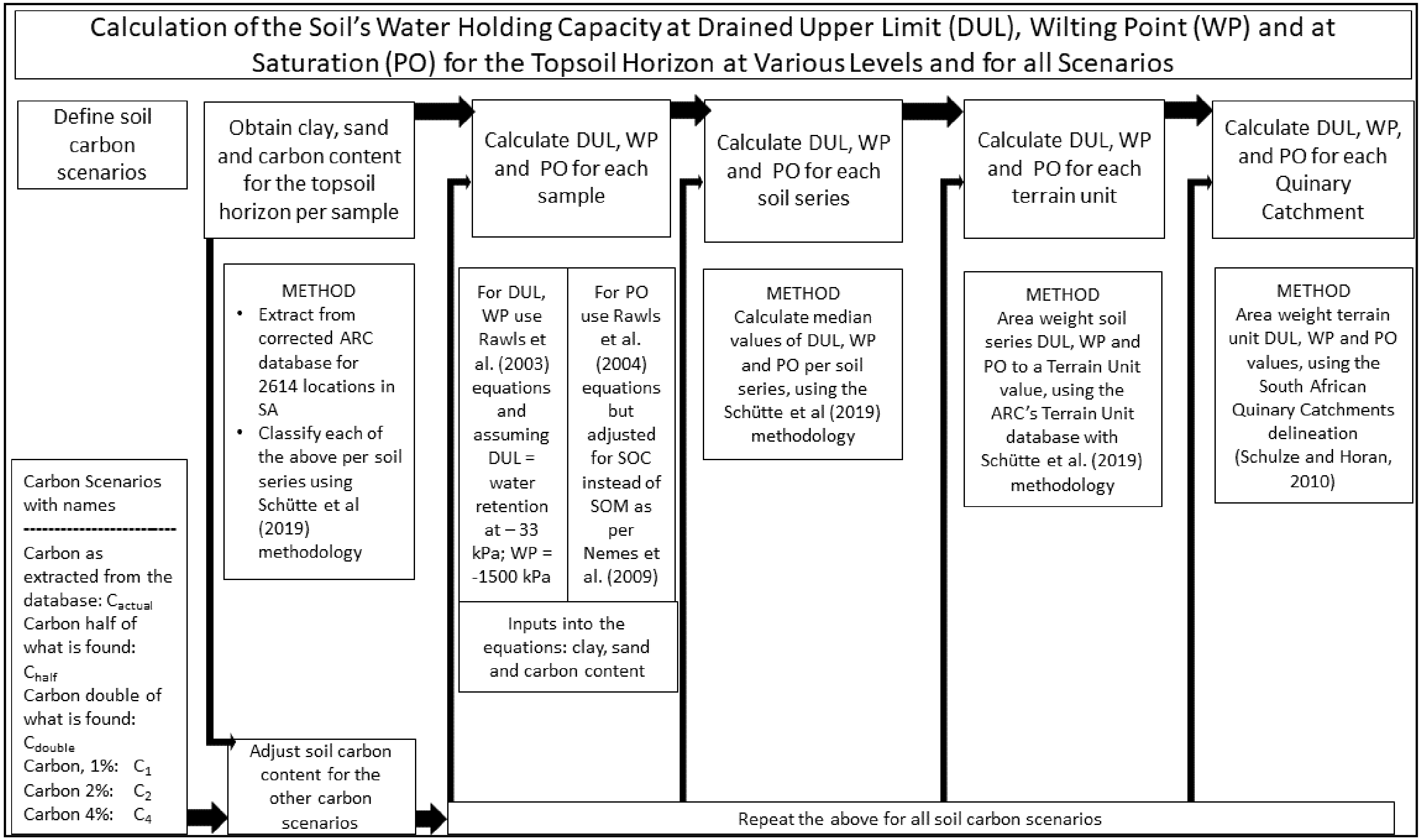

Figure 4-1 Schematic of the workflow to obtain values for the soil water content at drained upper limit (DUL), wilting point (WP) and porosity (PO) for the carbon values obtained and the different carbon scenarios, for the topsoil horizon

4.3.1 Detailed methodology

The methodology is now explained in more detail. First, the scenarios with varying carbon content are defined. The scenarios are the actual SOC contents in the topsoil, as derived from the soil carbon database (Schütte et al., 2019) used in this study and this will be explained later. To be able to calculate sensitivities to changes in SOC content, hypothetical doubling and halving of the actual SOC amount is undertaken, with the carbon scenarios being termed 'C_{actual}', 'C_{double}' 'C_{half}'. In addition, assumptions of hypothetical carbon contents of 1%, 2% and 4% are made, with the carbon scenarios being termed 'C_1' 'C_2' and 'C_4'.

The soil-dependent hydrological soil water variables of DUL, WP and PO were described earlier. These values need to be calculated and an outline of the methodology is given in Figure 4-1. First, soil textural contents of clay and sand, as well as SOC, including soil series and land use, were obtained from the Agricultural Research Council's (ARC's) Soil Profile Database (ARC-ISCW, undated), where soil samples at various depth were taken at more than 11 000 locations within South Africa. The database was first checked and any errors corrected to ensure the textural components of sand, silt and clay make up 100%. As only the topsoil horizon is likely to have substantial changes in SOC, only these values were investigated further, with the uppermost horizon, starting at 0 mm depth being defined as the topsoil horizon. Samples that were marked as being from agriculturally related land uses were excluded in order to try and eliminate impacts of land management. More detail on this part of the methodology can be found in Schütte et al. (2019).

Using the values of clay, sand and SOC content that were obtained from the Soil Profile Database, new DUL and WP values for the topsoil horizon were calculated assuming them to be equal to water retentions at -33 kPa and -1500 kPa (Rawls et al., 2003, 2004); respectively. This was done for each of the > 11 000 sample locations and for each carbon scenario.

Relevant pedo-transfer functions used were from Rawls et al. (2003), to estimate water retention at -33 kPa (θ_{33}) and -1500 kPa (θ_{1500}), and these are shown in Equations 1 and 2.

$$\theta_{33} = 29.7528 + 10.3544\,(0.0461615 + 0.290955x - 0.0496845x^2 + 0.00704802x^3 + 0.269101y - 0.176528xy + 0.0543138x^2y + 0.1982y^2 - 0.060699y^3 - 0.320249z - 0.0111693x^2z + 0.14104yz + 0.0657345xyz - 0.102026y^2z - 0.04012z^2 + 0.160838xz^2 - 0.121392yz^2 - 0.0616676z^3) \qquad \text{Equation 1}$$

$$\theta_{1500} = 14.2568 + 7.36318(0.06865 + 0.108713x - 0.0157225x^2 + 0.00102805x^3 + 0.886569y - 0.223581xy + 0.0126379x^2y - 0.017059y^2 + 0.0135266xy^2 - 0.0334434y^3 - 0.0535182z - 0.0354271xz - 0.00261313x^2z - 0.154563yz - 0.0160219xyz - 0.0400606y^2z - 0.104875z^2 + 0.0159857xz^2 - 0.0671656yz^2 - 0.0260699z^3)$$

Equation 2

with θ_{33} being water retention at -33 kPa, θ_{1500} being water retention at -1500 kPa, both in Vol% in the equations. $x = -0.837531 + 0.430183$ SOC(%); $y = -1.40744 + 0.0661969$ Clay (%); $z = -1.51866 + 0.0393284$Sand; in each case with the following limits: $0.02 <$ SOC(%) < 28.44; $0.0 <$ Clay% < 90; and $0.70 <$ Sand% < 95.

PO values for each location were calculated using the same inputs of clay, sand and SOC, but using the SOM equations to estimate soil porosity given by Rawls et al. (2004), but corrected as per Nemes et al. (2009) to read SOC as the soil carbon input instead of soil organic matter (SOM), shown in Equations 3 to 5.

In these equations

$\varphi = 1 - (\rho_b/\rho_p)$ Equation 3

where the soil porosity (φ) is the ratio of voids to the total volume of sample (cm^3/cm^3), ρ_p the particle density (typically = 2.65 g/cm^3), ρ_b the soil bulk density (g/cm^3), with the equation for bulk density (ρ_b) shown in Equation 4, also using Equation 5.

$$\rho_b = 1.36411 + 0.185628(0.0845397 + 0.701658w - 0.614038w^2 - 1.18871w^3 + 0.0991862y - 0.301816wy - 0.153337w^2y - 0.0722421y^2 + 0.392736wy^2 + 0.0886315y^3 - 0.601301z + 0.651673wz - 1.37484w^2z + 0.298823yz - 0.192686wyz + 0.0815752y^2z - 0.0450214z^2 - 0.179529wz^2 - 0.0797412yz^2 + 0.00942183z^3)$$

Equation 4

where

$x = -1.2141 + 4.23123$ sand%; $y = -1.70126 + 7.55319$ clay%;

$z = -1.55601 + 0.507094$ SOC%; and

$$w = -0.0771892 + 0.256629x + 0.256704x^2 - 0.140911x^3 - 0.0237361y - 0.098737x^2y - 0.140381y^2 + 0.0287001y^3$$

Equation 5

Because the equation for soil porosity had recommended boundary values which would have excluded a large part of South African soils, which are generally low in carbon, a study was undertaken, using hypothetical amounts of clay and sand in order to be able to establish the sensitivity of PO to carbon content, to see how much would change if the equations were to be used below these recommended values (Figure 4-2). Because there are only small changes in PO between Carbon = 1% and 0%, compared to the much larger influence of sand and clay components, it was decided to use the formula without limiting SOC to > 1%.

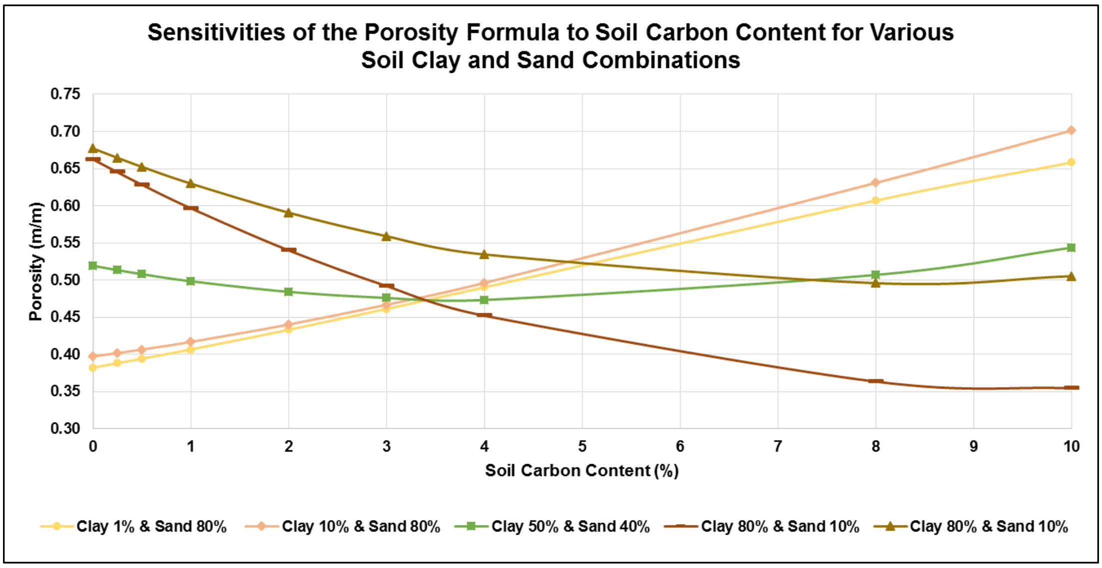

Figure 4-2 Sensitivities of the PO formula to soil carbon content, using various texture combinations of clay and sand content (%)

From these per-sample values, median DUL, WP and PO values were calculated. This was done for each of the 501 soil series identified in South Africa in the Binomial Soil Classification System (MacVicar et al., 1977), and for each carbon scenario. The calculation was either by direct median values of each sample with the same soil series in the data set or by lumping similar soil series and thus obtaining indirect median values. For more detail, the reader is referred to Schütte et al. (2019).

To be able to upscale from a point to an area, and preferably to the whole of South Africa, the ARC's Terrain Units Database (TU Database) was used. This database contains 27 491 spatially defined TUs, based on delineation with a 90 m Digital Elevation Model and refined by Beukes (Beukes, pers. comm., 2018), thereby enhancing existing surveys (ARC-ISCW, undated).

Each of over 6 000 previously surveyed and mapped soil land types (ARC-ISCW, undated), which had been the basic soil mapping unit in South Africa up until recently was sub-delineated into up to five terrain unit (TU) types made up of the crest, the scarp, midslope, footslope and the valley bottom, to give a total of 27 491 spatially defined TUs. Each TU consists of different soil series, of known proportions (Beukes, pers. comm., 2018, see also Schütte et al., 2019). By then area weighting each soil series within a TU, the DUL, WP and PO values were calculated for each TU for the actual carbon scenario, as well as for the hypothetical carbon scenarios described previously. The terrain unit values of DUL, WP, PO values were then area-weighted per Quinary (sub-) catchment, the latter is further explained below. While the per-terrain unit values would have been providing a finer scale of soil related inputs, climate and vegetation related inputs were not available on this fine scale for the hydrological modelling at this point in time.

For example, the calculated ACRU input variables changed as follows for a selected Quinary catchment (No. 4686), representing Cedara (see below) as a result of incorporating SOC of 1% and 4% into the equations for soil water content. For the topsoil horizon DUL increased from 0.301 m/m (C_1) to 0.335 m/m (C_4), WP increased from 0.179 m/m (C_1) to 0.181 m/m (C_4) and PO increased from 0.454 m/m to 0.496 m/m. Inputs for the subsoil horizon were not changed. Soil depth was also kept constant with no changes made for the different carbon scenarios. For Cedara the topsoil horizon was 0.24 m thick and the subsoil horizon was 0.47 m.

A schematic on the more detailed methodology of modelling impacts of soil carbon on hydrological responses is shown in Figure 4-3. To be able to model hydrological responses in Southern Africa, the Quinary Catchments Database (QCD, Schulze and Horan, 2010; Schulze et al., 2010) is often used, with South Africa, Lesotho and Eswatini (formerly known as Swaziland) delineated to 5 838 hydrological response units, the so-called Quinary catchments, which are hydrologically interlinked and with each containing a 50 year daily dataset of climate as well as location, natural vegetation and soil properties. This existing database is used here to model hydrological responses, but the DUL, WP and PO values of the topsoil horizon are replaced with the newly calculated or prescribed values.

By using this approach to model the various scenarios, per-scenario results of hydrological responses can be obtained on a Quinary catchment resolution, with the responses including transpiration, runoff, and its components of stormflow and baseflow, all for a statistically median year, for the 1:10 dry year, the 1:10 wet-year, as well as for design 1-day, 2-day and 3-day runoff events calculated for a range of return periods by volumes. All of these were explained previously in Section 4-2.

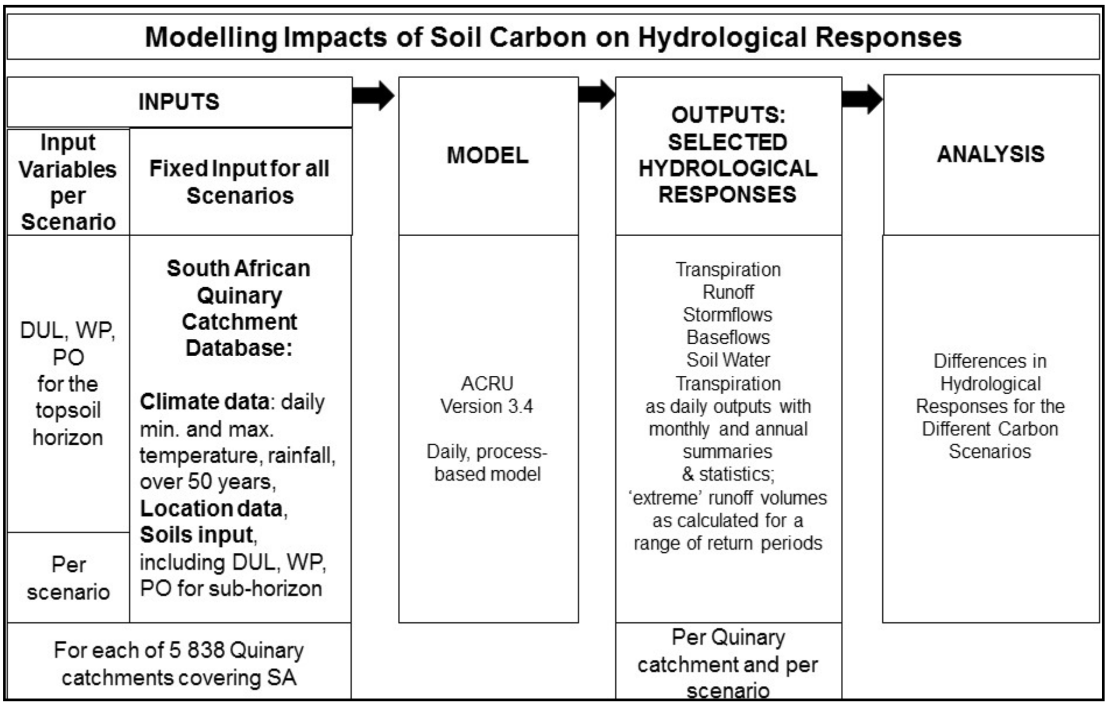

Figure 4-3 Schematic describing modelling impacts of soil carbon on hydrological responses

4.3.2 The ACRU Modelling System

Model Attributes

The ACRU agro-hydrological modelling system (Schulze, 1995 and updates), which has been, and is currently being, used extensively in water resources and climate change studies in southern Africa is centred around the following objectives and attributes (Figure 4-4):

- It is a daily time step, conceptual-physical model,
- with variables (rather than optimised parameters values) estimated from physically-based characteristics of the catchment, and
- with the model revolving around daily multi-layer soil water budgeting.
- As such, the model has been developed essentially into a versatile simulation model of the hydrological and related system (Figure 4-4), structured to be highly sensitive to climate drivers and to land cover, land use and management changes on the soil water and runoff regimes, and with its water budget being responsive to supplementary watering by irrigation, to changes in tillage practices, to enhanced atmospheric CO_2 concentrations associated with climate change, or to the onset and degree of plant stress, which may change with global warming.
- ACRU is a multi-purpose model which integrates the various water budgeting and runoff production components of the terrestrial hydrological system. It can be applied

as a versatile model for design hydrology (including flow routing through channels and dams), crop yield estimation, reservoir yield simulation, ecological requirements, wetlands hydrological responses, riparian zone processes, irrigation water demand and supply, water resources assessment, planning optimum water resource utilisation / allocation, conflict management in water resources and land use impacts - in each case with associated risk analyses - and all of which can respond differently with climate change.

- ACRU can operate at multiple scales as a point model or as a lumped small catchments model, on large catchments or at national scale as a distributed cell-type model with flows taking place from “exterior” through “interior” cells according to a predetermined scheme, with the facility to generate individually requested outputs at each sub-catchment’s exit.
- The model includes a dynamic input option to facilitate modelling of hydrological responses to climate or land use or management changes in a time series, be they long term / gradual changes (e.g. urbanisation or climate trends), or abrupt changes (e.g. construction of a dam), or changes of an intra-annual nature (e.g. crops with non-annual cycles).
- The ACRU model has been linked to the Southern African National Quaternary and Quinary Catchments Databases (Schulze and Horan, 2010) for applications at a range of scales in the RSA, Lesotho and Swaziland for climate change impacts and other studies.

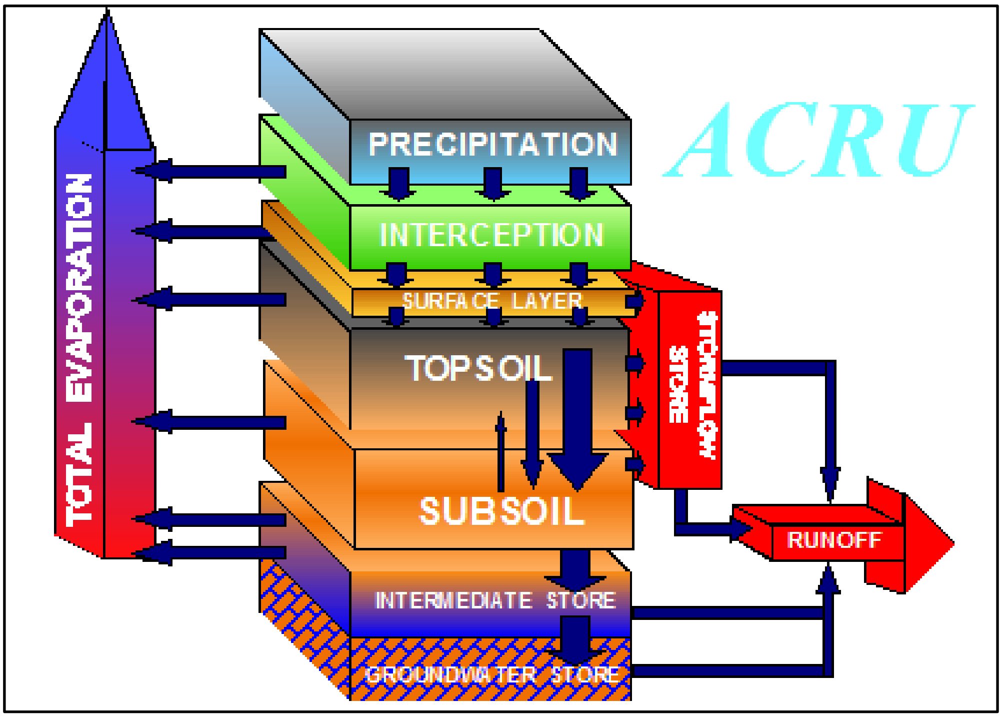

Figure 4-4 Schematic of major processes represented in the ACRU model (After Schulze, 1995)

General Structure of the ACRU Model

Multi-layer soil water budgeting by partitioning and redistribution of soil water is depicted in a highly simplified schematic in Figure 4-4. That rainfall and/or irrigation application that not abstracted as interception or converted to stormflow (either rapid response or delayed), first enters through the surface layer and "resides" in the topsoil horizon. When that is "filled" to beyond its drained upper limit (field capacity) the "excess" water percolates into the subsoil horizon as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness and other drainage related properties. Should the soil water content of the bottom subsoil horizon of the plant root zone exceed its drained upper limit, saturated vertical drainage/recharge into the intermediate and eventually the groundwater stores takes place, from which baseflow may be generated at an exponential decay rate dependent on geological / aquifer characteristics and the groundwater store.

Unsaturated soil water redistribution, both upwards and downwards, also occurs, but at a rate considerably slower than the water movement under saturated conditions, and is dependent, inter alia, on the relative wetnesses of adjacent soil horizons in the root zone. Evaporation takes place from water previously intercepted by the crop’s or vegetation’s canopy, as well as simultaneously from the various soil horizons, in which case it is either split into separate components of soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone), or combined, as total evaporation.

In the ACRU model, evapotranspiration is simulated on a day-by-day basis from four components, viz.

- transpiration from the topsoil horizon which depends, inter alia, on the day’s atmospheric demand, the vegetation’s water use (i.e. crop) coefficient, its active root fraction in that soil horizon and the soil water content of that horizon, which determines whether or not the crop/vegetation is stressed,
- transpiration from the subsoil horizon, which depends on the same factors, but with reference to the subsoil,
- evaporation from intercepted water by the plant after rainfall, and
- soil water evaporation from the topsoil, which will depend also on the surface material covering the topsoil horizon (Schulze, 2019).

Evaporative demand on the plant is estimated, inter alia, according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density within the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

Stormflow, Q, is defined as the water which is generated from a specific rainfall event, either at or near the surface in a catchment or sub-catchment, and which contributes to flows of streams within that catchment/sub-catchment. It is largely from stormflow events that, for example, reservoirs are filled and design runoffs for selected return periods are computed. Furthermore, the soil detachment process in the production of sediment yield from a catchment is highly correlated with the volume of stormflow from an event. Important statistics on stormflows include annual means, inter-annual variabilities, magnitudes in wet and dry years and the number of stormflow events per annum exceeding critical thresholds.

Stormflow is generated from both the impervious parts of the catchment connected directly to a stream (e.g. paved surfaces, roofs, permanently saturated areas directly adjacent to a stream and from the pervious portions of a catchment. The amount of the stormflow which is generated from the pervious areas (expressed either as a depth equivalent in mm, or as a volume in m^3) in essence depends on the magnitude of the rainfall event and how wet the catchment is just prior to the rainfall event. Not all stormflow generated from a rainfall event exits the catchment on the same day as the rainfall occurs, and the fraction that does depends on the size of the catchment, the catchment's slope and other factors (Schulze, 1995). This necessitates a stormflow response coefficient to be input, which controls the "lag" of stormflows and is effectively an index of interflow.

Baseflows consist of contributions to runoff from the intermediate / groundwater store which had been previously recharged. These contributions are made up of slow and delayed flows to the catchment's streams. In the ACRU model it is assumed that the groundwater store is always "connected" to the stream system. Unlike many other models which compute baseflow indirectly from total runoff hydrographs with an empirically derived "separation curve", ACRU computes baseflow explicitly from recharged soil water stored in the intermediate / groundwater zone (Schulze, 1995). The stored water is derived from rainfall of previous events which has been redistributed through the various soil horizons and has drained into the intermediate / groundwater store when the deepest soil horizon's water content exceeds its drained upper limit (field capacity). The rate of drainage of this "excess" water out of the deepest soil horizon into the groundwater store depends on that horizon's soil texture class, which is input to vary from catchment to catchment according to soil attributes. The rate of release of water from the groundwater store into the stream is determined by a release coefficient which is dependent inter alia on the geology, area and slope of the catchment and operates as a "decay" function which is input for a catchment as a single value, but is enhanced or decreased internally in ACRU, dependent on the magnitude of the previous day's groundwater store

In the ACRU model an estimate of the peak discharge associated with each day's stormflow volume generated for the selected simulation period can be made by assuming a single triangular unit hydrograph. For these simulations the significantly modified SCS peak discharge equation (USDA, 1972) is used (Schulze, 1995).

Model verfication and accuracies have been determined under different applications in different countries and are summerised in Schulze (2019). The ACRU model has been linked to historical daily climate databases for the 5 838 Quinary Catchments covering South Africa (Schulze et al., 2010).

4.3.3 Analyses

The analysis of hydrological responses shown here is focussed on seven strategic locations within South Africa, each represented by its respective Quinary catchment. These seven selected locations are considered to be representative of different climatic regimes and natural vegetation zones in South Africa and have been used as sample locations in previous studies (e.g. Schulze, 1995; Hughes, 2018). The selected locations, together with the natural vegetation types in these zones, are shown in Figure 4-5. In Table 4-1 the selected locations identifiers, elevations, Quinary catchment names and numbers, their dominant natural vegetation and soil types, as well as mean monthly rainfall and potential evaporation, and monthly means of daily maximum temperature for the 50 years of observed and/or infilled data (1950-1999; Lynch, 2004), is shown, with the Köppen Climate Zone (Schulze and Schütte, 2016) provided in the text.

Roodepoort is in Köppen Climate Zone Cwb (winters long, dry and cool) and has a mean annual precipitation (MAP) of 689 mm, falling mainly in the summer months (October to March). Mara is in Köppen Climate Zone of BSh (semi-arid, hot and dry) and has a low MAP of 375 mm. Upington is located in an area of very low MAP of 204 mm (Köppen Climate Zone BWh, arid, hot and dry). Elsenburg is in the winter rainfall region, with its highest rainfall in June and July, with a MAP of 796 mm and a Köppen Climate Zone of Csb (summers long, dry and cool). Outeniqua experiences rainfall throughout the year, but with slightly lower rainfall in the cool winter months, with a MAP of 985 mm and a Köppen Climate Zone of Cfb (wet all seasons, summers long and cool).

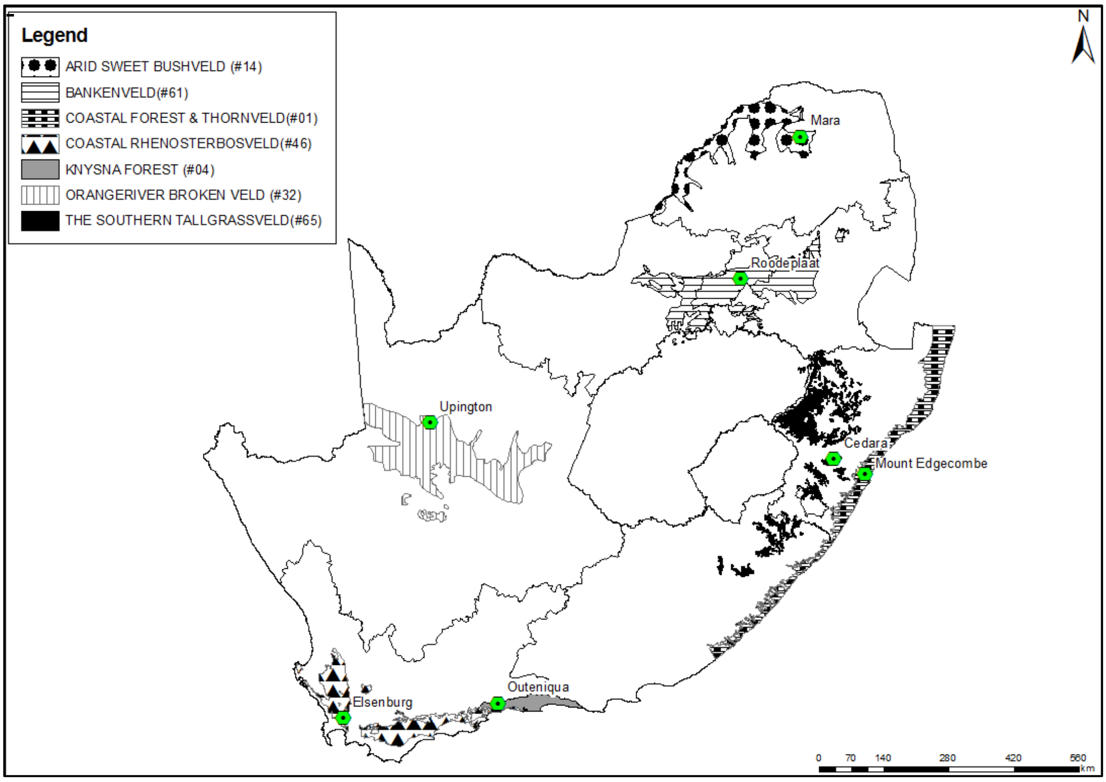

Figure 4-5 Locations of the seven hydroclimatic zones (selected after Schulze, 1995), with vegetation types according to Acocks (1988)

Cedara is in Köppen Climate Zone Cwb (winters long, dry and cool), with a MAP of 842 mm, mainly in the summer months. Mount Edgecombe has a MAP of 1068 mm and is in Köppen Climate Zone Cfa (wet all seasons, summers long and hot), but wetter in summer than in winter. The locations' mean annual rainfalls show wide ranges from 204-1068 mm and the annual mean temperature ranges from 19-29 °C. There is also a large elevation range from 83-1 542 m.

The ACRU Model (Schulze, 1995 and updates) was used first to simulate and explore the baseline hydrological characteristics of the seven hydroclimatic zones assuming naturally occurring vegetation types according to Acocks (1988). These simulations included volumes and monthly distributions of baseflow and stormflow (Schulze, 1995), and the model was then used to simulate the impacts of the various SOC scenarios.

Table 4-1 Selected stations, their locations and representative Quinary catchment and characteristics, monthly means of daily maximum temperature (˚C), monthly rainfall (mm) and of A-Pan equivalent evaporation totals (mm) for the period 1950-1999 for the seven hydro-climatic zones (Lynch, 2004; Schulze et al., 2010; Hughes, 2018)

Station; Quinary Name; Quinary Number	Latitude; Longitude Elevation (masl)	Acocks (1988) Vegetation Type, Dominant Soil Texture	Monthly Mean of Climatic Variable (˚C or mm)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Mount Edgecombe U20M3 Quinary 4707	29˚42’S	Coastal Forest and Thornveld (#01)	Daily Maximum Temperature	24	25	26	27	27	27	25	24	23	22	23	23	25
	31˚02’E		Rainfall	96	96	118	124	117	102	61	38	17	22	38	61	888
	82.9	Loam	A-Pan Evaporation	92	99	127	111	97	100	81	73	63	66	76	82	1,068
Mara A71D3 Quinary 327	23˚09’S	Arid Sweet Bushveld	Daily Maximum Temperature	28	28	29	29	28	27	26	24	22	22	24	26	26
	29˚33’E	(#14)	Rainfall	25	57	78	76	55	34	24	8	4	1	3	9	375
	918.8	Loamy Sand	A-Pan Evaporation	138	142	151	145	127	130	109	97	84	85	103	122	1,433
Upington D73E3 Quinary 2025	28˚27’S	Orange River	Daily Maximum Temperature	29	32	35	35	35	32	28	24	21	21	23	27	29
	21˚25’E	Brokenveld (#32)	Rainfall	12	18	21	28	34	41	26	12	4	3	4	3	204
	851.6	Loamy Sand	A-Pan Evaporation	165	189	216	213	177	162	116	91	73	79	101	135	1,716
Elsenburg G22G3 Quinary 2700	33˚51’S	Coastal Rhenoster-	Daily Maximum Temperature	22	25	27	28	29	27	24	20	18	17	17	19	23
	18˚50’E	bosveld (#46)	Rainfall	49	39	25	17	21	29	81	113	133	116	105	66	796
	181.4	Loam	A-Pan Evaporation	117	145	168	169	142	124	85	60	46	47	61	82	1,246
Outeniqua K30B1 Quinary 3307	33˚55’S	Knysna Forest	Daily Maximum Temperature	18	19	20	21	21	21	20	18	17	16	16	16	19
	22˚28'E	(#04)	Rainfall	109	94	86	91	91	101	80	66	51	50	84	82	985
	965.5	Loam	A-Pan Evaporation	82	93	103	97	79	80	62	50	43	45	53	64	850
Cedara U20E1 Quinary 4686	29˚31’S	Natal Mist Belt Ngongoni	Daily Maximum Temperature	22	23	25	25	25	25	23	21	19	19	20	22	22
	30˚17’E	Veld (#45)	Rainfall	84	107	131	136	109	101	48	25	12	14	30	45	842
	1101.5	Loam	A-Pan Evaporation	109	117	148	130	112	111	87	72	61	66	82	97	1,189
Roodeplaat A21A3 Quinary 12	25˚55’S	Bankenveld	Daily Maximum Temperature	26	26	26	27	27	25	23	21	18	18	21	24	24
	28˚21’E	(#61)	Rainfall	74	111	111	126	82	86	45	15	5	4	5	26	689
	1541.7	Loam	A-Pan Evaporation	135	140	147	150	126	123	95	80	65	71	91	116	1,338

4.4 Results

The results of the model runs are shown next.

4.4.1 Impact of SOC on hydrological responses for a selected location

The first result is for a daily time slice of five months is shown for one selected Quinary catchment (No. 4686), representing Cedara for the carbon scenarios of 1% and 4% SOC.

The runoff results are presented in Figure 4-6, with runoff events, as expected, being highly dependent on the magnitudes of rainfall events, which are also shown in the figure. The C_4 scenario showed reduced daily peaks compared to the C_1 scenario for this period and area. The interpretation would be that a higher SOC percentage (here 4% versus 1%) reduces the peak flows.

Impacts of the same two SOC scenarios on accumulated transpiration from the topsoil and subsoil horizons, as well as on runoff and its components of stormflow and baseflow, are shown for the same Quinary catchment, namely that representing Cedara, for a period of one year (Figure 4-7). With a change in the soil carbon scenario from 1% to 4%, transpiration from the topsoil horizon for this area and period show an increase of 14 mm (5%) for the year from 279 to 293 mm, with transpiration from the subsoil horizon showing a decrease of 8 mm (11%) from 66 to 58 mm, implying that overall the transpiration increased by 6 mm (2%) from 345 to 351 mm. Runoff decreased by 17 mm (13%) from 125 to 109 mm. The stormflow component of runoff was reduced by 11 mm (11%) from 106 to 95 mm, and the baseflow was also reduced by 5 mm (26%) from 19 to 14 mm. The interpretation is that in this example shifts from runoff (in mm equivalent), and especially from the stormflow component, towards transpiration are seen.

Transpiration is thus increasing overall, and more from the topsoil horizon, with a slight reduction for the subsoil horizon. It is hypothesized that this is so because more water is stored in the topsoil horizon, with less draining to the subsoil horizon. The reason for this could be because the infiltration rates were not changed in the model runs. Increased SOC has, however, been shown in trials by Franzluebbers (2002) to increase the infiltration rate. The runoff showed an expected reduction, mainly from the stormflows, but also from the baseflows. Again, if the infiltration rates were to be increased for higher carbon in the model, then baseflows could be unchanged or even increase.

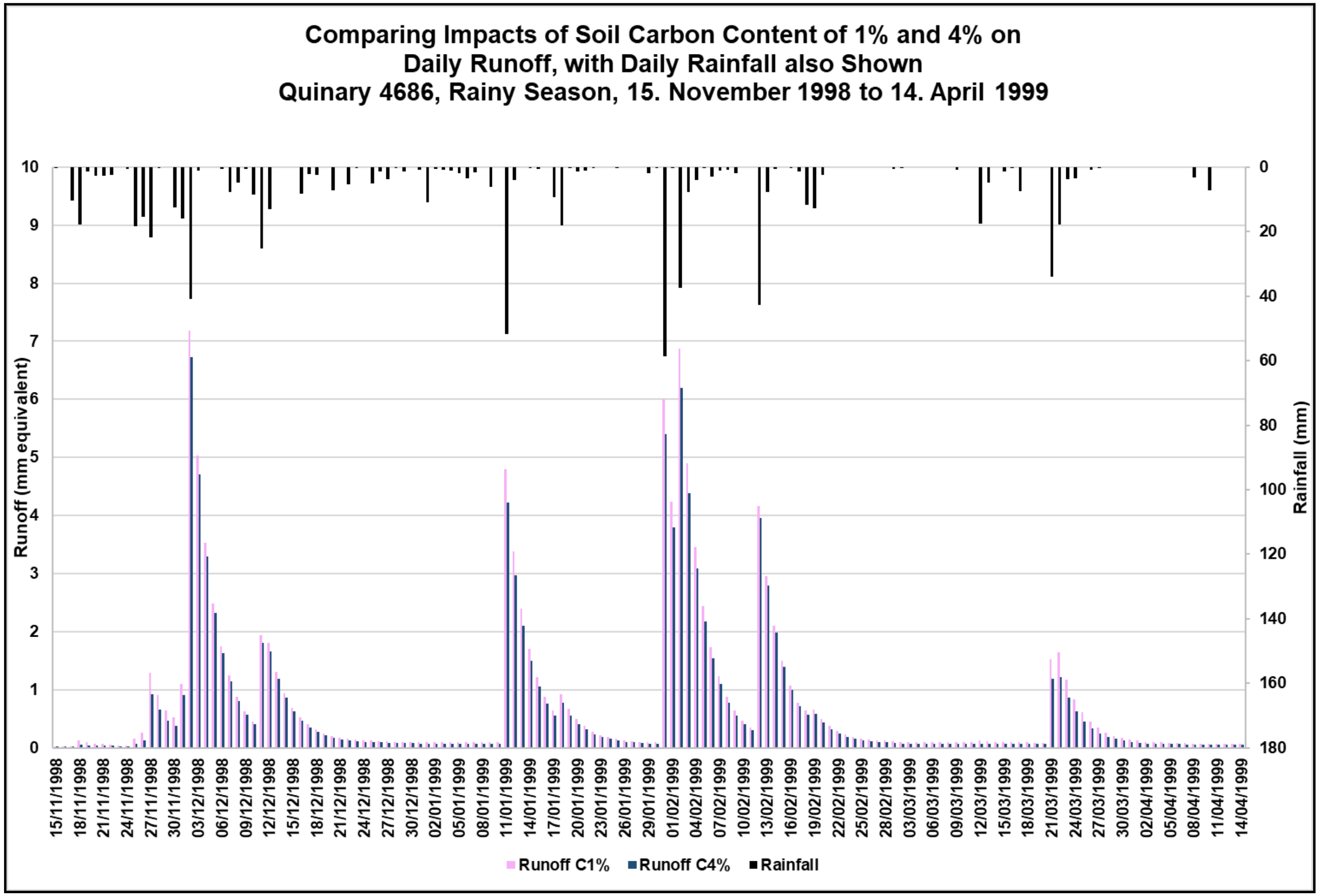

Figure 4-6 Simulated daily runoff for SOC of 1% (light pink) and 4% (dark blue), for the Quinary catchment representing Cedara during a 3.5-month time period during the rainy season, with daily rainfall shown on the secondary axis

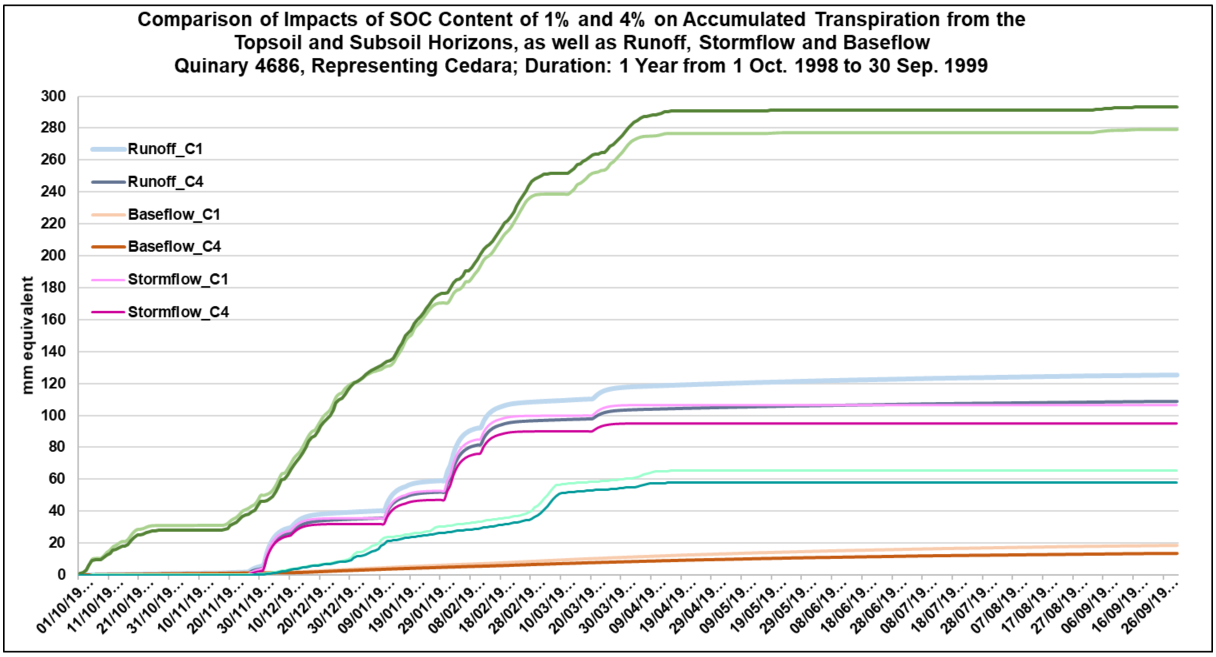

Figure 4-7 Daily accumulated transpiration from the top- and subsoil horizons, as well as runoff, stormflow and baseflow (all in mm) for a one-year period, using Quinary Catchment 4686 representing Köppen Climate Zone Cwb at Cedara

4.4.2 Impact of SOC on hydrological responses for climatically diverse selected locations

Median annual values for the 50 years of modelled daily values at the various locations are shown next. Changes in transpiration, representing plant water usage, from the top- and subsoil horizons for a median year are shown in Figure 4-8. As expected, median annual transpiration show large differences among the locations, being the lowest in arid Upington (Köppen Zone BWh) and the highest in moist Mount Edgecombe (Köppen Zone Cfa). With an increase in SOC, all locations show small increases in transpiration from the topsoil horizon, but small decreases from the subsoil horizon. Combined transpiration from the top- and subsoil horizon hardly show a change for Roodeplaat, Mara, Cedara and Upington. However, Elsenburg, in the winter rainfall zone and with a more temperate climate (Köppen Zone Csb), total transpiration shows an increase of 12 mm, equivalent to 9% for a change in SOC from 1% to 4% and an increase of 6 mm equivalent to 4% for a change in SOC from 1% to 2%., Mount Edgecombe (in the Cfa climate zone, wet all seasons, summers long and hot) shows an increase of 14 mm, equivalent to 3% for a change in SOC from 1% to 4%, but hardly a change (6 mm or 1%) when changing from 1 to 2% SOC. By and large, however, these locations show an increase in total transpiration with increased SOC.

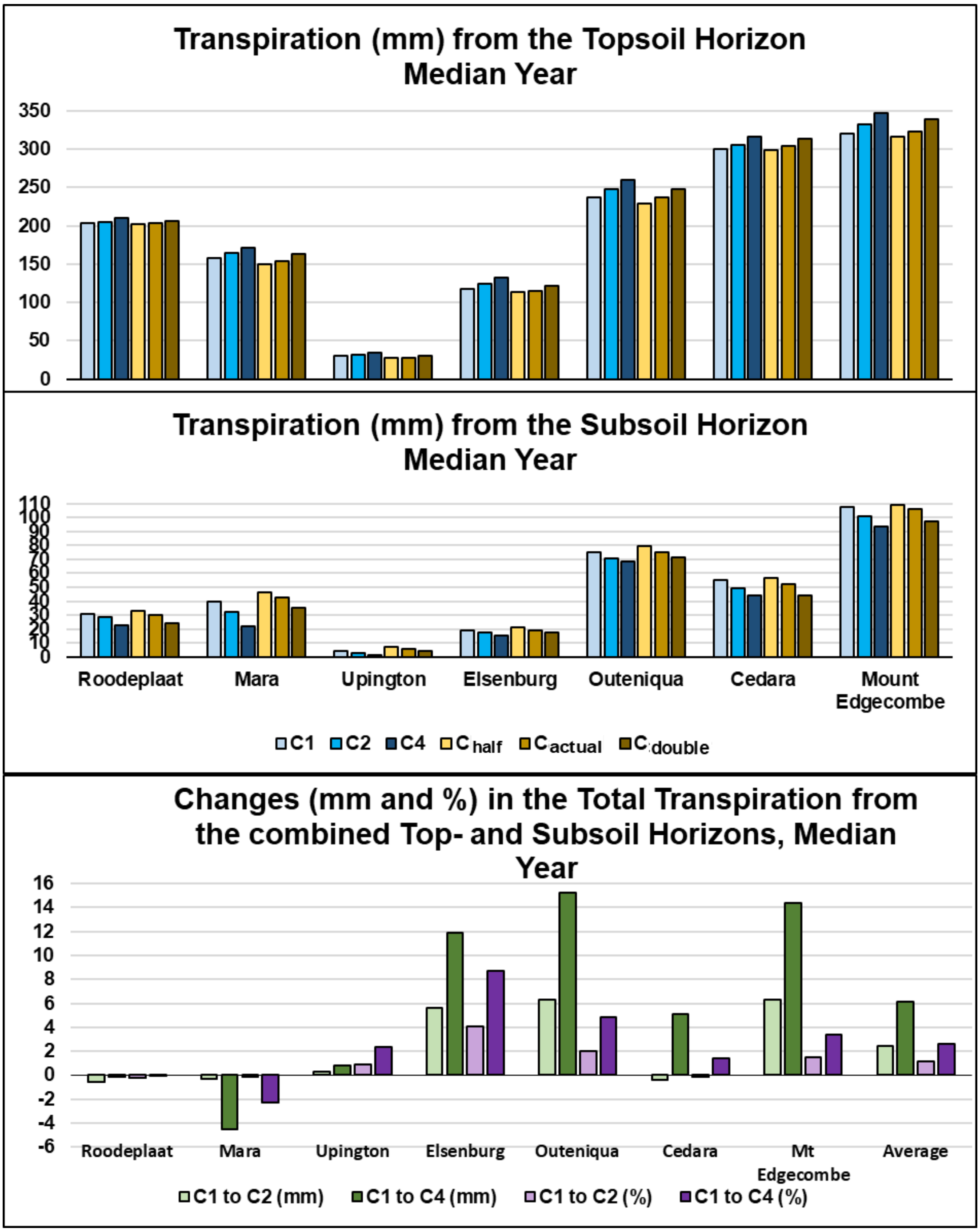

Figure 4-8 Transpiration (mm) from the top- and subsoil horizons for various soil carbon scenarios at selected locations in South Africa, as well as changes in total transpiration (% and mm, bottom graph), for a median year

The runoff figures (not shown), in a 1:10 dry year vary from no runoff for all carbon scenarios for Upington, to Elsenburg, with runoff of 56 mm in the C_1 scenario, 43 mm in the C_4 scenario, and 60 mm, 58 mm and 54 mm respectively for the C_{half}, C_{actual} and C_{double} scenarios. In a median year, the runoff ranges between 1 mm for Upington in the C_4 scenario to 196 mm, 193 mm and 187 mm for Elsenburg (winter rainfall zone, Csb) for the C_{half}, C_{actual} and C_{double} scenarios. For a 1:10 wet year, runoff ranges between 21 mm for Upington (dry, BWh) for the C_4 scenario, to between 468 mm, 463 mm and 452 mm for Mount Edgecombe (wet, Cfa) for the C_{half}, C_{actual} and C_{double} scenarios (not shown).

Selected changes in runoff results are shown in Figure 4-9. The impact of SOC varies from zero, as in Upington in a 1:10 dry year, because there is no runoff anyway, to substantial sensitivities to SOC for the other, wetter areas, with the largest absolute reduction of 24 mm for Cedara in a 1:10 wet year, when looking at a change from 1 to 4% SOC, and the largest relative reduction (but only a small absolute reduction) in runoff for Upington at 44% for a median year, with a change in SOC from 1% to 4%. In interpreting the results, it is seen that with increased SOC, the soil holds water more *in situ* in the landscape, with this being available for plant growth, which in turn leads to a reduction in runoff. Where, however, there is very little rain, as is in the case of Upington in a 1:10 dry year, then there is no runoff with any of the soil carbon scenarios.

Stormflows are rapid surface, or near surface, flows (Section 4.2) and are generally the major component of total runoff. The highest results are from Mount Edgecombe (wet, Cfa), where stormflows are 330 mm and 310 mm for the C_1 and C_4 scenarios (not shown). The results for changes (mm and %) in stormflows in a 1:10 dry year, a median year and a 1:10 wet year for changing scenarios from the C_1 to the C_4 scenario, are shown in Figure 4-9. Most important are the results of the 1:10 wet year, where the biggest absolute change can be seen for Cedara (wet, Cwb) with a 24 mm reduction for a change from 1% to 4% SOC, while the biggest relative change can be seen in Upington (dry, BWh) with a 27% reduction. In summary, an increase in SOC can lead to significant reductions in stormflows, but this depends on the inherent climate of an area and whether it is a dry, medium or wet year.

Baseflows are the slow release component of runoff (Section 4.2) and are the only water source in rivers in the non-rainy season. Most important in this sensitivity study are baseflows in the 1:10 dry year, with no baseflows for any of the SOC scenarios generated at Roodeplaat, Mara and Upington and very little at Cedara. The highest annual baseflows are found at Elsenburg (winter rainfall, temperate climate) with respectively 58, 56 and 52 mm for the C_{half}, C_{actual} and C_{double} SOC scenarios (not shown). In the cases where baseflow occurred, generally, a small reduction in baseflows was evident, although on a relative basis this could be high, with up to 99% for Upington for a change of SOC from 1% to 4% in a 1:10 wet year (not shown).

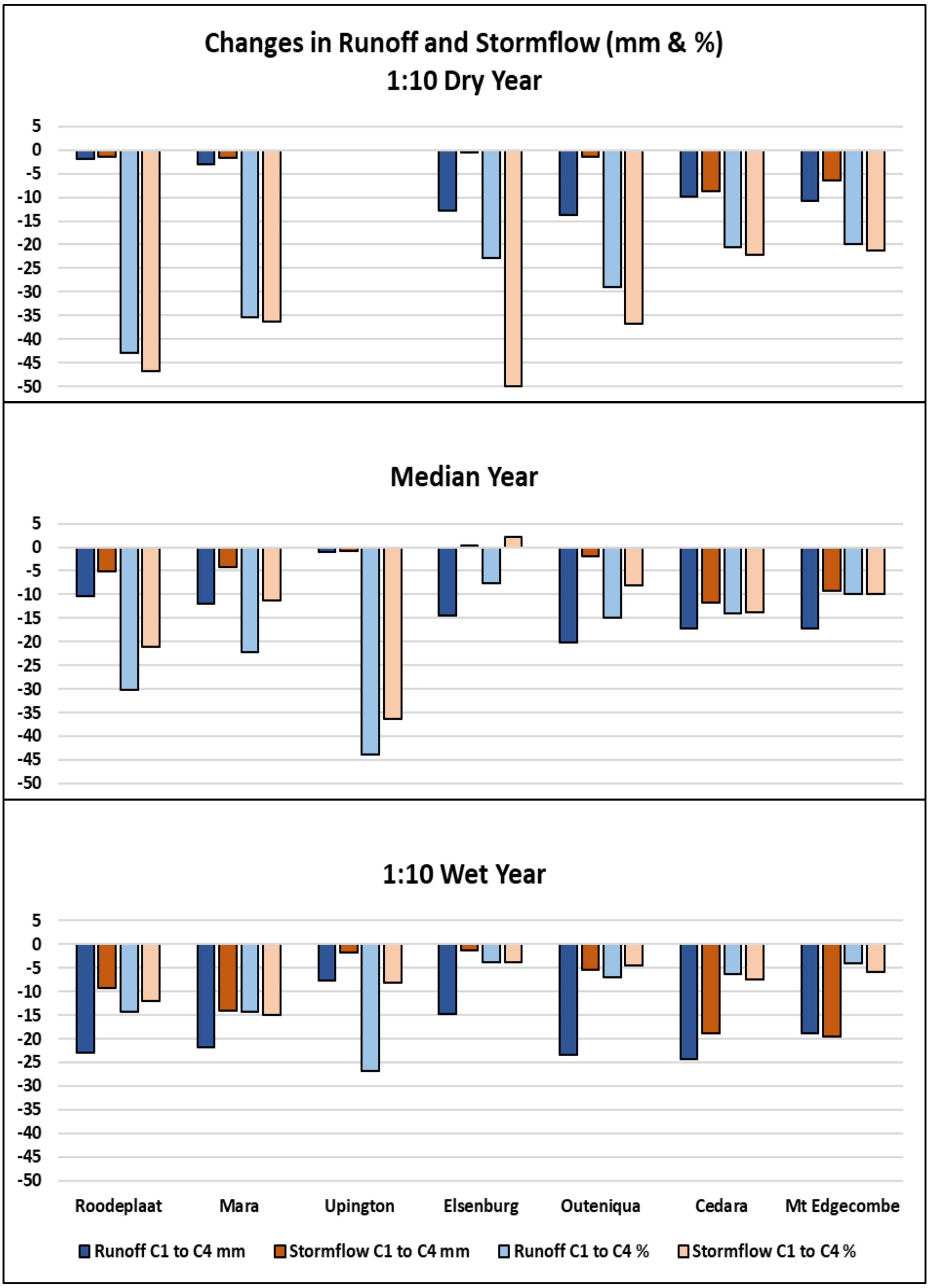

Figure 4-9 Changes in runoff and stormflow (mm and %) for carbon scenarios of 1% to 4% in a 1:10 dry year, a median year and a 1:10 wet year, for selected locations in South Africa

Changes in more extreme runoff design events for one-day and three-day accumulated magnitudes for design return periods of 2-, 5-, 10- and 50-year return periods are shown in Figure 4-10. While the Quinary catchments at Elsenburg and Outeniqua show no significant changes, the highest absolute reduction was at Mount Edgecombe (wet, Cfa), from 2.9 mm for a 3-day event for the 2-year return period to 4.4 mm for a 3-day event for the 50-year return period. Relative reductions were highest for Upington (dry, BWh), up to 20% for a 2-day runoff event for a 50-year return period (not shown), with a reduction of 2.2% for 3-day and 2-day runoff events for a 50-year return period.

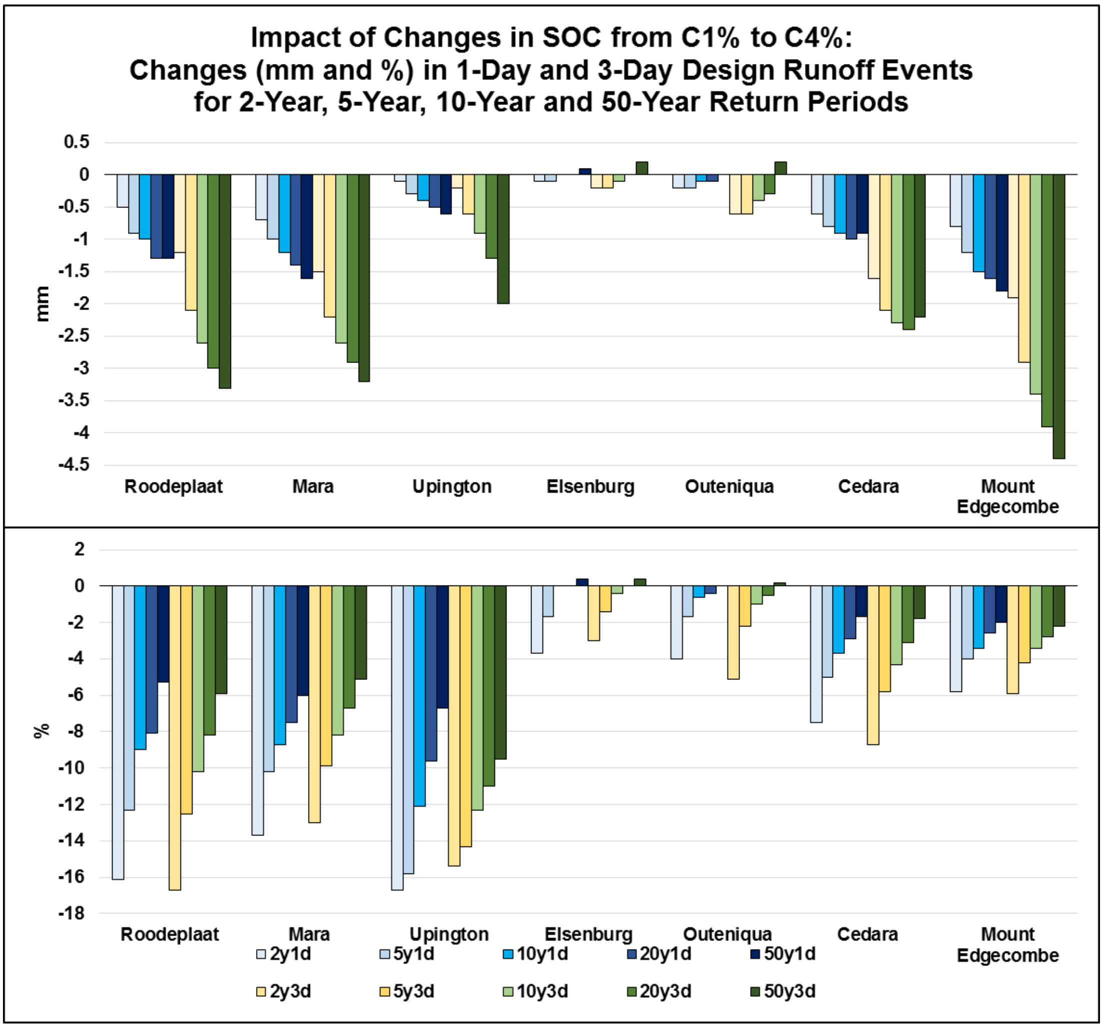

Figure 4-10 Changes in 1-day and 3-day design runoff events for return periods of 2, 5, 10, 20 and 50 years, with absolute changes (mm, top graph) and percentage changes (bottom graph) shown for selected areas in South Africa

In interpreting changes to design events with SOC changes, it is seen that not all areas show a change in extreme runoff, but most show a slight reduction in extreme runoff events. When expressed as relative changes, this reduction is higher in smaller floods with shorter return periods compared to changes in bigger floods with higher return periods. However, when expressed as absolute changes the reductions are higher for larger floods with higher return periods compared to smaller floods with shorter return periods. Overall, an increase in soil carbon is shown to reduce extreme runoff events in most areas, but with different magnitudes. Increases in soil carbon should thus help to reduce some flood damage, thereby providing an important ecosystem service.

4.5 Discussion and Conclusions

Soil water holding capacities impacted by SOC were found to be a link between the carbon and the hydrological cycles. SOC was shown to impact hydrological responses, but the magnitude of these are influenced strongly by rainfall regimes and vary between the different climatic zones and soil properties at the various locations examined in South Africa. In assessing runoff on a daily basis for Cedara, for example, an increase in SOC led to a reduction in the conversion of rainfall to runoff, with the peak runoff magnitudes generally being reduced. Changes in runoff range between insignificant, in very dry areas, to up to 24 mm of absolute reduction for Cedara in a 1:10 wet year, when looking at a change from 1 to 4% SOC, and the largest relative reduction (but only a small absolute reduction) in runoff for Upington at 44% for a median year, with a change in SOC from 1% to 4%. The significant reductions in runoff results mainly from stormflow, but also from more muted reductions in baseflow. An increase in SOC leads to transpiration increases, as was expected, and found as well by Ankenbauer and Loheide. In this study, the increases in transpiration came from the topsoil horizons, with small reductions from their subsoil horizons. As mentioned already, this could be the result of less infiltration from the topsoil horizon to the subsoil horizon, or because infiltration properties were not adjusted, given that it has been shown that the SOC also influences infiltration properties (Franzluebbers, 2002). Future research could examine SOC impacts on infiltration rates, for the corresponding ACRU inputs ABresp and BFresp. With an increase of infiltration rate, the stormflow component of runoff and the extreme runoff design events should be reducing further.

For the first time in South Africa, sensitivities of hydrological responses to SOC content changes have been calculated for selected locations with widely differing climatic regimes. The results are based on regression equations not yet verified in South Africa, and should be seen as initial first-cut results revealing direction and magnitude of changes to hydrological responses due to changes in carbon levels in the topsoil. While the results correspond to intuitive findings by others (Shaxson, 2006), in this study a quantification of the overall reduction in runoff, and especially in stormflows, has been presented. Land management practices that increase carbon content would keep more water on the land, which would be available for plant use, and would thus usually lead to reduced runoff and flood events, but the impact depends on the location and other climatic and soil factors. Increased SOC, with increased plant water availability is an additional benefit to climate change mitigation and is thus a win-win situation. The methodology developed in this study could be used for sensitivity studies elsewhere. Bearing in mind uncertainties regarding input values of carbon content, climate and soil variables, as well as pedo-transfer functions established elsewhere in the world, further improvements to impact modelling can be made, if locally derived equations of WP, DUL and PO which include a soil carbon factor and improved model inputs become available. Changes in SOC content also affects soil water and further work is recommended of SOC impacts on plant growth in the form of changes to soil water and plant stress-free days, for agricultural crop yield and primary production assessments.

5. IMPACT OF REDUCED TRANSPIRATION DUE TO ELEVATED ATMOSPHERIC CO2 CONCENTRATIONS ON HYDROLOGICAL RESPONSES

Journal article under review:

The value of including changes in maximum transpiration, due to elevated atmospheric CO_2 levels, in the ACRU hydrological model for South Africa

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Keywords:

Elevated carbon dioxide, transpiration rates, runoff rates, hydrological models, South Africa

Abstract

Elevated atmospheric carbon dioxide levels (eCO_2) have been shown in experiments to impact plant physiological processes, with increased photosynthesis and decreased stomatal and canopy conductance. Reduced canopy conductance results in reduced transpiration. There are, however, uncertainties in quantitatively linking eCO_2 to instantaneous transpiration reductions and thus to maximum transpiration (with optimal soil water availability) over a time period (e.g. daily, monthly or annual) and actual transpiration (reduced with water stress). Varying approaches are used in other hydrological and ecosystem models resulting in a range of responses for identical CO_2 changes.

In South Africa, ACRU, a processed-base daily time-step hydrological model is frequently used for hydrologically-related climate change studies with eCO_2 affecting climate inputs. The direct plant physiological effects of eCO_2 are currently not taken into account. However, it is important to know what the sensitivities of hydrological responses to eCO_2 induced reductions in maximum transpiration rate would imply for South Africa.

In this study, the spatially varying maximum daily transpiration (assuming optimal water availability), which is an input into the ACRU model, is reduced by a range of ratios, to represent an increase of up to double of pre-industrial CO_2 levels. The also spatially varying 50 years of daily climate information, and soil and location specific inputs remain unchanged. This results in a reduction in mean annual actual transpiration, while runoff and streamflow (accumulated runoff) from the study area increases. The magnitudes of change depend on the level of reduction in maximum transpiration rate, as well as on climatic inputs, thus vary spatially within the study area.

eCO_2 induced changes in maximum plant transpiration should not be ignored in models when used for hydrologically-related climate change studies. However, eCO_2, impacts on maximum transpiration rates are only one effect of many. Other eCO_2 effects include climate change with an increase in temperatures, possible changes in precipitation patterns and amount, photosynthesis, root-to-shoot ratios, and vegetation composition, which also effect hydrological responses.

5.1 Introduction

5.1.1 Hydrological Responses in South Africa

South Africa (SA) is a water-scarce country, with a range of climatic zones (Schulze and Schütte, 2016). Mean annual precipitation is estimated at 497 mm, compared with a world average of 860 mm, and displays a range from 46 mm to 2004 mm (South African Weather Service, 2017), with the distribution being higher in the wetter east and lower in the dryer north-west (Figure 5.1, top left; Lynch, 2004). Atmospheric water demand is high and again spatially variable, higher in the north west of the country (shown as potential reference crop evaporation in Figure 5.1, top right; Schulze et al., 2011). Water availability and atmospheric water demand impacts rainfall-to-runoff conversion (Schulze et al., 2011; Schütte and Schulze, 2017), which is low across the country, averaging 9% (Whitmore, 1971). This implies that the largest part of the precipitated water is evapotranspired rather than being converted to runoff, and many plant physiological processes are limited by water availability, especially during dry seasons and in times of drought. The study area is SA, but includes the countries of Lesotho and Eswatini (formally Swaziland), which are land-locked within SA and its river network is shown in Figure 5-2. South Africa, Lesotho and Eswatini have previously been spatially delineated into Primary catchments (A, B, C *etc.,* Figure 5-2), with a further delineations into smaller inter-linked catchments, up to fifth level Quinary catchments (Schulze and Horan, 2010; Schulze et al., 2010, see also Section 5.2.2).

Hydrological responses describe hydrological processes which include daily, monthly or annual volumes or depth equivalents per square meter of area of transpiration and evaporation, as well as runoff and its components of stormflows and baseflows and streamflow, which includes runoff from upstream (Schulze and Maharaj, 2008). These responses for SA are discussed in more detail later in Section 5.3. Modelled streamflow (accumulated runoff) in mm eq for the study area are shown in Figure 5-1 (bottom left; Schulze, 2011).

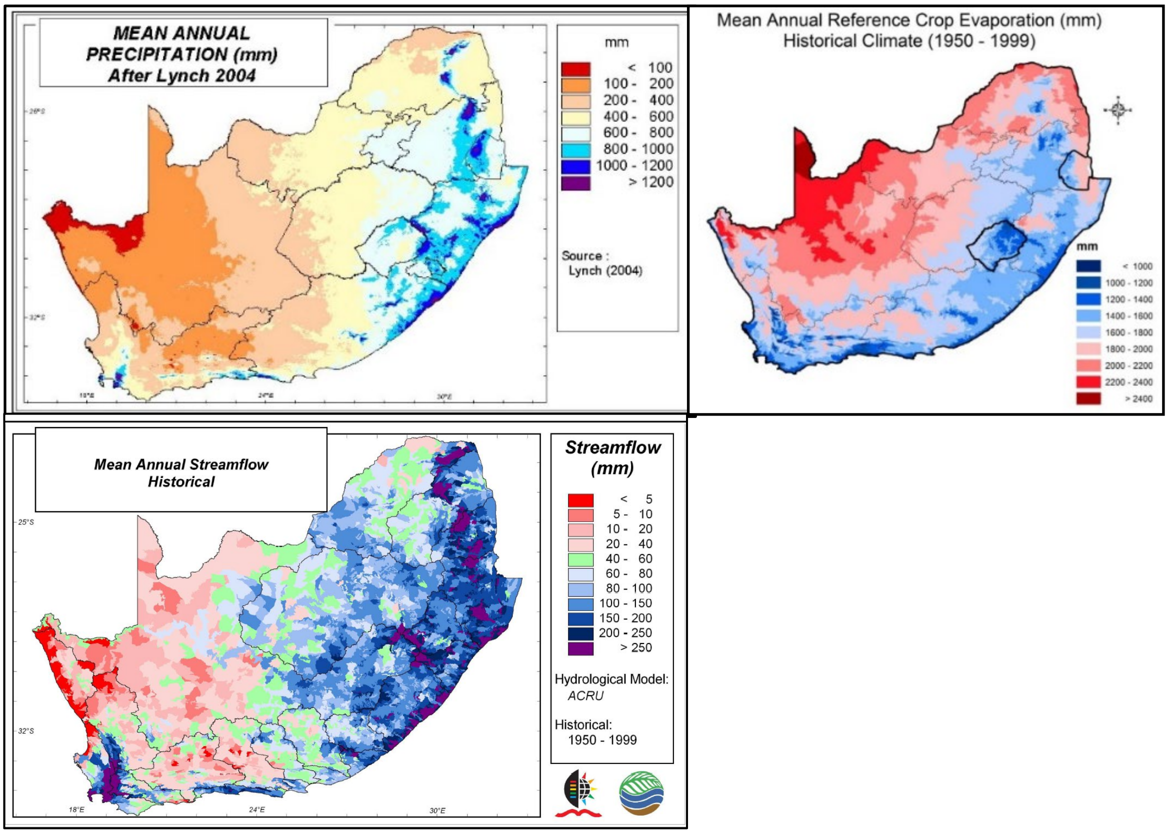

Figure 5-1 Mean annual precipitation (top left, after Lynch, 2004), mean annual reference crop evaporation potential (right, after Schulze et al., 2011) and mean annual streamflow (accumulated runoff) per Quinary catchment (bottom left, Schulze, 2011) in South Africa, Lesotho and Eswatini, all using climate information for 1950 – 1999

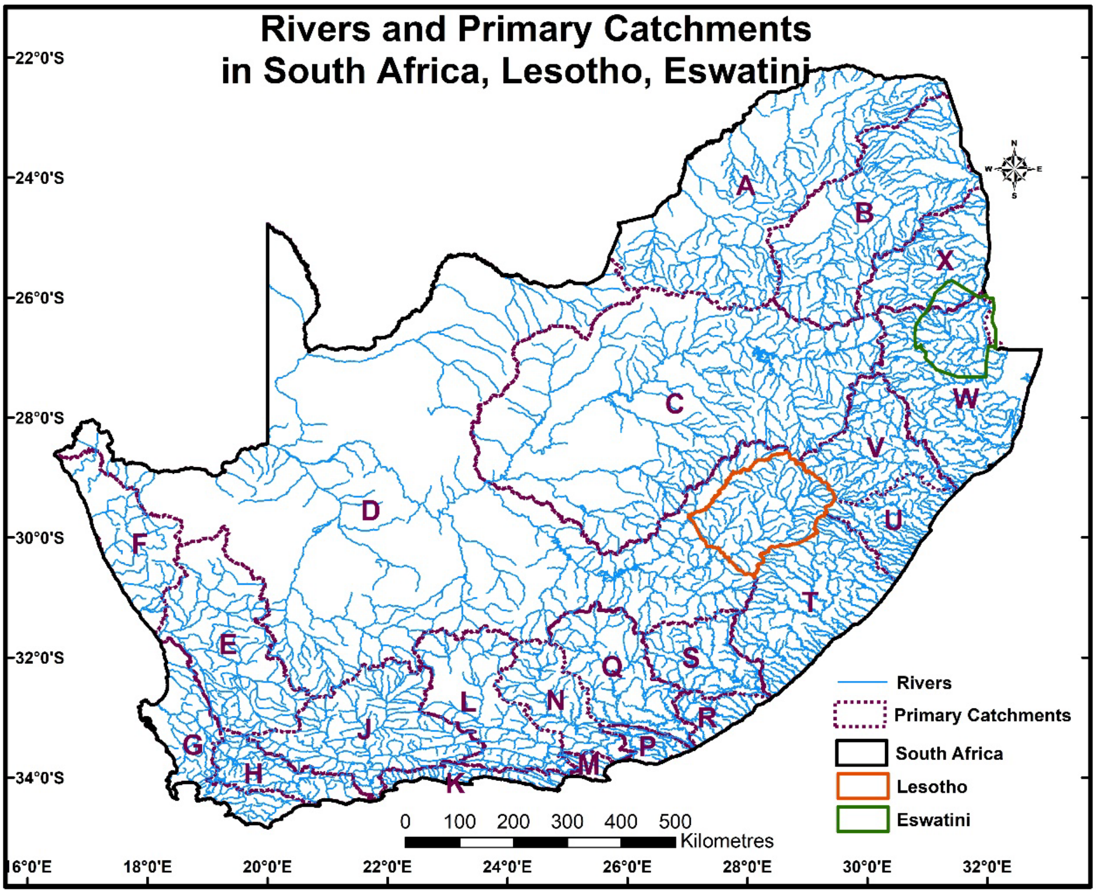

Figure 5-2 Primary catchments and river networks in South Africa, Lesotho and Eswatini (Midgley et al., 1994)

Hydrological responses can be simulated across a range of temporal and spatial scales by using hydrological models with inputs of climatic data, which includes precipitation, temperature and humidity, as well as soil and vegetation/ land use information, including the maximum daily transpiration of vegetation under optimum water conditions. This maximum transpiration will be a focus of this paper. Changes in carbon concentrations, in the form of atmospheric CO_2, have to our knowledge to date not been included in South African hydrological modelling studies. However, the hydrological cycle is impacted upon by changes to the carbon cycle in several ways.

5.1.2 Atmospheric CO_2 levels

The global average concentration of CO_2 in the atmosphere has increased rapidly in the last 400 years from 280 ppm to over 400 ppm and the projections are that it will continue to increase for at least 50 years, even if the Paris agreement is successful (Quéré et al., 2018). Associated effects include changes in radiative forcing, the enhanced greenhouse effect, and increase in temperatures and changes in weather patterns and precipitation (Lacis et al., 2010), thus impacting hydrological responses. However, elevated CO_2 concentrations (eCO_2) also change plant physiological processes and these, in turn, are likely to have effects on hydrological responses as well (Betts et al., 2007).

5.1.3 CO_2 controls on plant physiological effects

The process of photosynthesis, which takes place in plant leaves, involves both light and dark reactions, the products of which are reducing compounds, ATP and glucose. Carbon dioxide is taken into the leaves through the stomata and water vapour is released through the same stomata in the process of transpiration. The rate of these physiological processes is determined by the many factors which control the functioning of the stomata (Long et al., 2004). One of these factors is the atmospheric concentration of carbon dioxide and this is a focus of this study.

Global observations using remote sensing have linked global increased river flow to eCO_2 (Gedney et al., 2006). However, larger-scale observations include many other factors, making the isolation of CO_2 impacts difficult. While there are various methods of studying biosphere-atmospheric carbon exchanges in relation to vegetation and/or water vapour fluxes, this is a complex system (Baldocchi et al., 2001). On a smaller scale, experiments of plants grown under eCO_2 have taken place in controlled environments, greenhouses, open-top chambers and Free-Air CO_2 Enrichment (FACE) experiments (e.g. Long et al., 2004; Ainsworth and Rogers, 2007).

Principal physiological plant responses to eCO_2

Principal physiological plant responses to eCO_2 concentrations include an increase in leaf photosynthetic potential and a decrease in stomatal conductance (Jarvis and Mcnaughton, 1986), and therefore canopy conductance (e.g. Drake et al., 1997; Cox et al., 2000; Baldocchi et al., 2001; Naumburg et al., 2003; Long et al., 2004; Ainsworth and Long, 2005; Ainsworth and Rogers, 2007; Leakey et al., 2009; Wehr et al., 2017). Looking at eCO_2 effects on stomatal conductance in more detail, plants generally respond to eCO_2 with a reduced stomatal conductance, as was overwhelmingly reported in the literature (e.g. Drake et al., 1997; Baldocchi et al., 2001; Hungate et al., 2002; Long et al., 2004; Ainsworth and Rogers, 2007; Leakey et al., 2009), with limited exceptions reported, e.g. in the case of some studies (but not all) on conifers (Long et al., 2004), on *Pinus tadea* (Ellsworth, 1999) and on certain desert shrubs (Naumburg et al., 2003). Stomatal sensitivity to eCO_2 was found to be consistent over time (Long et al., 2004; Leakey et al., 2006, 2009), with both C_3 and C_4 species showing a decrease in stomatal conductance (Ainsworth and Rogers, 2007). For example, with increased of CO_2 from 366 and 567 ppmv, an average 22 % reduction of stomatal conductance was found in a review of FACE experiments, but different plant types reacted differently, ranging from 37% for C_3 grasses to 14% for shrubs (Ainsworth and Rogers, 2007). While stomatal conductance decreases in roughly inverse proportion to increases in CO_2 for a doubling of CO_2 (Long et al., 2004), this might taper off with further CO_2 increases (Li et al., 2019). The reduction of stomatal conductance by eCO_2 depends on plant type and is subject to environmental feedback (e.g. Ellsworth, 1999; Wullschleger et al., 2002; Naumburg et al., 2003; Bunce, 2004; Morgan et al., 2004; Leakey et al., 2006; Ainsworth and Rogers, 2007), with several studies finding water stress to generally reduce the eCO_2 effect compared to trials without water stress (e.g. Wullschleger et al., 2002; Naumburg et al., 2003; Morgan et al., 2004; Ainsworth and Long, 2005; Leakey et al., 2006; Ainsworth and Rogers, 2007). Scaling up of conductance changes from the leaf levels to canopy level involves many assumptions and often large error terms (Jarvis and Mcnaughton, 1986; Wilson et al., 1999; Baldocchi et al., 2001; Miglietta et al., 2011; Knauer et al., 2016) thus leading to numerous assumptions and algorithms used to represent this in models (see also Section 5.1.4). This field needs further clarification. A proportional relationship between the photosynthetic to stomatal responses to eCO_2 is supported by some FACE experimental results (Ainsworth and Rogers, 2007; Leakey et al., 2009; Barton et al., 2012) and this proportionality is used in some models (Ball et al., 1987; De Kauwe et al., 2013; Medlyn et al., 2015; see also Section 5.1.4), but this also needs further studies.

Transpiration

There is a link from the carbon cycle to the hydrological cycle through stomatal conductance and transpiration (Lin et al., 2015; Wehr et al., 2017; Knauer et al., 2016; Hong et al., 2019). Transpiration (instantaneous, as well as over a time period, is influenced by vapour pressure deficit, but also by changes in stomatal conductance (Wehr et al., 2017). Transpiration is found in some experiments to be proportional to leaf stomatal conductance (Long et al., 2004), but on the larger scale depends on canopy conductance (Betts et al., 2007). While the effects of increased photosynthesis with possibly increase in leaf area index and reduced stomatal conductance on transpiration are opposing, the net effect is usually a reduction in transpiration (Bates et al., 2008; Wu et al., 2012; Kirschbaum and McMillan, 2018; Hong et al., 2019), but with uncertainties over the magnitude of the resulting effect (Bates et al., 2008). The rate of reduction depends on various factors, including the different photosynthetic processes (C_3/C_4; Rosenzweig and Hillel, 1998; Bates et al., 2008; Leakey et al., 2009), the functional groups within the plants (Ainsworth and Rogers, 2007), stomatal to canopy relations, initial CO_2 level, the amount of CO_2 enhancement, as well as limiting factors, e.g. water stress (Baldocchi et al., 2001; Hungate et al., 2002; Morgan et al., 2004) or nutrient limitations, e.g. nitrogen (Luo et al., 2004). The uncertainties of upscaling eCO_2 effects from leaf to canopy conductance also translates into uncertainties in upscaling transpiration. The usefulness of eCO_2 experiments could be improved if mean daily, monthly and annual transpiration and total water use would be measured and reported on consistently, and also under water stressed conditions.

Other effects of eCO_2 on plant growth

eCO_2 also might or might not affect primary production (Wand et al., 1999; Falkowski et al., 2000; Baldocchi et al., 2001; Peñuelas et al., 2011) and leaf area index (Betts et al., 2000; Hungate et al., 2002; Long et al., 2004). Both primary production and leaf area index have been modelled to show spatial differences, often due to water availability (Baldocchi et al., 2001; Leipprand and Gerten, 2006). eCO_2 also might affect water use efficiency (Peñuelas et al., 2011; Bonan et al., 2014; Knauer et al., 2016). The likely increase in water use efficiency should imply that more carbon can be taken up by plants, even if water is a limiting factor (Knauer et al., 2016). An unchanged leaf area index and reduced stomatal conductance should lead to reduced stand transpiration and increased soil water content (Long et al., 2004). eCO_2 also might change the vegetation composition, e.g. by changing the limiting growth factor or by increasing tree saplings resistance against fire events (Kgope et al., 2010).

eCO_2 effects in South Africa

eCO_2 effects in South Africa have been a subject of limited experiments, (e.g. Wand et al., 1999; Kutsch et al., 2008; Kgope et al., 2010; Buitenwerf et al., 2012) and there has also been a recent increase in flux towers in SA (Feig et al., 2017). However, no quantification of eCO2 and transpiration could be found. Limited work has also been undertaken on possible projected shifts in vegetation composition, with a higher tree dominance in savanna and grassland areas and a shift of grasslands into desert areas predicted (Scheiter and Higgins, 2009) and observed (Bond and Midgley, 2000; Bond et al., 2003; Kutsch et al., 2008; Buitenwerf et al., 2012; Masubelele et al., 2014).

5.1.4 Models that take eCO_2 into account

Models aid in understanding, predicting, and managing water and natural systems and represent a simplification of the real-world. Measured physiological processes can be scaled up to landscape and catchment scale using verified parameters and algorithms. There are several crop and ecosystem models that take eCO_2 into account (henceforth called eCO_2 models), but differences in algorithms and approaches result in a range of responses for identical CO_2 changes (De Kauwe et al., 2013; Medlyn et al., 2015; Vanuytrecht and Thorburn, 2017). Several crop eCO_2 models target photosynthesis/production, often stomata/transpiration, and sometimes nutrient dynamics, but no standard approach has been found (Vanuytrecht and Thorburn, 2017), e.g. the eCO_2 effect in the AquaCrop Model only affects normalized biomass water productivity (Vanuytrecht et al., 2014), thus this model is not useful for modelling direct impacts on water flows. Studies comparing process-based eCO_2 models (De Kauwe et al., 2013; Medlyn et al. 2015) also found major differences in the modelling approaches, with highlighting differences in coupling of transpiration via canopy conductance to leaf stomatal conductance (Medlyn et al., 2015). Under eCO_2 conditions, most models predicted a significant reduction in stomatal conductance. The resultant change in transpiration, however, varied from almost nothing to close to a proportional response (Medlyn et al., 2015). Models usually do not capture eCO_2 effects of leaf area changes (Medlyn et al., 2015) and impacts on root-to-shoot ratios (Seneweera et al., 1998; Vanuytrecht and Thorburn, 2017), as this is not fully understood as yet and is complicated. Further model development and harmonisation are still required to make confident predictions of terrestrial ecosystem dynamics related to eCO_2 (Walker et al., 2014).

In hydrological models, plant response to eCO_2 is infrequently addressed (Butcher et al., 2014). A limited number of hydrological model sensitivity comparisons and model development was undertaken by Butcher et al. (2014), using an adjusted ‘Soil and Water Assessment Tool’ (SWAT) model (Arnold et al., 1998) including eCO_2 effects on photosynthesis (by linking to the ‘Environmental Policy Integrated Climate’ (EPIC) model, Easterling et al., 1992), as well as including conductive changes, the latter with the Penman-Monteith equation (Penmen, 1948; Monteith, 1981). Results were compared to outputs from the ‘Hydrological Simulation Program Fortran’ (HSPF) model (Bicknell et al., 2005), where monthly adjustment factors for the lower soil moisture parameter were developed (Butcher et al., 2014), to model conductive changes, but no photosynthesis changes are included. eCO_2 effects on water flows modelled with the HSPF model are small and substantially less than those predicted with the SWAT watershed model (Butcher et al., 2014).

eCO_2 affect equations adjustments to the Penman-Monteith leaf conductance (Penman, 1948; Monteith, 1981) and equations for this were developed and improved upon (Easterling et al., 1992; Wu et al., 2012; Li et al., 2019). All of these adjustments can be used with the SWAT model. The daily leaf area index is used to partition the total evaporation (ET) into potential soil evaporation and potential plant transpiration in SWAT (Wu et al., 2012). While SWAT is capable of modelling eCO_2 effects on water flows, a disadvantage of this method is that eCO_2 effects are modelled for ET, while it only affects the transpiration component of ET. Also, a proportionality change of leaf to canopy conductance is assumed, which might not be the case (Knauer et al., 2016). A further disadvantage is that SWAT does not take canopy interception into account (Butcher et al., 2014). It also uses FAO reference evaporation, which might change differently to modelled crops or vegetation under eCO_2.

In SA, the daily time-step agro-hydrological process-based model 'Agricultural Catchments Research Unit Model' (ACRU, Schulze, 1995 and updates) is frequently used, with the model having been widely validated (Schulze, 1995; Jewitt and Schulze, 1999; Hope et al., 2004; Smithers and Schulze, 2004; Warburton et al., 2010), also for hydrological climate change studies. Direct eCO_2 plant physiological effects are currently not taken into account in the model. Some consideration was given in the ACRU system previously to account for eCO_2 concentrations, with limited options of maximum transpiration suppression (Schulze et al., 1993; Perks, 2001). The allocation step and functioning of the ACRU model are discussed in the more detail later in Section 5.3. In ACRU, actual transpiration is calculated by either a leaf area index or by the use of crop coefficients, the latter is used with the Quinary catchments database (Section 5.1; Schulze and Horan, 2010; Schulze et al., 2010) The crop coefficient is the water use of the plant when not under soil water stress compared to a reference potential, which in ACRU is equivalent to A-pan evaporation. Under soil water stress the daily actual transpiration is reduced by a stress factor (Kunz, 1994; Schulze, 1995). The advantage of ACRU is that A-Pan reference potential evaporation is not affected by changes in eCO_2. In addition, transpiration can be reduced separately from evaporation. However, ACRU has currently no coupled vegetation model to account for any changes in photosynthesis.

Modelling studies of the impacts of eCO_2 physiological forcing

There have been several studies modelling the impacts of eCO_2 on physiological forcing. Global studies with continental, or more regional results (e.g. Cox et al., 2000; Betts et al., 2004, Leipprand and Gerten 2006, Betts et al., 2007), find either increased runoff due to physiological forcing by CO_2 or a smaller reduction than with radiative forcing alone. Some studies include the eCO_2 effect, but unfortunately do not report separately on the effects of eCO_2, prompting for calls for more transparency in eCO_2 inputs used in modelling studies (Ainsworth et al., 2008).

For continental Africa Betts et al. (2007) modelled a reduction in runoff with radiative forcing, but an increase for combined radiative forcing and eCO_2 effects. They suggest that the influence of physiological forcing on runoff is not significantly modified by changes in leaf area index or by vegetation distribution, at least at the global scale, while acknowledging that there might be large impacts of vegetation dynamics on runoff on a regional scale (Betts et al., 2007).

Other examples of modelling studies on more local scales include climate change effects on pasture systems in Australia (Cullen et al., 2009), with eCO_2 responses depending on the plant type, soil moisture and soil nutrient availability. The effects of eCO_2 for the watershed-scale Upper Mississippi River Basin, USA was modelled, using the original and modified SWAT model (Wu et al., 2012). For both versions, the effects of stomatal closure exceeded those of increasing leaf area and resulted in reduced evapotranspiration and increased water yield (Wu et al., 2012), as also reported by some dynamic global vegetation models (Leipprand and Gerten 2006; Betts et al., 2007; Bates et al., 2008), although not everywhere and with regional differences (e.g. Leipprand and Gerten 2006).

Evapotranspiration (ET) is a key variable in linking feedbacks of carbon and climate and water resources, as well as ecosystem functioning, agricultural management and water resources (Fisher et al., 2017). ET partitioning into transpiration and soil water evaporation in ecosystem models needs further model development (Wehr et al., 2017).

Several authors conclude that the conventional global warming potentials based on radiative forcings by greenhouse gases are incomplete and that the ET and hydrological impacts also need to include physiological forcings (Leipprand and Gerten, 2006; Betts et al., 2007; Kruijt et al., 2008; Butcher et al., 2014). Thus eCO_2 should be considered in hydrological related climate change studies.

5.2 Methodology

In light of the uncertainties and different approaches relating to eCO_2 effects in other models, this research focusses on what eCO_2 induced reductions in maximum transpiration rate would imply in hydrological responses in SA. A sensitivity study in SA is reported on, using naturalised flow regimes (meaning without included land use change effects, dams, inter-basin transfers or water abstractions, previously shown in Figure 5-2).

5.2.1 The Model used

In SA, ACRU (Schulze, 1995 and updates), a processed-base daily time-step agro-hydrological model, is frequently used for hydrologically-related climate change studies. Direct eCO_2 plant physiological effects are currently not taken into account in the model.

The model used in this study was an adjusted version of ACRU, *viz.* Version 3.4.1. The adjustment was made to the model so that there could be user-defined options for the reduction in daily maximum transpiration. Options of the model input variable 'CO_2TRAN', which entails the CO_2 related transpiration reductions, can be changed by the user to suppress the maximum transpiration rate by 0%, 5%, 10%, 15 %, 20%, 25% or 30%.

The allocation steps in ACRU with regards to the daily water budget and eCO_2, assumed to start at the commencement of a day (Schulze, 1995) are

1. evaporation of previously intercepted water,
2. apportionment of maximum evaporation to maximum soil water evaporation and maximum transpiration,
3. suppression of maximum transpiration under conditions of elevated atmospheric CO_2 levels,
4. apportionment of available maximum transpiration to different soil horizons,
5. estimation of actual soil water evaporation,
6. estimation of actual transpiration from the plant,
7. compensations for differentially wetted soil horizons,
8. interception losses on a day with precipitation, with precipitation assumed at the end of daylight hours,
9. precipitation abstractions in cracking soils (where these exist),
10. generation of quickflow (i.e. immediate response flow) from impervious areas,
11. stormflow generation from pervious areas from a rainfall event and apportionment of same-day stormflow, plus stormflow carry-over (lag) from previous days,
12. "saturated" drainage processes,
13. accumulation of soil water under waterlogged conditions,
14. redistribution of unsaturated soil water,
15. baseflow generation and
16. setting final values of the water budget for resumption the next day.

The suppression of maximum transpiration under conditions of eCO_2 is Step 3, following the apportionment of maximum evaporation and maximum transpiration. This suppression then affects actual transpiration (Step 6) and the steps that follow.

The daily vegetative water use is based on crop-coefficients, against an A-Pan reference evaporation. Under water stress, the daily crop coefficients are adjusted by a stress index based on daily soil water stress (Kunz, 1994; Schulze, 1995 Section AT6-14), thus reducing the maximum daily transpiration to the so-called actual daily transpiration in mm equivalent or volumes / area.

5.2.2 The Quinary Catchments Database

South Africa, Lesotho and Eswatini (formally Swaziland) have previously been spatially delineated into primary catchments (A, B, C *etc.* previously shown in Figure 5-2), with a further delineations into smaller catchments, up to fifth level Quinary catchments (QCD, Schulze and Horan, 2010; Schulze et al., 2010), the latter to allow for modelling relatively homogeneous hydrological responses. Each of the 5838 Quinary catchments are linked to soil-, location- and altitude-related input and 50 years of daily (observed or patched, 1950-1999) climate input (Lynch, 2004), or to daily output from Global Circulation Models to enable projected future climate effects to be simulated. The QCD facilitates the modelling of climate change or land use change impact scenarios within South Africa. The QCD is used in this study, with naturalised river flows (previously shown in Figure 5-2), meaning no impacts of dams, water abstraction, inter-catchment transfers are taken into account, with vegetation inputs related to Acocks (1988) representing natural vegetation. Actual transpiration is calculated by using the crop coefficient method. Runoff from each quinary catchment is accumulated to streamflow according to the flow path within the QCD. For more information see Schulze and Horan (2010) and Schulze et al. (2010).

5.2.3 Assumptions

No additional possible eCO_2 effects of changes over time in vegetation type or vegetation extend, root-shoot-ratio, leaf-area index and climate have been modelled in this study and all these model inputs are taken from the standard QCD.

5.2.4 Scenario modelling

Scenario modelling with ACRU is performed, using suppression of the maximal transpiration rate by each, 0% (base run), 5%, 10%, 15%, 20%, 25% and 30%. These scenarios were chosen to cover an average 22 % reduction of stomatal conductance ranging from 37% for C_3 grasses to 14% for shrubs, as were found in a review of well-watered FACE experiments, with increased of CO_2 from 366 and 567 ppmv (Ainsworth and Rogers, 2007), and the assumption that transpiration is proportional to leaf stomatal conductance (Long et al., 2004), but there might be some reduction on canopy conductance and thus transpiration (Betts et al., 2007). All other climate-, soil- and location- related model inputs are taken from the standard QCD. The base run without any CO_2 suppression should be same or very similar to the standard QCD hydrological outputs previously published (Schulze, 2011, Figure 5-1, bottom right), because the same model inputs were used. However, it needs to be noted that an updated model was used in this study.

The following per Quinary catchment ACRU model outputs were selected or calculated: transpiration (calculated from top- and subsoil output) in mm equivalent (eq); total evapotranspiration (made up of transpiration and evaporation), in mm eq; per Quinary runoff in mm eq; streamflow (accumulated runoff, in mm eq and calculated by multiplying with the relevant total catchment area in 10^6 m^3), all for mean annual values. The ACRU model sums up the 50 years of daily values first to monthly means (or other statistical outputs), and these monthly values in-turn to calculate the mean annual values. Selected outputs were analysed for the different scenarios and the results shown as maps of changes in the model output for 10, 20 and 30% suppression runs, to be able to compare the impacts for a range of maximum transpiration suppression rates for the area. The increase in streamflow from Primary catchments was shown as graphs that include all the scenarios modelled.

5.3 Results

The baseline modelled hydrological responses per Quinary catchment without any eCO_2 suppression in maximum transpiration are shown in Figure 5-3. The mean annual actual transpiration (mm eq) shows a gradient between the dry west and the wetter east of the study area, which also can be seen with the mean annual runoff (mm eq), and the mean annual streamflow (mm eq), which is the accumulated runoff including from upstream. The mean annual streamflow (10^6 m^3) shows up the larger volume from the large upstream area of some of the west flowing rivers.

A 30% (as well as with 20% and 10%) reduction in maximum transpiration results in an area averaged reduction in mean annual actual transpiration of 27.6 mm (16.8 mm; 7.7 mm), with a range between from 0.8-119.0 mm eq (0.4-74.8 mm eq; 0.2-35.1 mm eq) or a relative reduction of 13.5% (8.3%; 3.9%) with a range from 3.8%-27.3% (2.2%-18.0%; 0.9%-8.9%). Figure 5-4 shows the reduction in mean annual actual transpiration for absolute changes in mm eq and relative changes in percentage per Quinary catchment with suppression of maximum transpiration by 10%, 20% and 30%. Spatial differences can be seen with the wetter east of the region showing a bigger absolute reduction. As expected, the reduction increases with a higher maximum transpiration suppression rate.

A 30% (20%, 10%) reduction in maximum transpiration results in an increase in the region-averaged mean annual runoff generated per Quinary of 22.6 (13.6, 6.2) mm eq, with a range of 0-122.4 (0-77.2; 0-36.4) mm eq. Figure 5-5 shows spatial differences in absolute changes in mm eq. and relative changes (percentage) per Quinary catchment with suppression of maximum transpiration of 10%, 20% and 30%. Again, in absolute terms, the changes are larger in the wetter east, compared to the dry west and become larger with an increase in maximum transpiration suppression.

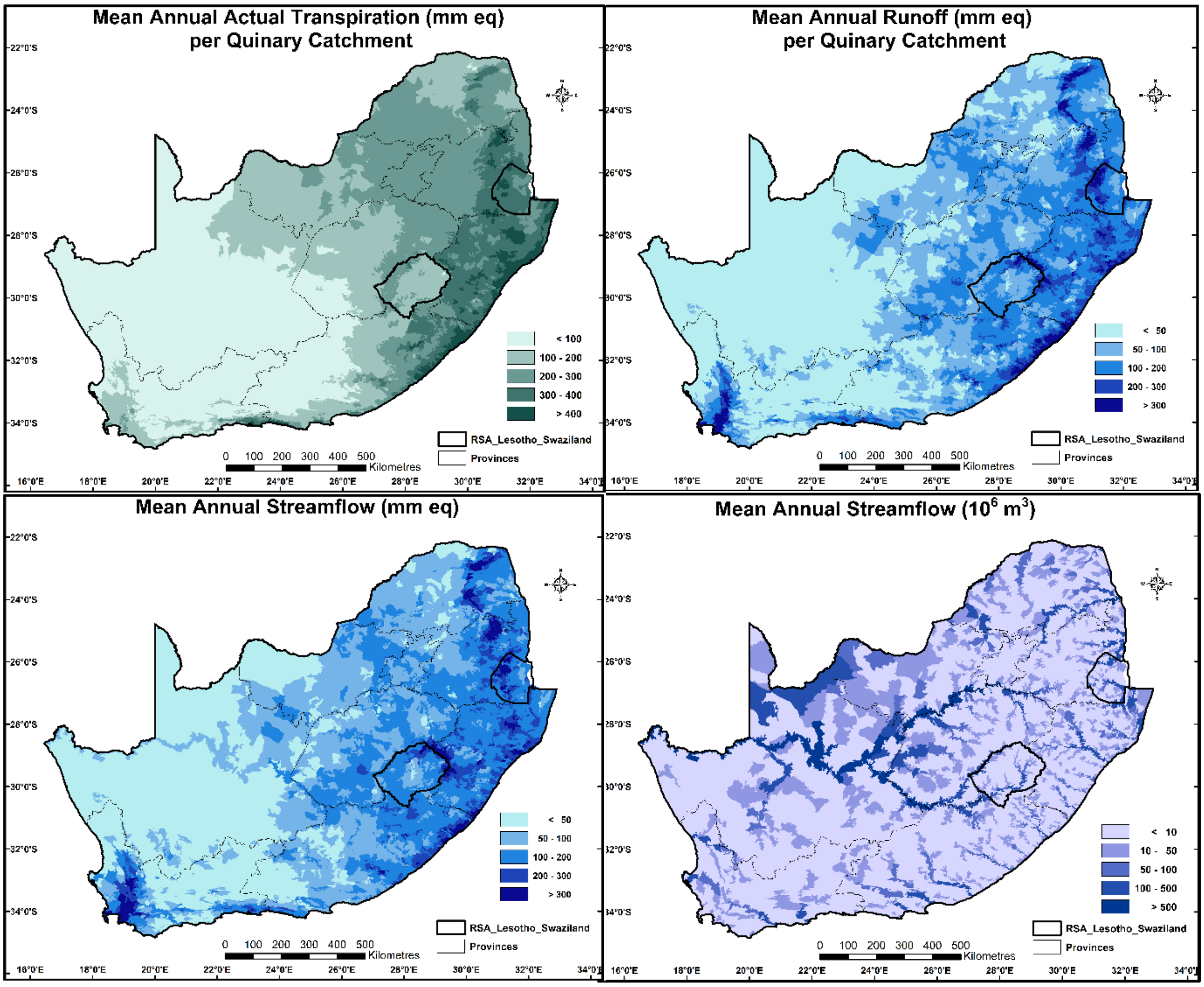

Figure 5-3 Baseline modelled hydrological responses per Quinary catchment without a eCO_2 suppression in maximum transpiration, showing mean annual actual transpiration (mm eq, top left), mean annual runoff (mm eq, top right), mean annual accumulated streamflow (mm eq, bottom left) mean annual accumulated streamflow (10^6 m^3, bottom right)

A 30% (20%, 10%) reduction in maximum transpiration results in an increase of per Quinary of mean annual accumulated streamflow, which is the accumulated runoff, inclusive of runoff from upstream. These average per Quinary changes are 23.5 (14.2, 6.5) mm eq, with a range of 0 to 122.4 (0-77.2, 0-36.4 mm eq), or in relative changes in average of 17.4% (10.5%, 4.8%), with a range from zero to 57.4% (33.4%, 16.7%). Figure 5-6 shows spatial differences in absolute changes in mm eq and relative changes (percentage) per Quinary catchment with suppression of maximum transpiration of 10%, 20% and 30%. Again, in absolute terms, the changes are larger in the wetter east, compared to the dry west and larger, with an increase in maximum transpiration suppression.

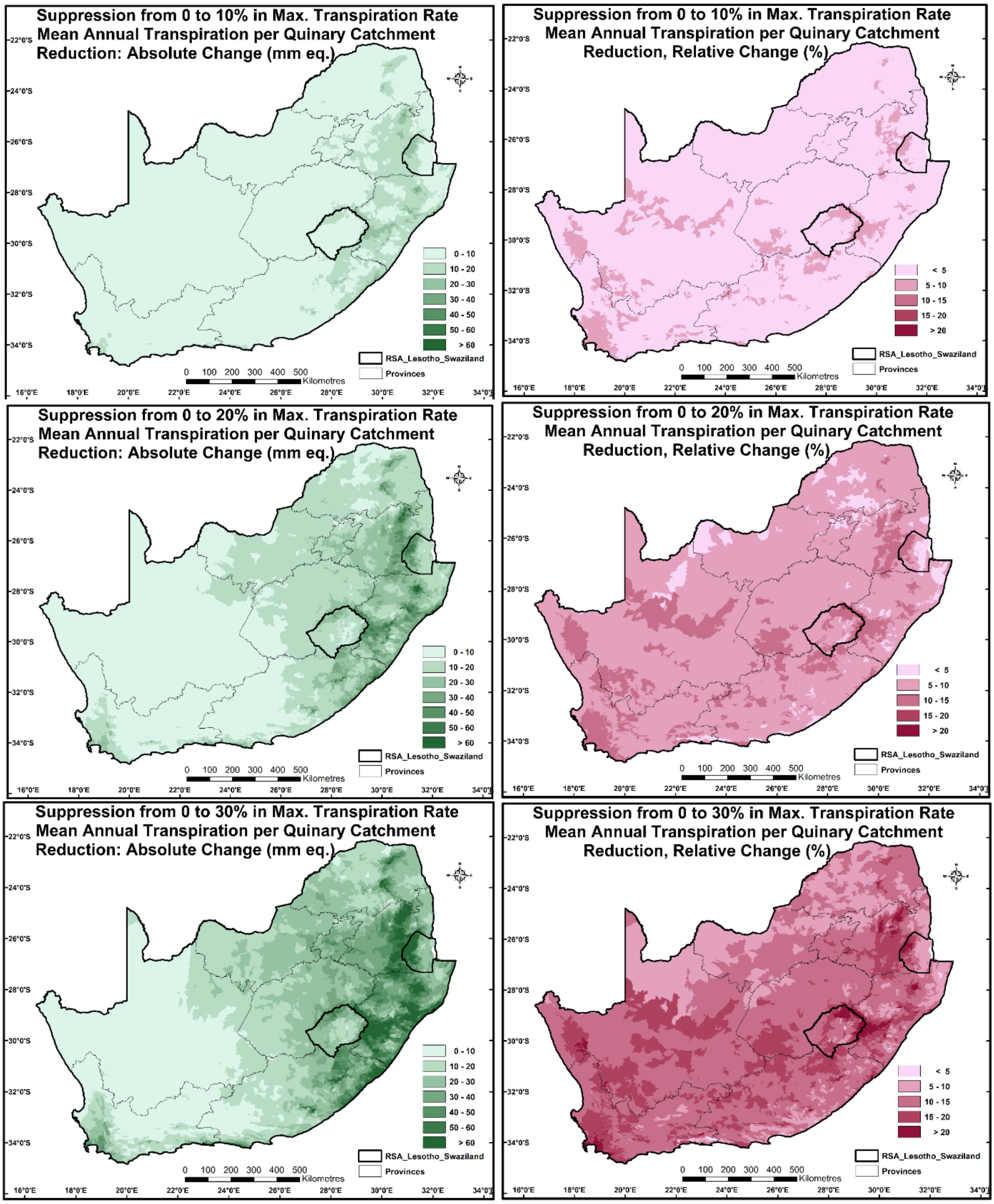

Figure 5-4 Reduction in mean annual actual transpiration in mm equivalent (left) and as a percentage (right) per Quinary catchment with suppression of maximum transpiration of 10% (top), 20% (middle) and 30% (bottom)

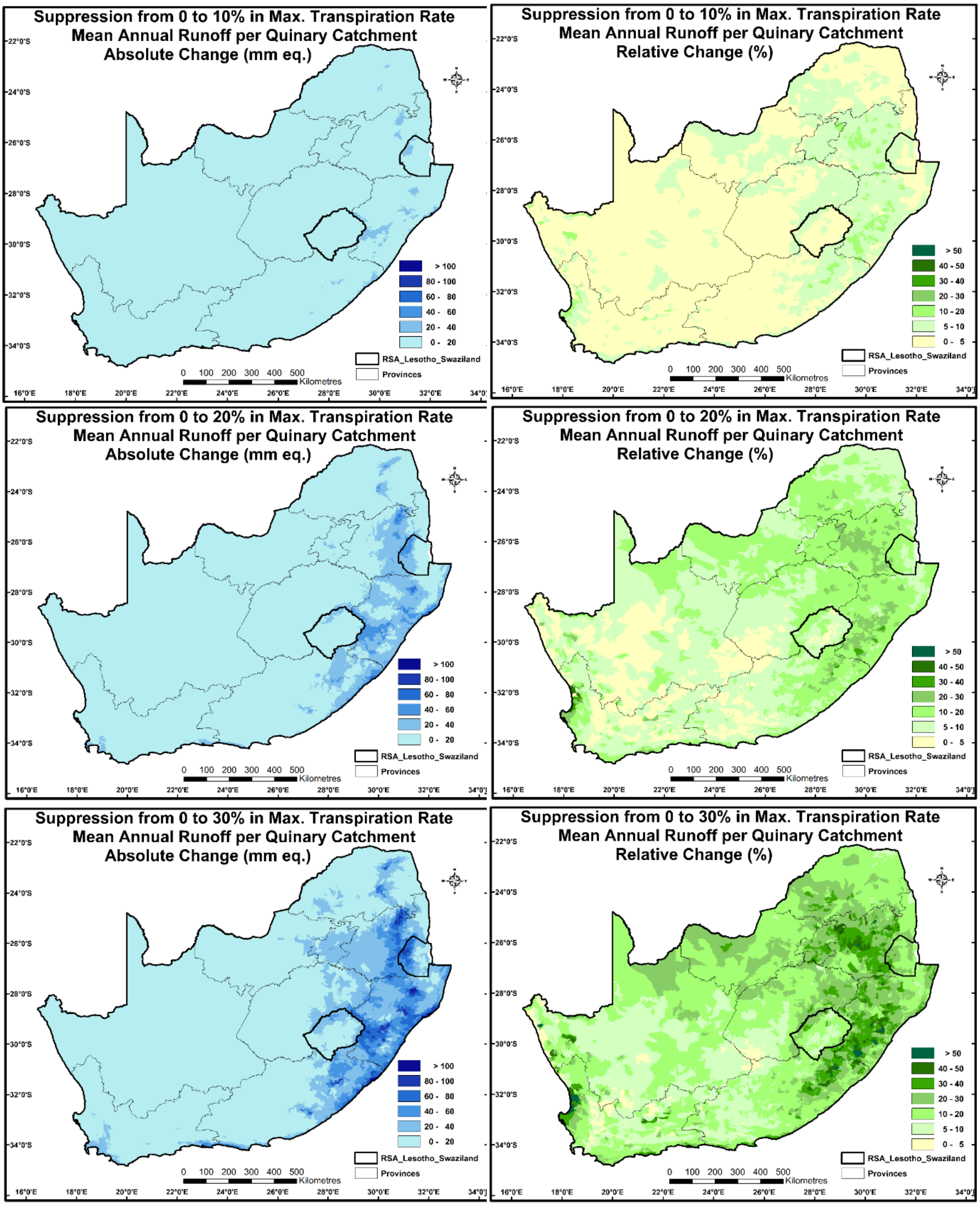

Figure 5-5 Increases in mean annual runoff per Quinary catchment in mm equivalent (left) and as percentages (right) with suppression of maximum transpiration of 10% (top), 20% (middle) and 30% (bottom)

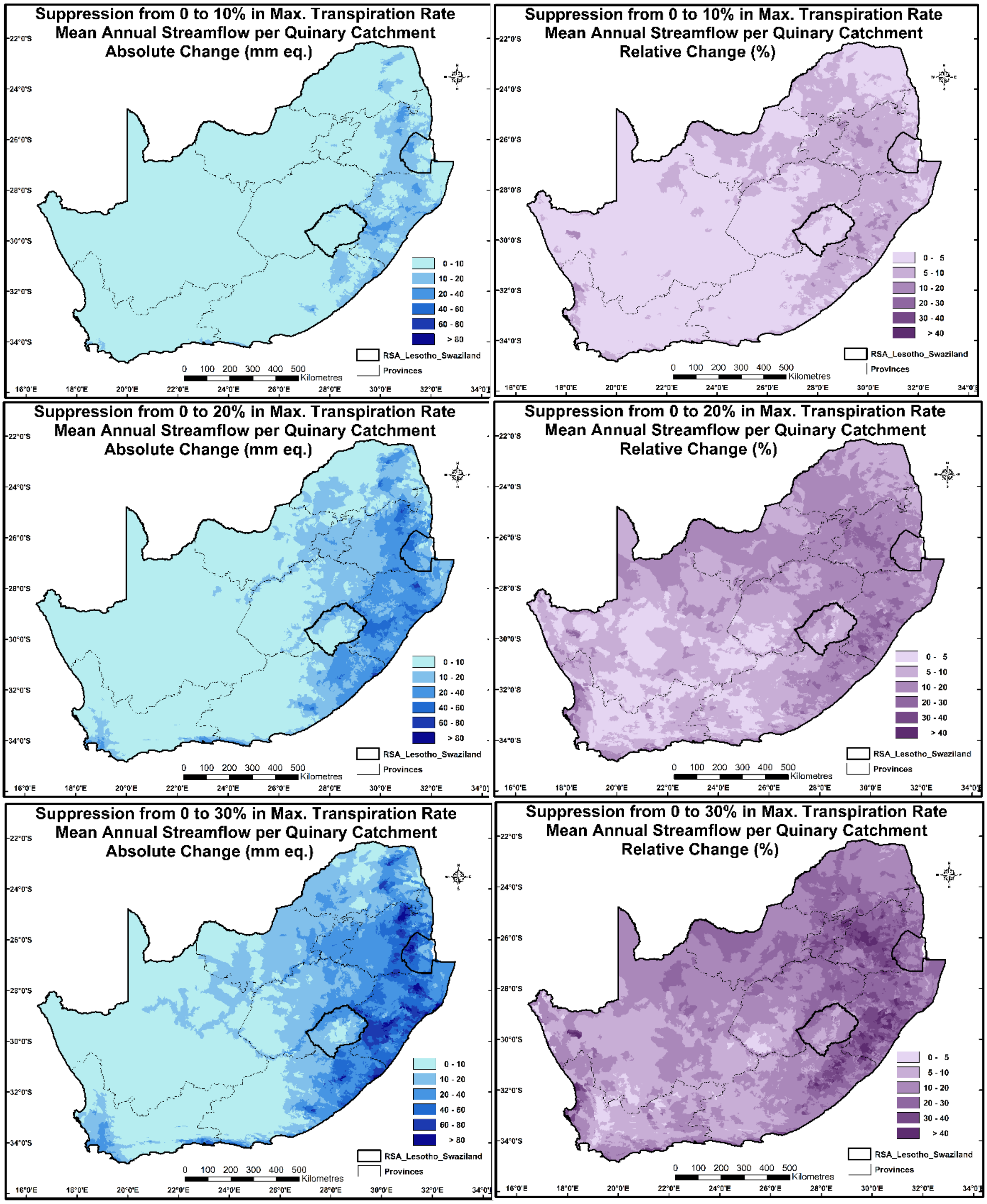

Figure 5-6 Changes in accumulated streamflows (mm equivalent, (left) and as percentages (right) with a suppression of maximum transpiration by 10% (top), 20% (middle) and 30% (bottom)

A 30% (20%, 10%) reduction in maximum transpiration results in an increase in per Quinary mean annual streamflow when expressed in m^3. These changes average 17.4% (10.5%; 4.8%), with a range from 0% to 57.4% (33.4%; 16.7%). Figure 5-7 shows spatial differences in absolute changes in mm eq and in relative changes (percentage) per Quinary catchment with suppression of maximum transpiration of 10%, 20% and 30%. As expected, the changes are higher with an increased reduction in maximum transpiration. Here, the larger rivers with accumulated flow from wetter upstream areas show bigger changes.

Relations of relative changes (percentage) of total streamflow at outlets into the ocean are shown in Figure 5-8 for selected Primary catchments as well for the whole area with suppression in maximum transpiration by up to 30%. As the reduction in maximum transpiration increases, so streamflows increase. Differences for the Primary catchments can be seen, with the total streamflow increasing by 18% (with a reduction of 30% in maximum transpiration), but depending on the Primary catchment, this ranges from 7% to 29%. Relations between absolute changes in total streamflow volume (10^6 m^3) from South Africa, Lesotho and Eswatini for a summary of at outlets into the ocean with suppression in maximum transpiration by up to 30% are shown in Figure 5-9.

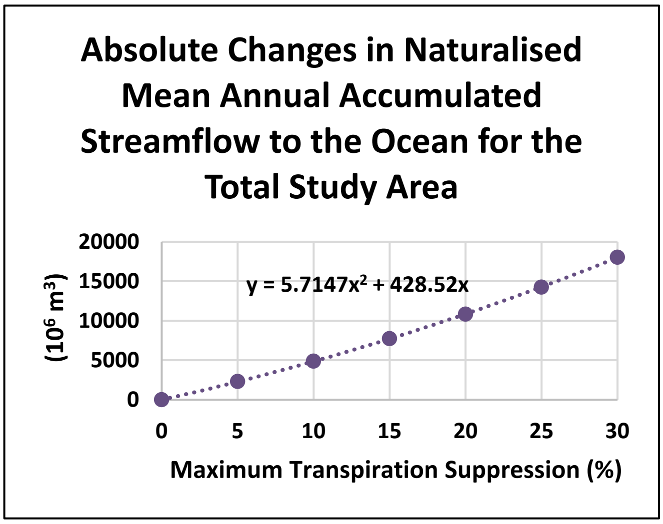

Figure 5-7 Relationship between absolute changes in total streamflow (106 m3) from South Africa, Lesotho and Eswatini at river outlets into the ocean, showing an 18036 million m3 increase with a suppression in maximum transpiration of 30%, 10829 million m3 for 20% and 4888 million m3 for a 10% suppression in maximum transpiration

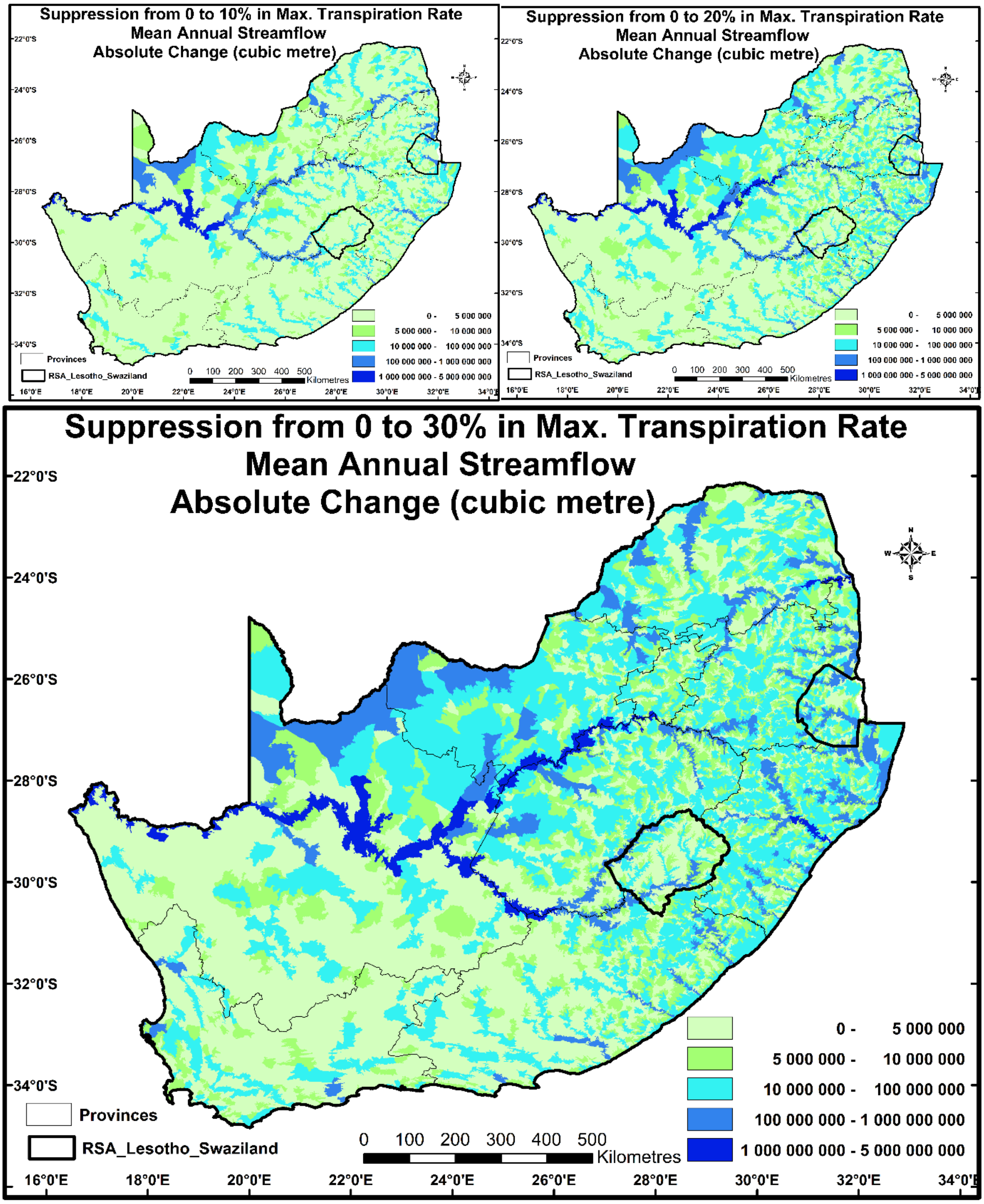

Figure 5-8 Increases in per Quinary catchment accumulated streamflow (10^6 m^3) with a reduction of maximum transpiration by 10% (top left), by 20% (top right) and by 30% (bottom)

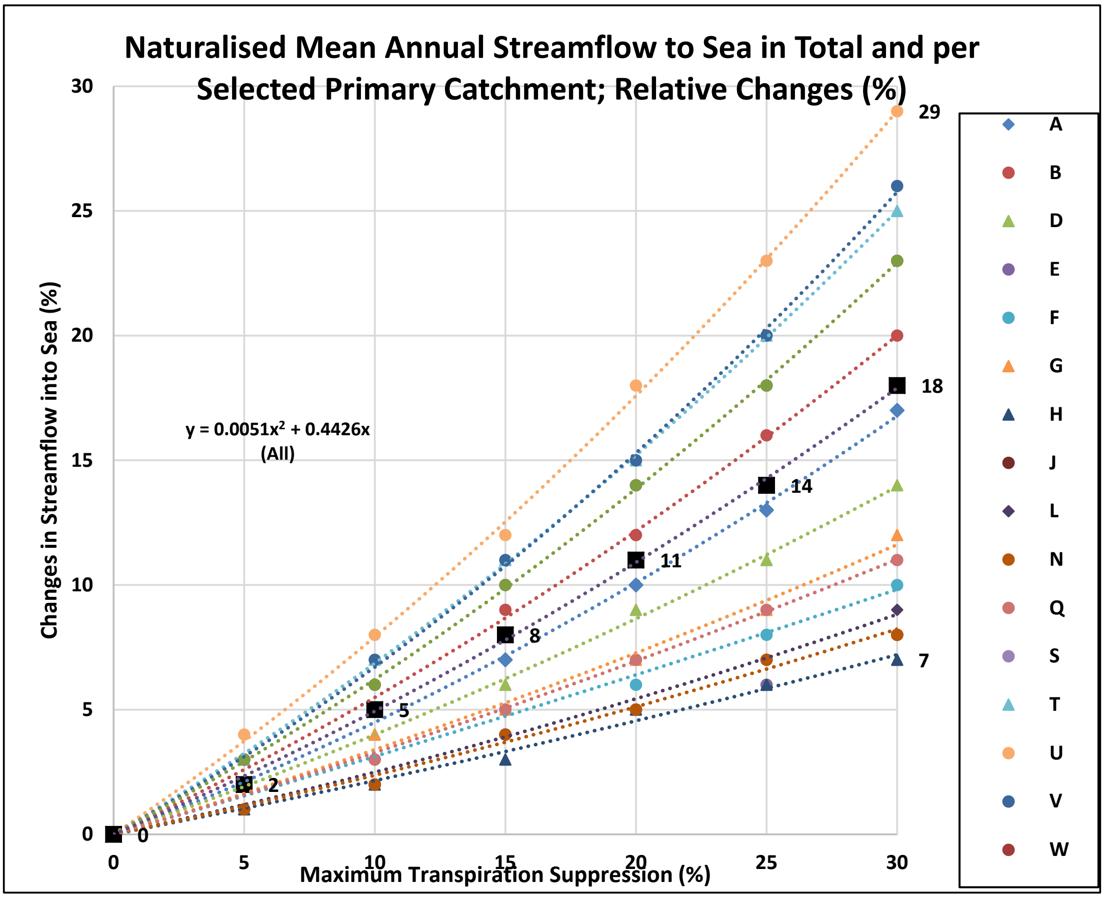

Figure 5-9 Relations of relative changes (percentage) in total accumulated streamflows at outlets into the ocean, for selected Primary catchments, as well for the whole area (black squares) with suppression in maximum transpiration by up to 30%

5.4 Discussion and conclusion

eCO_2 is likely to influence transpiration, as well as other factors, e.g. primary production, water use efficiency, leaf area index and vegetation composition. An unchanged leaf area index and reduced stomatal conductance should lead to reduced stand transpiration (Long et al., 2004). While there are ways to upscale from stomatal to canopy conductance (Bonan et al., 2014), this is still a field full of uncertainty, translating also in uncertainties about transpiration changes, as was described previously.

In this study sensitivities of hydrological responses in SA to eCO_2 induced maximum transpiration suppression are researched. The maximum transpiration is the maximum value for the vegetation type in a particular area, assuming optimum water availability. The actual transpiration is usually smaller than the maximum transpiration, because daily soil water stress is taken into account. 50 years of daily climate, soil, location and vegetation information from the existing QCD are used in this study, but using scenarios of various levels of suppression (between 0% and 30%) of maximum transpiration were used as model input. It was found that the higher the suppression of maximum transpiration, the higher potential there is for the suppression in actual transpiration. As was shown in Section 5.1.1, the study area is climatically diverse (Schulze, 2011, Figure 5-1), with a wetter east and a drier north west. With a suppression of maximum transpiration, strong spatial differences in reduction in actual transpiration can be seen across the study area. The differences can be between no or small absolute change in the drier areas, where there is no or hardly any water available for transpiration, to significant changes in the wetter areas of the east. This means, as could be expected, that the regional climate conditions have a strong impact on the eCO_2 induced reduction in actual transpiration. This corresponds to several studies finding water stress to generally reduce the eCO_2 effect compared to trials with no water stress (e.g. Wullschleger et al., 2002; Naumburg et al., 2003; Morgan et al., 2004; Ainsworth and Long, 2005; Leakey et al., 2006; Ainsworth and Rogers, 2007).

The higher the suppression of maximum transpiration, the higher the potential for increases in runoff, calculated on a per-Quinary basis. Again, strong spatial differences can be seen and the changes in the drier western areas are between zero or very little to a significant increases in per Quinary runoff in the wetter east. Streamflow is the accumulated runoff from the quinary catchments according to the flow path in the QCD (see Chapter 5.2.2 in Methods). The accumulation of per-Quinary runoff downstream thus also translates into absolute changes between zero to significant increases for accumulated streamflow, especially in the wetter east, but also in those Quinary catchments containing the larger rivers flowing to the west, compared to the previous studies (Figure 5-1, bottom left; Schulze, 2011) and to the baseline scenario without eCO_2 effects (Figure 5-3, bottom left). By streamflow volume, the increases can be seen especially in the larger rivers flowing to the west, with a large upstream catchment area (ref Section 5.1.1), but also in the comparatively smaller rivers flowing to the east, but situated in a wetter climatic zone (Section 5.1.1; Schulze and Schütte, 2016), compared to the baseline scenario without eCO2 effects (Figure 5-3).

A reduction in maximum transpiration rate leads to an increase in visible water production in streams in the study area. The more the suppression, the higher the increase. The relative change in mean annual streamflow produced in the study area differs between the Primary catchments, with their different locations, river volumes, possibly different climatic zones and rainfall to runoff conversion (Schulze 2011; Schulze and Schütte, 2016; 2017; Section 5.1.1).

Scaling up of eCO_2 conductance changes from the leaf levels to canopy level involves many assumptions and often large error terms (Jarvis and Mcnaughton, 1986; Wilson et al., 1999; Baldocchi et al., 2001; Miglietta et al., 2011; Knauer et al., 2016) thus leading to numerous assumptions and algorithms used to represent this in models (see also Section 5.1.4). This field needs further clarification. The uncertainties of upscaling eCO_2 effects from leaf to canopy conductance also translates into uncertainties in upscaling transpiration. The usefulness of eCO_2 experiments could be improved if transpiration and total water use and supply would be measured and reported on consistently, including under water stressed conditions, alongside CO_2 levels.

By isolating the link between reduced maximum transpiration and hydrological responses, the sensitivities in SA could be shown. eCO_2 levels result in reduced maximum transpiration, and as equations become available to quantitatively link eCO_2 directly to maximum transpiration, this can be used to model hydrological effects in a more direct link between eCO_2 and hydrological responses. However, doing it this way provides for transparency in modelling as called for by Ainsworth et al. (2008); Section 5.1.4).

Changes in eCO_2 should not be ignored in hydrologically related climate change studies, as was also recommended by others (e.g. Leipprand and Gerten, 2006; Betts et al., 2007; Kruijt et al., 2008; Butcher et al., 2014). However, it must be borne in mind that this effect would be part of a range of possibly competing effects caused by eCO_2, including an increase in temperatures, possible changes in precipitation patterns and amount, changes in root-to-shoot ratio, increases of photosynthesis and changes in vegetation composition.

This paper contributes towards a better understanding of the links between the carbon and hydrological cycles through an assessment of sensitivities of reduced transpiration rates as a result of eCO_2 levels on hydrological responses in South Africa.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

In Chapter 1 an overview of the research was provided, including an outline of anticipated impacts of changes of carbon concentrations on hydrological responses, in order to facilitate the integration of the carbon cycle with the hydrological cycle at local scales. Carbon related impacts on the hydrological cycle were found and two effects were discussed in more detail as a background to enable better assessments of impacts of carbon concentration changes on hydrological responses in South Africa. An overview of the thesis structure was given, followed by the research statement. Thereafter sections on the significance of the research, research questions, activities and objectives followed.

To be able to assess impacts of soil organic carbon (SOC) on hydrological responses, the author was involved in a research project (Schütte et al., 2019), which set out to achieve just that, and results for the project were reported on in Chapter 2. A background on SOC was given, with special emphasis on previous findings in South Africa. Background information on several existing South African soils databases obtained from the Agricultural Research Council's (ARC's) Institute for Soil, Climate and Water was presented. One of the data bases included soil information at terrain unit spatial resolution, which is linked to the soils 'Land Type' information. Each of the more than 27 000 terrain units consists of several usually related soil series. The other soils database (ARC-ISCW, undated) contains, among other information, measured soil carbon contents. Methodologies were then developed for complementing and linking these databases. Median SOC contents for each soil series were calculated for both the topsoil and for the subsoil, and for both natural vegetation land cover and for agricultural land uses. Detailed mapped results of SOC contents were presented, again for the topsoil and the subsoil separately, and each for assumed natural vegetation and for agricultural land uses.

In Chapter 3, SOC content, via soil water attributes, were linked to hydrological responses. The impacts varied, *inter alia*, with soil texture as well as with the initial SOC content. Pedo-transfer functions that include SOC in addition to textural soil components were determined, and these could be used to calculate impacts of SOC changes on the soil water parameters of the drained upper limit, wilting point and porosity. In the absence of suitable South African derived pedo-transfer functions that include SOC, equations derived by Rawls et al. (2003; 2004) from US data were chosen in order to be able calculate these variables for South African soils.

In Chapter 4, these soil water variables were calculated for selected areas in South Africa for the actual SOC content taken from the soil carbon database developed and reported on in Chapter 2. Further scenarios were halving and doubling the actual SOC content, as well as using assumed SOC contents of 1%, 2% and 4%. Hydrological responses for these seven scenarios were modelled for selected areas in South Africa with different climate regimes, using the process-based daily time-step ACRU Agro-hydrological model (Schulze, 1995 and updates). All other soil-related, vegetation-related, location-related and climate-related inputs remained the same for all scenarios. Results showed that changes in SOC levels impacted on hydrological responses, by generally increasing transpiration, as well as by reducing the conversion of rainfall to runoff, with a reduction in peak discharge also shown. Overall, significant reductions in runoff were modelled, and these coming mainly from the stormflow component of runoff. As was expected, the magnitudes of these changes were influenced strongly by rainfall regimes and varied between the different climatic zones and inherent soil properties at the various locations examined.

In Chapter 5 the effects of elevated atmospheric carbon dioxide levels (eCO_2) on hydrological responses were explored. eCO_2 had been shown in experiments to impact on plant physiological processes, with increased photosynthesis and decreased stomatal and canopy conductance shown, by, for example, Ainsworth and Rogers (2007), Leakey et al., (2009) and Wehr et al. (2017). The latter usually translates into reduced transpiration (e.g. Long et al., 2004; Betts et al., 2007; Knauer et al., 2016; Wehr et al., 2017), which is an important hydrological response.

In South Africa, the ACRU model (Schulze, 1995) has frequently been used for hydrological climate change studies. The direct plant physiological effects of eCO_2 had to date, however, not been taken into account. In light of uncertainties and different approaches used in other hydrological and ecosystem models, it was decided that is was important to know what an eCO_2 induced reduction in maximum transpiration rate would imply in regards to hydrological responses in South Africa. Using again the ACRU model, an assumed 30% reduction in maximum transpiration, for example, resulted in a modelled reduction in mean annual actual transpiration of 13.5% per Quinary catchment, with a 20% maximum transpiration reduction leading to an 8.3% reduction in actual transpiration. With that, accumulated runoff from the study area was simulated to increase by 18% and 11% respectively.

6.2 Conclusions and recommendations

The research statement of this thesis was to focus on researching impacts of altered carbon concentrations in the soil and in the atmosphere on plant physiological water use and on soil water properties in South Africa, so as to be able to model these impacts on hydrological responses in order for hydrological projections to be improved. Changes in soil organic carbon as well as changes in atmospheric CO_2 content were identified as having impacts on hydrological responses.

This thesis has contributed to new and improved knowledge, by providing

- a better understanding of the impacts of changes in the carbon cycle on the hydrological cycle;
- a new methodology and fine-scale mapping of soil organic carbon at terrain unit spatial resolution for South Africa;
- a better understanding of impacts of changes in SOC on hydrological responses in general, and more specifically in South Africa in different climatic regimes;
- a quantification of sensitivities of hydrological responses to changes in SOC for selected areas in South Africa;
- a better understanding of impacts of eCO_2 on hydrological responses in general, and more specifically in South Africa;
- a quantification of sensitivities of hydrological responses to eCO_2 induced suppression in maximum transpiration in South Africa at a Quinary catchment scale.

In Chapter 2, mapping of SOC was undertaken at a spatial resolution and with innovative techniques thus far not attempted in South Africa. When comparing results from previous mapping exercises with results from this project, the overall soil carbon contents in the topsoil horizon appear fairly similar, but this research has provided much more spatial detail compared to that by Stronkhorst and Venter (2008).

While every step in the methodology was considered to be scientifically sound, further validation would be advisable. First, the matching process of the South African Binomial and Taxonomic soil classification systems (MacVicar et al., 1977; Soil Classification Working Group, 1991) should be further validated in future research work, so as to identify and correct any possible misinterpretations. Secondly, for a number of soil series other than those of the carbon rich organic soil form and the humic soil form, high SOC contents (> 2%) were found in other soil series. These soil series should be checked and re-assessed to identify whether the assumptions in obtaining these values were valid. Thirdly, in some cases anomalously high or anomalously low SOC estimates were obtained when using the developed methodology, and these results should be further scrutinised. Furthermore, additional in-field assessments of those soils identified to be high in SOC should be undertaken, to be able to consider protecting these soils as carbon sinks.

In this thesis, SOC maps were prepared assuming the entire area of South Africa to be either under natural vegetation or under agricultural land use practices. In reality though, South Africa consists of a mix of natural vegetation and land which has been converted to agricultural (and other) uses. These converted agricultural land uses may, furthermore, be under either intensive or extensive agricultural land practices, under commercial forest plantations or under irrigation, and thus they would vary on their impacts on SOC. Further research to account for impacts of actual land uses is advisable. Such an analysis would also show which areas with soils potentially high in SOC have already been irreversibly converted to, for example, urbanisation or to dams.

Additional research recommended also includes an assessment of SOC contents of soils within wetlands and possibly those soils experiencing lateral drainage, in intensive consultation with experienced soil scientists. The outcome of this research could also be used to calculate new and finer-scale soil erodibility factors which include SOC content in the equation. Lastly, more research into improving soil bulk density estimation in South Africa is recommended, as this would allow the conversion of soil carbon content into carbon densities and thus into soil carbon stocks.

The outcome of this project has, however, provided a way forward to be able to investigate impacts of changes in SOC on hydrological responses, reported on as a literature review in Chapter 3 and as an applied modelling study for selected areas in South Africa in Chapter 4. Soil carbon concentrations affect soil water holding capacities and by implication, therefore, hydrological responses, thus linking the hydrological cycle to the carbon cycle. These impacts differ depending on soil type, soil texture, SOC concentrations and climate. While soil water parameters were calculated for selected areas in South Africa using identified pedo-transfer functions containing carbon content, more research is, however, recommended on the update of the whole South African soil property databases, incorporating the new calculated soil water parameters of drained upper limit, wilting point and plant available water, and validating these based on observation. Furthermore, a better understanding of soil carbon water adsorption mechanisms would be beneficial to the research community in order to better understand SOC and the related soil organic matter impacts on soil water holding capacity.

SOC was shown to impact on hydrological responses in selected areas in South Africa (Chapter 4), but the magnitudes of these impacts are influenced strongly by rainfall regimes and vary amongst the different climatic zones and soil properties at the various locations examined in South Africa. In assessing daily runoff in a relatively humid area in the eastern part of the country, increased SOC led to reduced conversion of rainfall to runoff and generally reduced the peak discharge. A significant reduction in runoff was also modelled, with this resulting mainly from the stormflow component of runoff.

An increase in SOC often leads to transpiration increases, as was expected and also found by others (e.g. Long et al., 2004; Betts et al., 2007; Knauer et al., 2016; Ankenbauer and Loheide, 2017; Wehr et al., 2017). In this study, the increases in transpiration came predominantly from the topsoil horizons in which most plant roots are resident, with only small reductions from the subsoil horizons. This could possibly also be the result of infiltration properties not having been adjusted, given that it has been shown that the SOC also influences infiltration properties (Franzluebbers, 2002). Thus further research on impacts of SOC on soil water infiltration processes associated model algorithms is recommended, to be able to adjust the relevant variables and thereby improve simulated results.

For the first time in South Africa sensitivities of hydrological responses to SOC content changes have been calculated for selected locations with widely differing climatic regimes. While the results correspond to intuitive findings by others (e.g. Shaxson, 2006, in the USA), in this study a quantification of the overall reduction in runoff, and especially in stormflows, has been presented. Land management practices that increase carbon content would thus keep more water on the land, which would be available for plant use, and would thus usually lead to reduced runoff and flood events, but the impact depends on the location and other climatic and soil factors. The ability of the soil to hold more water, in turn, reduces runoff and its stormflow component and associated soil erosion, as well as steadying streamflows and reducing the effects of more extreme events such as high return period floods, thereby potentially increasing adaptation to climate extremes and climate change. Increased SOC, in addition to resulting in increased plant water availability, is a climate change mitigation measure and thus provides multiple benefits, validating findings by Paustian et al. (2016) and others. Agricultural and other practices leading to an increase of SOC should thus be supported by policy and regulation. Reducing SOC through, for example, certain agricultural practices, is likely to decrease soil water storage, thereby producing the opposite outcome, should be discouraged and rather be replaced by climate-smart practices.

The methodology developed in this study could be used for sensitivity studies elsewhere. Bearing in mind uncertainties regarding input values of soil carbon content, climate and other soil variables, as well as pedo-transfer functions established elsewhere in the world, further improvements to impact modelling can be made, especially if locally derived equations of soil water parameters of wilting point, drained upper limit and porosity which include a soil carbon factor were to become available. Changes in SOC contents also affects day-to-day soil water content, and further research is recommended on SOC impacts on plant growth in the form of changes to daily soil water contents, which could possibly reduce the impacts of dry spells on plant growth in the short term by increasing plant stress-free days, as well as influencing agricultural crop yield and primary production assessments. This analysis is recommended as a follow-up to the research presented.

Moving on to the atmospheric eCO_2 effects, as shown in Chapter 5, where assumed reductions in maximum transpiration rate lead respectively to modelled reductions in mean annual actual transpiration and to increases in accumulated runoff from the study area, the following are important. The maximum transpiration is the maximum or instantaneous rate for the vegetation type in a particular area, assuming optimum water availability, meaning no mild or sever water stress because of too little or too much water. The actual transpiration is usually lower than the maximum transpiration, because daily soil water content and hence stress is taken into account. Elevated CO_2 has been shown by others to reduce stomatal conductance, which has impacts on canopy conductance and translates into (instantaneous) transpiration suppression. Scaling up of eCO_2 conductance changes from the leaf level to canopy level involves many assumptions and often large error terms (Jarvis and Mcnaughton, 1986; Wilson et al., 1999; Baldocchi et al., 2001; Miglietta et al., 2011; Knauer et al., 2016) thus leading to numerous assumptions in the algorithms used to represent this process in models. This field needs further clarification. The uncertainties of upscaling eCO_2 effects from leaf to canopy conductance also translates into uncertainties in upscaling transpiration. The usefulness of eCO_2 experiments could be improved if transpiration and total water use would be measured and reported on consistently, including under water stressed conditions.

In this study, the maximum transpiration was suppressed by up to 30% to account for an up to doubling of pre-industrial CO_2 levels. The higher the suppression of maximum transpiration, the higher the potential is for the suppression in actual transpiration. However, strong spatial differences were seen across the study area and the differences can be between zero, or small, absolute change in the drier areas where there is no (or hardly any) water available for transpiration, to significant changes in the wetter areas of the east.

The higher the suppression of maximum transpiration, the higher the potential for an increase in runoff. Again, strong spatial differences were seen and the changes in the drier western areas were between zero (or very little) increase to significant increases in Quinary catchment runoff in the wetter east. This also translates into absolute changes between zero to significant increases for accumulated streamflow, especially in the wetter east, but also in those Quinary catchments containing the larger rivers flowing towards the west. In regards to streamflow volumes, the increases can be seen especially in the larger rivers flowing to the west, were these larger rivers have a large upstream catchment area in the wetter east, but the effect is also seen in the comparatively smaller rivers flowing to the east, but situated in a wetter climatic zone.

A reduction in maximum transpiration rate leads to an increase in water production in streams in the study area. The more the suppression, the higher the increase. The relative change in mean annual streamflow produced in the study area varies amongst the Primary catchments with their different locations and different climatic zones, and hence different rainfall to runoff conversions. Further research could link the differences in response magnitudes to the Köppen climate zones.

The quantification of the direct eCO_2 effect on transpiration was also found to be complex, and no easy algorithm was found to describe this. If this algorithm were to have existed, this could have been programmed into the ACRU model. However, once the science is more advanced on the impacts of eCO_2 and transpiration effects, this can be programmed into ACRU more directly, rather than indirectly as a percentage of maximum transpiration suppression, thereby providing for more transparency in modelling, as called for by Ainsworth et al. (2008). By isolating the link between reduced maximum transpiration and hydrological responses, the sensitivities in South Africa could be shown. As equations become available to link eCO_2 directly to maximum transpiration, this can be used to model hydrological effects in a more direct manner.

This study found that changes in eCO_2 should not be ignored in hydrologically related climate change studies, as has also been recommended by others (e.g. Leipprand and Gerten, 2006; Betts et al., 2007; Kruijt et al., 2008; Butcher et al., 2014). However, it must be borne in mind that this effect would be part of a range of possibly competing counteracting effects caused by eCO_2, including any increase in temperature which enhances evaporation rates, possible changes in precipitation patterns and amounts, changes in root-to-shoot ratios, increases of photosynthesis and changes in vegetation composition. This is thus a higher complex system to model, as was found by others (e.g. Baldocchi et al., 2001; Medlyn et al., 2015; Vanuytrecht and Thorburn, 2017). A recommendation for future research is to assess the impacts of reduced maximum transpiration on selected areas within South Africa, located in different climatic zones. The original intention of this component of research was to account for more eCO_2 factors which impact on hydrological responses, including root-to-shoot ratios, photosynthesis changes and vegetation changes. However, this was found to be not feasible at this stage for South Africa, as there were too many uncertainties still to be resolved, both worldwide and in South Africa. A recommendation to improve the usefulness of eCO_2 experiments is that transpiration and total water use and supply would be measured and reported on consistently, including under water stressed conditions, alongside CO_2 levels.

Given the above discussion, this thesis contributes towards a better understanding of the links between the carbon and hydrological cycles, and especially the impacts of soil organic carbon on hydrological responses, as well as the impacts of atmospheric CO_2 on hydrological responses in South Africa.

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8. APPENDICES

Table 8-1 Original land cover groupings in the Soil Carbon Database and simplified land cover clusters

Land Cover per original ARC Classification	**Land Cover Grouping (simplified)**
Blank	Unspecified
Abandoned field / Disturbed land	Agricultural
Agronomic cash crops	Agricultural
Barren	Natural vegetation
Built-up area	Other
Bushland	Natural vegetation
Cultivated flowers	Agricultural
Cultivated pastures	Agricultural
Cultivated, unknown	Agricultural
Dwarf shrubveld, open	Natural vegetation
Dwarf shrubveld, sparse	Natural vegetation
Fruit trees	Agricultural
Fynbos	Natural vegetation
Grassveld, closed	Natural vegetation
Grassveld, open	Natural vegetation
Grassveld, sparse	Natural vegetation
Marsh	Natural vegetation
Natural forest	Natural vegetation
Normal weathering	Natural vegetation
Origin unknown	Unspecified
Other	Other
Other fragments	Other
Plantation (Forestry)	Agricultural
Plantation (Non-Forestry)	Agricultural
Shrubveld, closed	Natural vegetation
Shrubveld, closed dwarf	Natural vegetation

Land Cover per original ARC Classification	**Land Cover Grouping (simplified)**
Shrubveld, open	Natural vegetation
Shrubveld, open dwarf	Natural vegetation
Shrubveld, sparse	Natural vegetation
Shrubveld, sparse dwarf	Natural vegetation
Succulent (Karoo)	Natural vegetation
Thicket	Natural vegetation
Treeveld, closed	Natural vegetation
Treeveld, open	Natural vegetation
Treeveld, sparse	Natural vegetation
Type unknown	Unspecified
Unknown	Unspecified
Vegetables	Agricultural
Vineyards	Agricultural

Table 8-2 Examples of matching of soil classes from the Taxonomic to the Binomial system, the left column showing the soil class, the next two columns showing the number of samples found for each soil series in the topsoil - and subsoil horizons and the single or multiple association of pool of soil series from which the median soil carbon content was calculated for each soil series. For the full table and more details please see the full report (Schütte et al., 2019), which also distinguishes between natural vegetation and agricultural land uses

Natural Vegetation			
Binomial	Topsoil horizon	Subsoil horizon	Sample pool: binomial and taxonomic
Soil series	No. locations Carbon %	No. locations Carbon %	Single or Multiple Association
Ar10	24	1	Ar10
Ar11	1	0	Ar11new=Ar11+Ar10+Ar12
Ar12	2	1	Ar11new
Ar20	37	24	Ar20
Ar21	2	1	Ar21new=Ar20+Ar21+Ar22
Ar22	3	1	Ar21new
Ar30	7	3	Ar30
Ar31	4	0	Ar31new=Ar31+Ar30
Ar32	0	0	Ar31new
Ar40	28	20	Ar40
Ar41	2	1	Ar41new=Ar41+Ar40
Ar42	1	1	Ar42new=Ar42+Ar40
Av10	0	0	Cv10
Av11	1	1	Av11new=Av11+Cv11+Cv10
Av12	0	0	Cv10
Av13	1	0	Av13new=Av13+Av15+Cv14
Av14	0	0	Cv14
Av15	2	2	Av15new=Av15+Cv14+Cv15
Av16	18	15	Av16
Av17	10	9	Av17
Av20	0	0	Cv21
Av21	2	1	Av21new=Av21+Cv21
Av22	1	1	Av22new=Av22+Cv22
Av23	1	0	Av23new=Av23+Cv23
Av24	18	4	Av24
Av25	3	3	Av25new=Av25+Av24
Av26	38	29	Av26
Av27	11	10	Av27
Av30	2	2	Av30new=Av30+Av31
Av31	12	7	Av31
Av32	0	0	Av31

Table 8-3 Median soil carbon content (% by mass) for the topsoil and subsoil horizon under land cover conditions of natural vegetation and agricultural land uses

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Ar10	1.795	1.07	0.82	0.775
Ar11	1.65	0.78	0.82	0.775
Ar12	1.65	0.78	0.82	0.775
Ar20	1.25	0.7	1.26	0.86
Ar21	1.165	0.7	1.32	0.875
Ar22	1.165	0.7	1.32	0.875
Ar30	2	1.207	1.055	1.49
Ar31	3.08	1.206	1.055	1.49
Ar32	3.08	1.206	1.055	1.49
Ar40	1.525	0.7	0.8	0.5
Ar41	1.41	0.7	0.8	0.5
Ar42	1.5	0.7	0.8	0.5
Av10	0.65	N/A	0.36	0.15
Av11	0.445	0.23	0.36	0.15
Av12	0.65	N/A	0.36	0.17
Av13	0.75	0.34	0.36	0.17
Av14	0.77	0.5	0.3	0.169
Av15	0.62	0.324	0.3	0.169
Av16	1.15	0.384	0.3	0.169
Av17	2.4	0.549	0.36	0.195
Av20	0.43	0.19	0.36	0.25
Av21	0.45	0.271	0.36	0.2
Av22	1.215	0.108	0.625	0.215
Av23	0.89	0.174	0.46	0.21
Av24	1.115	0.415	0.26	0.1
Av25	1	0.37	0.79	0.21
Av26	0.7	0.3	0.88	0.379
Av27	1.25	0.37	1.1	0.46
Av30	0.29	0.12	0.29	0.14
Av31	0.29	0.12	0.29	0.14
Av32	0.29	0.12	0.28	0.23
Av33	0.4	0.3	0.28	0.23
Av34	0.55	0.185	0.28	0.23
Av35	0.53	0.2	1.18	0.588
Av36	0.655	0.3	0.31	0.33
Av37	0.99	0.399	1.89	1.09
Bo10	2.3	1.11	2.4	1.11
Bo11	2.76	1.115	2.66	0.925

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Bo20	1.2	0.278	2.22	1.11
Bo21	1.265	0.511	1.46	0.56
Bo30	2.27	0.472	1.36	0.6
Bo31	2.635	1.01	0.31	0.16
Bo40	1.2	0.3	1.89	1.09
Bo41	1.355	0.441	1.355	0.6
Bv10	0.59	0.23	0.3	0.169
Bv11	0.445	0.23	0.3	0.169
Bv12	0.445	0.23	0.3	0.169
Bv13	0.75	0.34	0.3	0.169
Bv14	0.75	0.5	0.3	0.169
Bv15	0.62	0.324	1.01	0.335
Bv16	1.19	0.381	2.07	0.657
Bv17	2.6	0.627	0.36	0.195
Bv20	0.44	0.21	0.36	0.23
Bv21	0.44	0.21	0.36	0.2
Bv22	0.43	0.13	0.625	0.215
Bv23	0.98	0.174	0.36	0.225
Bv24	1	0.37	0.26	0.1
Bv25	0.6	0.233	0.85	0.46
Bv26	0.735	0.306	0.785	0.485
Bv27	1.4	0.37	0.85	0.46
Bv30	0.455	0.1	0.23	0.1
Bv31	0.29	0.12	0.29	0.14
Bv32	0.36	0.196	0.28	0.23
Bv33	1.4	0.37	0.2	0.23
Bv34	1.01	0.3	0.2	0.23
Bv35	1.4	0.37	0.24	0.24
Bv36	0.5	0.304	0.33	0.34
Bv37	1	0.403	1.15	0.601
Cf10	0.92	0.18	0.73	0.28
Cf11	0.8	0.38	0.71	0.382
Cf12	1.365	0.676	1.285	0.636
Cf13	1.3	1.015	0.75	0.47
Cf20	0.6	0.17	0.26	0.145
Cf21	1.185	0.446	0.635	0.322
Cf22	1.4	0.904	0.69	0.325
Cf30	0.6	0.2	0.8	0.31
Cf31	0.65	0.28	0.71	0.382
Cf32	1.52	0.904	0.91	0.364
Ch10	13.3	6.26	7.05	1.411

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Ch11	11.505	6.26	7.05	1.411
Ch20	9.2	1.05	7.05	1.411
Ch21	9.28	1.05	7.05	1.411
Ct10	0.93	0.155	0.52	0.153
Ct11	0.91	0.204	0.52	0.153
Ct12	0.89	0.254	0.52	0.153
Ct13	1.2	0.497	1.16	0.383
Ct14	1.21	0.587	1.16	0.383
Ct15	1.21	0.587	1.16	0.383
Ct20	0.28	0.187	0.83	0.175
Ct21	0.28	0.187	0.83	0.175
Ct22	0.28	0.187	0.83	0.175
Ct23	0.53	0.17	0.8	0.46
Ct24	0.53	0.17	0.8	0.46
Ct25	0.53	0.17	0.8	0.46
Cv10	0.65	N/A	0.36	0.15
Cv11	0.65	N/A	0.36	0.15
Cv12	0.65	N/A	0.36	0.17
Cv13	0.685	0.34	0.3	0.169
Cv14	0.77	0.5	0.3	0.169
Cv15	0.75	0.42	0.3	0.169
Cv16	1.77	0.56	1.2	0.65
Cv17	2.95	0.835	2.7	0.65
Cv18	3.29	1.036	2	0.7
Cv20	0.43	0.19	0.36	0.19
Cv21	0.43	0.19	0.36	0.19
Cv22	0.44	0.11	0.36	0.195
Cv23	0.8	0.174	0.36	0.23
Cv24	0.7	0.147	0.335	0.24
Cv25	0.7	0.196	0.335	0.24
Cv26	1.39	0.5	1	0.391
Cv27	1.32	0.57	1.4	0.71
Cv28	2.49	0.91	1.89	0.839
Cv30	0.455	0.1	0.29	0.145
Cv31	0.36	0.196	0.29	0.15
Cv32	0.36	0.196	0.29	0.15
Cv33	0.2	0.1	0.39	0.2
Cv34	0.565	0.225	0.39	0.22
Cv35	0.73	0.513	0.39	0.22
Cv36	0.89	0.4	0.55	0.44
Cv37	0.8	0.326	1	0.6

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Cv38	1.63	0.7	1.47	0.82
Cv40	0.4	0.155	0.29	0.145
Cv41	0.35	0.128	0.29	0.15
Cv42	0.3	0.14	0.29	0.15
Cv43	0.245	0.12	0.39	0.2
Cv44	0.57	0.26	0.39	0.22
Cv45	0.76	0.531	0.39	0.22
Cv46	0.4	0.282	0.55	0.44
Cv47	0.8	0.326	1	0.6
Cv48	1.585	0.7	1.47	0.82
Du10	0.7	0.399	0.865	0.375
Es10	0.5	0.1	0.515	0.161
Es11	0.5	0.153	0.515	0.161
Es12	0.62	0.183	0.76	0.142
Es13	0.6	0.27	1.2	0.38
Es14	0.67	0.268	0.94	0.35
Es15	1.115	0.352	0.82	0.351
Es16	1.086	0.643	1.285	0.56
Es17	0.93	0.56	0.805	0.47
Es20	0.51	0.333	0.49	0.208
Es21	0.615	0.237	0.49	0.208
Es22	0.71	0.2	0.3	0.2
Es30	0.46	0.148	0.57	0.237
Es31	0.53	0.183	0.57	0.237
Es32	0.5	0.174	0.57	0.237
Es33	0.59	0.3	0.81	0.394
Es34	0.6	0.325	1.04	0.338
Es35	1.15	0.302	1.27	0.419
Es36	0.795	0.4	1.08	0.608
Es37	0.905	0.537	0.59	0.29
Es40	0.5	0.305	0.45	0.2
Es41	0.405	0.2	0.45	0.2
Es42	0.405	0.2	0.45	0.2
Fw10	0.675	0.1	0.27	0.155
Fw11	0.36	0.18	0.27	0.155
Fw12	0.36	0.18	0.27	0.155
Fw20	0.44	0.1	0.28	0.155
Fw21	0.2	0.27	0.28	0.16
Fw22	0.25	0.187	0.27	0.155
Fw30	0.675	0.1	0.27	0.155
Fw31	1.44	0.1	0.28	0.145

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Fw32	0.4	0.1	0.27	0.155
Fw40	0.5	0.1	0.27	0.155
Fw41	0.44	0.23	0.27	0.155
Fw42	1.27	0.1	0.27	0.155
Gc10	0.65	N/A	0.36	0.15
Gc11	0.65	N/A	0.36	0.15
Gc12	0.65	N/A	0.36	0.15
Gc13	0.57	0.198	0.3	0.169
Gc14	0.57	0.198	0.3	0.169
Gc15	0.57	0.198	0.3	0.169
Gc16	1.19	0.396	1.035	0.462
Gc17	2.2	0.549	2.625	0.654
Gc20	0.43	0.15	0.36	0.195
Gc21	0.43	0.15	0.36	0.195
Gc22	0.43	0.15	0.36	0.195
Gc23	0.6	0.3	0.93	0.27
Gc24	0.625	0.317	0.93	0.27
Gc25	0.725	0.316	0.93	0.27
Gc26	0.85	0.2	0.83	0.379
Gc27	1.25	0.37	1.98	0.76
Gc30	0.29	0.12	0.26	0.1
Gc31	0.29	0.12	0.29	0.14
Gc32	0.3	0.125	0.27	0.1
Gc33	0.4	0.226	0.27	0.1
Gc34	0.61	0.17	0.28	0.23
Gc35	0.7	0.407	0.39	0.295
Gc36	0.655	0.307	0.31	0.33
Gc37	0.99	0.399	1.18	0.588
Gf10	2.95	0.956	0.3	0.169
Gf11	2.95	0.956	1.66	0.58
Gf12	3	0.878	1.5	0.5
Gf13	3.54	0.91	1	0.469
Gf20	0.605	0.2	0.335	0.26
Gf21	3.63	0.786	0.74	0.353
Gf22	3.1	1.125	1.38	0.7
Gf23	2.5	0.929	1.685	0.81
Gf30	0.48	0.23	0.33	0.27
Gf31	0.7	0.36	0.54	0.355
Gf32	1.165	0.5	0.96	0.6
Gf33	1.63	0.7	1.685	0.89
Gs10	0.61	0.3	0.57	0.28

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Gs11	0.61	0.3	0.57	0.28
Gs12	0.51	0.4	0.57	0.28
Gs13	0.82	0.42	0.7	0.4
Gs14	0.76	0.485	0.62	0.38
Gs15	0.63	0.544	0.62	0.38
Gs16	1.59	0.615	1.1	0.5
Gs17	1.565	1.155	1.74	0.66
Gs18	1.6	0.915	1.66	0.58
Gs19	2.16	0.98	1.345	0.55
Gs20	0.6	0.203	0.57	0.28
Gs21	0.6	0.203	0.57	0.28
Gs22	0.6	0.203	0.57	0.28
Gs23	0.3	0.3	0.7	0.4
Gs24	1.04	0.45	0.62	0.38
Gs25	0.905	0.375	0.62	0.38
Gs26	0.5	0.4	1.1	0.5
Gs27	1.135	N/A	1.74	0.66
Gs28	0.82	0.5	1.66	0.58
Gs29	2.16	0.98	1.345	0.55
Hh10	0.72	0.218	0.64	0.325
Hh11	2	1.44	1.18	0.421
Hh20	0.725	0.236	0.64	0.325
Hh21	2	1.44	1.18	0.421
Hh30	0.9	0.295	0.64	0.325
Hh31	1.5	1.22	1.18	0.421
Hu10	0.65	N/A	0.35	0.145
Hu11	0.67	N/A	0.35	0.145
Hu12	0.65	N/A	0.35	0.145
Hu13	0.52	N/A	0.3	0.169
Hu14	0.52	N/A	0.3	0.169
Hu15	0.52	0.1	0.3	0.169
Hu16	1.57	0.442	0.895	0.458
Hu17	2.4	0.611	1.7	0.605
Hu18	3.2	0.93	1.97	0.699
Hu20	0.745	0.079	0.35	0.17
Hu21	0.42	0.135	0.35	0.17
Hu22	0.42	0.135	0.36	0.19
Hu23	0.48	0.23	0.335	0.26
Hu24	0.48	0.23	0.33	0.27
Hu25	0.3	0.1	0.33	0.27
Hu26	1.03	0.395	0.72	0.335

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Hu27	1.75	0.505	1.34	0.7
Hu28	2.49	0.91	1.89	0.839
Hu30	0.125	0.132	0.305	0.19
Hu31	0.3	0.11	0.305	0.19
Hu32	0.2	0.1	0.31	0.215
Hu33	0.24	0.2	0.485	0.2
Hu34	0.5	0.23	0.27	0.22
Hu35	0.4	0.2	0.27	0.22
Hu36	0.695	0.36	0.54	0.355
Hu37	1.165	0.5	0.96	0.6
Hu38	1.63	0.7	1.685	0.89
Hu40	0.2	0.1	0.305	0.19
Hu41	0.2	0.1	0.305	0.19
Hu42	0.2	0.15	0.31	0.215
Hu43	0.335	0.267	0.485	0.2
Hu44	0.19	0.12	0.27	0.22
Hu45	0.2	0.1	0.27	0.22
Hu46	0.385	0.26	0.54	0.355
Hu47	1.1	0.5	0.96	0.6
Hu48	1.585	0.7	1.685	0.89
Ia10	3.54	1.61	2.19	0.6
Ia11	3.21	0.864	2.46	0.812
Ia12	3.275	0.836	3.31	1.27
Ik10	2.095	1.28	2.57	1.13
Ik11	3.045	1.83	2.72	0.932
Ik20	0.895	0.463	1.13	0.34
Ik21	1.27	0.511	1.355	0.555
Ka10	1.7	0.6	2.08	1.86
Ka20	1.08	0.348	1.065	0.63
Kd10	0.5	0.1	0.45	0.159
Kd11	0.5	0.153	0.47	0.161
Kd12	0.62	0.183	0.47	0.158
Kd13	0.65	0.312	0.9	0.29
Kd14	1.07	0.397	0.81	0.337
Kd15	1.15	0.274	0.81	0.337
Kd16	1.105	0.495	0.915	0.6
Kd17	1.55	0.5	1.08	0.608
Kd18	1.9	0.581	1.19	0.56
Kd19	1.17	0.53	0.3	0.25
Kd20	0.5	0.253	0.4	0.2
Kd21	0.505	0.2	0.4	0.2

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Kd22	0.51	0.176	0.35	0.2
Kp10	3.9	0.944	3.875	2.06
Kp11	3.06	0.813	2.46	0.872
Kp12	3.7	0.788	3.31	1.27
Lo10	0.67	0.16	0.685	0.28
Lo11	0.695	0.197	0.525	0.243
Lo12	1	0.222	0.945	0.364
Lo13	1.2	0.24	0.75	0.47
Lo20	0.535	0.187	0.33	0.13
Lo21	0.81	0.29	0.635	0.322
Lo22	0.9	0.44	0.59	0.323
Lo30	0.6	0.2	0.42	0.151
Lo31	0.75	0.343	0.645	0.331
Lo32	1.45	0.748	0.64	0.325
Lt10	0.61	0.2	0.52	0.08
Lt11	0.72	0.246	0.5	0.2
Lt12	0.81	0.291	1.21	0.588
Lt13	2	1.44	1.16	0.383
Lt14	1.5	1.129	1.18	0.421
Lt15	1.5	1	1.16	0.383
Lt20	0.61	0.2	0.33	0.13
Lt21	0.72	0.246	0.635	0.322
Lt22	0.81	0.291	0.59	0.323
Lt23	2	1.44	1.18	0.421
Lt24	1.5	1.129	1.18	0.421
Lt25	1.5	1	1.16	0.383
Ma10	2.63	1.167	2.13	0.59
Ma11	2.77	1.151	2.46	0.872
Ma12	3.535	N/A	3.31	1.27
Ms10	0.84	0.62	1.22	#VALUE!
Ms11	0.79	0.395	1.22	N/A
Ms12	0.83	0.396	1.22	N/A
Ms13	0.385	N/A	1.22	N/A
Ms14	0.385	N/A	1.22	N/A
Ms20	0.59	0.2	1.26	N/A
Ms21	0.775	0.33	1.26	N/A
Ms22	0.775	0.33	1.68	#VALUE!
Ms23	0.775	0.33	1.26	N/A
Ms24	0.36	N/A	1.26	N/A
Mw10	3.245	0.4	2.6	1.23
Mw11	2.845	0.8	3.2	0.6

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Mw20	2.16	0.68	2.6	1.23
Mw21	1.78	1.124	1.355	0.555
My10	2.4	0.653	2.6	1.23
My11	2.81	1.06	3.2	0.6
My20	2.16	0.68	1.355	0.555
My21	1.78	1.124	1.355	0.555
No10	2.895	1.3	2.75	1.66
No11	3.345	3.51	3.74	0.93
Oa10	0.42	0.52	0.36	0.15
Oa11	0.42	0.52	0.36	0.15
Oa12	0.465	0.5	0.36	0.15
Oa13	0.43	0.39	0.38	0.2
Oa14	0.76	0.25	0.38	0.2
Oa15	0.76	0.48	0.38	0.2
Oa16	0.68	0.306	1.01	0.525
Oa17	0.935	0.41	0.65	0.356
Oa20	0.3	0.87	0.36	0.19
Oa21	0.3	0.87	0.36	0.19
Oa22	0.3	0.87	0.36	0.19
Oa23	0.47	0.295	0.545	0.235
Oa24	0.425	0.33	0.69	0.25
Oa25	0.42	0.32	0.69	0.25
Oa26	0.67	0.42	0.795	0.398
Oa27	0.74	0.32	0.98	0.614
Oa30	0.42	0.52	0.29	0.145
Oa31	0.39	0.5	0.29	0.15
Oa32	0.405	0.48	0.29	0.15
Oa33	0.465	0.39	0.55	0.6
Oa34	0.72	0.34	0.565	0.6
Oa35	0.785	0.37	0.565	0.6
Oa36	1.13	0.597	0.845	0.73
Oa37	1.315	0.822	1.06	0.59
Oa40	0.47	0.37	0.29	0.145
Oa41	0.47	0.37	0.29	0.15
Oa42	0.47	0.37	0.29	0.15
Oa43	0.45	0.254	0.795	0.27
Oa44	0.735	0.42	0.8	0.26
Oa45	0.68	0.39	0.8	0.26
Oa46	0.76	0.394	0.76	0.402
Oa47	0.89	0.508	1.31	0.685
Pn10	0.65	N/A	0.27	0.14

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Pn11	0.65	N/A	0.305	0.13
Pn12	0.65	N/A	0.27	0.14
Pn13	0.685	0.34	0.3	0.169
Pn14	0.77	0.5	0.3	0.169
Pn15	0.77	0.42	0.3	0.169
Pn16	1.72	0.56	1.2	0.65
Pn17	2.95	0.8	2.625	0.735
Pn20	0.43	0.19	0.27	0.18
Pn21	0.43	0.19	0.34	0.185
Pn22	0.69	0.066	0.31	0.186
Pn23	0.89	0.174	0.61	0.24
Pn24	0.89	0.57	0.46	0.25
Pn25	1.015	0.57	0.46	0.25
Pn26	1.4	0.5	1	0.391
Pn27	1.32	0.57	2.195	0.798
Pn30	0.42	0.16	0.2	0.1
Pn31	0.42	0.16	0.285	0.14
Pn32	0.42	0.16	0.28	0.1
Pn33	0.53	0.16	0.405	0.293
Pn34	1.04	N/A	0.405	0.293
Pn35	0.53	0.16	0.405	0.293
Pn36	1.035	0.421	0.64	0.36
Pn37	0.79	0.359	1.19	0.55
Rg10	1.805	0.59	0.9	0.735
Rg20	1.26	0.312	1.335	0.41
Sd10	2.1	0.88	1.01	0.525
Sd11	1.94	1.375	1.23	0.5
Sd12	2.585	0.75	1.98	0.7
Sd20	0.79	0.4	1.01	0.43
Sd21	1.43	0.662	1.6	0.56
Sd22	2.095	0.97	1.545	0.87
Sd30	0.4	0.3	0.795	0.398
Sd31	0.6	0.371	0.975	0.532
Sd32	1.63	0.7	1.08	0.65
Sp10	0.93	0.155	0.52	0.153
Sp11	0.91	0.204	0.52	0.153
Sp12	0.89	0.254	0.52	0.153
Sp13	1.2	0.497	1.16	0.383
Sp14	1.2	0.497	1.16	0.383
Sp15	1.2	0.497	1.16	0.383
Sp20	0.28	0.187	0.83	0.175

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Sp21	0.28	0.187	0.83	0.175
Sp22	0.28	0.187	0.83	0.175
Sp23	0.35	0.104	0.995	0.379
Sp24	0.53	0.19	0.83	0.383
Sp25	0.45	1.365	0.83	0.383
Ss10	0.2	0.191	1.23	0.55
Ss11	0.225	0.23	0.775	0.49
Ss12	0.225	0.23	1.145	0.715
Ss13	0.36	0.32	0.63	0.415
Ss14	0.48	0.493	0.63	0.415
Ss15	0.7	0.489	0.63	0.415
Ss16	0.7	0.4	0.61	0.36
Ss17	0.935	0.41	0.65	0.356
Ss20	0.365	0.485	0.21	0.34
Ss21	0.365	0.485	0.21	0.34
Ss22	0.39	0.48	0.21	0.34
Ss23	0.48	0.293	0.485	0.485
Ss24	0.6	0.43	0.56	0.57
Ss25	0.615	0.535	0.56	0.57
Ss26	0.9	0.49	1.13	0.71
Ss27	1.77	0.64	0.98	0.614
Sw10	0.87	0.665	0.51	0.54
Sw11	0.84	0.615	0.955	0.569
Sw12	1.1	0.8	1.2	0.73
Sw20	0.45	0.38	0.7	0.4
Sw21	0.72	0.595	0.78	0.41
Sw22	1.175	0.765	1.2	0.608
Sw30	1	0.63	1	0.43
Sw31	1.06	0.742	0.655	0.52
Sw32	1.025	0.75	0.715	0.57
Sw40	0.79	0.455	0.8	0.51
Sw41	1.05	0.543	0.72	0.432
Sw42	0.99	0.635	0.815	0.83
Tk10	2.16	1.415	2.57	1.13
Tk11	3.045	1.83	2.72	0.932
Tk20	0.895	0.463	2.22	1.11
Tk21	1.27	0.5	1.355	0.555
Va10	1.07	0.411	1.41	0.621
Va11	0.85	0.535	0.83	0.58
Va12	1.11	0.74	1.145	0.715
Va20	0.725	0.3	0.7	0.29

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Va21	0.8	0.4	0.76	0.395
Va22	0.91	0.576	1.015	0.628
Va30	1.16	0.54	0.58	0.61
Va31	1.3	0.685	1.16	0.775
Va32	0.85	0.6	1.155	0.8
Va40	0.9	0.473	0.9	0.535
Va41	0.785	0.4	0.72	0.432
Va42	0.77	0.549	1.015	0.6
Vf10	0.35	0.11	0.52	0.153
Vf11	0.335	0.104	0.52	0.153
Vf12	0.35	0.11	0.52	0.153
Vf13	1.21	0.587	1.16	0.383
Vf14	1.12	0.587	1.16	0.383
Vf15	1.12	0.587	1.16	0.383
Vf20	0.28	0.187	0.675	0.15
Vf21	0.28	0.187	0.675	0.15
Vf22	0.28	0.187	0.675	0.15
Vf23	1.5	0.943	0.8	0.46
Vf24	0.3	1.89	0.8	0.46
Vf25	0.45	1.365	0.8	0.46
Vf30	0.35	0.11	0.52	0.153
Vf31	0.32	0.104	0.52	0.153
Vf32	0.455	0.2	0.52	0.153
Vf33	1.3	0.677	1.16	0.383
Vf34	1.015	0.497	1.16	0.383
Vf35	0.785	0.37	1.16	0.383
Vf40	0.29	0.225	0.675	0.15
Vf41	0.29	0.225	0.675	0.15
Vf42	0.29	0.23	0.675	0.15
Vf43	1.5	0.943	0.8	0.46
Vf44	0.3	1.89	0.8	0.46
Vf45	0.45	1.365	0.8	0.46
Wa10	0.3	0.18	0.685	0.28
Wa11	0.695	0.405	0.71	0.382
Wa12	0.91	0.61	1.285	0.636
Wa13	1.2	0.24	0.75	0.47
Wa20	0.56	0.187	0.26	0.145
Wa21	0.515	0.205	0.63	0.375
Wa22	0.9	0.371	0.69	0.325
Wa30	0.555	0.2	0.42	0.151
Wa31	0.515	0.28	0.645	0.331

Soil class	Median Soil Carbon content (%)			
	Natural Vegetation (incl. Unspecified)		Agricultural Land Uses	
	Topsoil	Subsoil	Topsoil	Subsoil
Wa32	1.28	0.282	0.64	0.325
We10	0.43	0.19	0.35	0.165
We11	0.75	0.34	0.32	0.225
We12	0.5	0.333	0.32	0.18
We13	0.9	0.48	0.72	0.5
We20	0.79	N/A	0.35	0.2
We21	0.72	0.63	0.6	0.33
We22	0.98	0.52	0.645	0.375
We30	2.19	0.15	0.38	0.17
We31	0.535	0.198	0.36	0.205
We32	0.7	0.3	1.12	0.37
Wo10	1.7	0.384	2.03	1.11
Wo11	2.095	0.64	1.32	0.6
Wo20	1.82	0.2	1.89	1.09
Wo21	1.355	0.441	1.355	0.6