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Research paper

Critical source areas of diffuse nutrient and suspended solid pollutants – an assessment in two contrasting South African catchments

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Water quality in South Africa's river systems is declining, driven in part by changes in land use and management. Diffuse pollution significantly contributes to river degradation, requiring identification of critical source areas of diffuse pollutants, including nutrients and suspended solids. This study assesses diffuse pollution risks in two contrasting catchments: the Thukela and the Breede. A risk-based assessment was undertaken using the Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP). SCIMAP integrates a digital elevation model (to determine hydrological connectivity), land use based diffuse pollution potential, here assessed from national land cover classes using the Automated Land-based Activity Risk Assessment Method (ALARM), and rainfall information (representing runoff dilution potential). Results are presented as (i) risk generation of diffuse nutrients based on land use attributes, (ii) the connectivity risk of the movement of pollutants to the river channel, (iii) nutrient risk from the landscape component's critical source areas, (iv) nutrient concentration risk in the channel component of the catchment, and (v) suspended solid risks from the landscape component. In the Thukela Catchment, landscape-scale nutrient risk patterns were relatively uniform at catchment scale, with distinctions only emerging at finer spatial scales, where elevated risks were associated with some commercial and subsistence agricultural areas. The Breede Catchment exhibited distinct nutrient risk patterns even at catchment scale, with high-risk areas closely linked to some commercial agriculture areas. Channel segments of high nutrient risk for both catchments became evident only at detailed spatial scales. Landscape-based diffuse suspended solids risk areas within the Thukela Catchment range from lows under undisturbed natural vegetation or areas of low connectivity, to highs dominated by degradation and subsistence farming, combined with a high connectivity risk. The Breede Catchment was more muted. This approach is useful to backtrack from polluted river sections to areas with high risk of generating and mobilising pollutants.

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INTRODUCTION

The South African National Water Act (No. 36 of 1998) stipulates that water of adequate quality and quantity is required for basic human needs and for the functioning of ecosystems. The deteriorating water quality in the river systems of South Africa (SA) is caused, inter alia, by land use changes in SA's catchments since the 1850s, with diffuse pollution contributing significantly to river degradation (Nsibirwa, 2018). Nutrients, sediments, organic materials, pathogens and metals are different forms of possible pollutants. The environmental problems of water pollution include eutrophication, unpleasant smells, high microbial activity and reduced water clarity. Nutrient pollution is the cause of eutrophication, which may arise when excessive nutrients, often from fertilisers, reach water bodies, which may lead to algal blooms, oxygen depletion, possible toxicity of algae, odour and taste deterioration, biodiversity loss, reduced aesthetics and increased water purification needs (Nyenje et al., 2010; Matthews and Bernard, 2015; Nsibirwa, 2018).

While causes and effects of point pollution are more straightforward to identify, non-point-source pollution is more difficult to monitor and manage, contributing to SA's surface water degradation (Miller et al., 2012). Non-point, or diffuse, pollution can be defined as the pollution of water that has occurred through a variety of land use activities. It is transported to a river via surface runoff and down a river system, including dams, the riparian zone and wetlands (DWA, 2014).

Diffuse pollution source areas are difficult to identify, as impacts might only be identified further downstream (Lane et al., 2009; Nsibirwa, 2018). Also, the ways by which contaminants enter water bodies may vary. Across catchments, diffuse pollution risk differs and is a complex function of land management and use, topography, soil type, climate, as well as hydrology (Hewett et al., 2009). The link between the source and transport parameters determines how diffuse contaminants enter a stream network (Heathwaite et al., 2005).

However, not all catchment areas contribute to water quality problems equally. Rather, within a landscape, 'critical source areas' (CSAs) may be present, which are areas within a catchment that provide a significant risk of creating and moving pollutants into rivers (Pionke et al., 2000; Heathwaite et al., 2005; Adams et al., 2014; Thomas et al., 2016).

Pionke et al. (2000) introduced the concept of CSAs, with three primary characteristics defining CSAs (Fig. 1), viz. (i) a significant source of pollutants (for example, fertilisers from agricultural areas); (ii) large risks of mobilisation (such as steep slopes); and (iii) large risks of transportation (hydrological connectivity). Understanding hydrological connectedness is important (Bracken et al., 2013), with

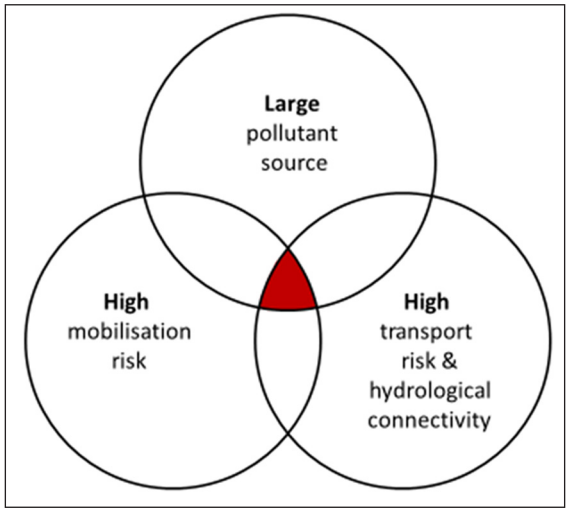

Figure 1. Diffuse pollution 'critical source areas' (CSAs, in red), where pollutant source, mobilisation risk and hydrological connectivity overlap (after Thomas et al., 2016)

it being the water-mediated transport of matter, energy and organisms within, or between, elements of the hydrologic cycle (Pringle, 2001).

The creation and implementation of best management practices are typically necessary to control diffuse pollution. In order for these practices to be successful, CSA management must be given priority (Lane et al., 2006; Miller et al., 2012; Nsibirwa, 2018). Examples of such practices include farming on soils with reduced tillage, controlling cattle grazing and watering, and bolstering the management and rehabilitation of riparian areas, denuded grasslands and hillslopes (Gburek et al., 2000).

For catchment water quality assessments, water quality networks might be used. Water quality monitoring networks in SA, however, are relatively sparse, and monitoring is often of short duration only. Additionally, limitation of routine pollution monitoring includes difficulties of distinguishing pollution sources, their connectivity and their destinations (Pegram and Görgens, 2000).

Water quality modelling is one method to assess and quantify diffuse pollution (Malan et al., 2003), using either empirical, export coefficient models, or more complex process-based models. The process-based models have the benefit of trying to account for all characteristics of transport and destinations of contaminants. According to Malan et al. (2003), the use of such complex models in SA may, however, not necessarily lead to more accurate results, owing to the lack of detailed input information.

A risk-based modelling approach is another method of assessing diffuse pollution. This approach allows for locating areas of pollution sources connected with streams (Reaney et al., 2011; Miller et al., 2012; Thomas et al., 2016). Risk-based modelling identifies (i) potential pollution sources, (ii) the risk that these pollution sources can be mobilised, (iii) the risk that the pollutants actually reach streams, and (iv) the impact risk of the pollutants, due to insufficient dilution within the river.

A detailed review of risk-based pollution assessment methods and suitability for use in SA catchments has been given by Nsibirwa (2018). These methods include the TopManage Model (Hewett et al., 2009), the 'Analysis of Hydrologically Sensitive Areas' approach (Xue et al., 2014), the 'Height Above Nearest Drainage' approach (Gharari et al., 2011), and the Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP; Lane et al., 2006).

SCIMAP provides a diffuse pollution risk estimation, identifying CSAs and in-stream pollutant concentration risks. SCIMAP was developed by the Lancaster and Durham Universities in the UK, aiming to answer the question: 'Given the observed degradation of water quality downstream of catchments, which areas are likely to be most responsible for that?' (Lane et al., 2006; Reaney et al., 2011; Milledge et al., 2012), with the foundation of SCIMAP being the conceptualisation of catchments as a network of flow channels that link dispersed potential pollutant sources on land to receiving rivers across a landscape (Lane et al., 2006).

Maps of study catchments, that highlight regions thought to be at highest risk of producing contamination downstream, are one of the main outputs and advantages of risk-based approaches (Lane et al., 2006; Heckrath et al., 2008). These maps, however, show only the risk level and do not provide pollutant concentration and other quantified values, but they are easy to understand and contribute to catchment management decision making (Cherry et al., 2008; Hewett et al., 2009). This allows a shift in focus from the observed in-river pollution to the source, viz. the CSAs. Such information is practical and implementable in the form of guiding investments in ecological infrastructure for managers (Nsibirwa, 2018) and focusing local intervention, monitoring and mitigation by water managers (Gburek et al., 2000). At a catchment scale, these outputs can also guide national or regional policy as well as local decision-making (Hewett et al., 2009). The SCIMAP risk-based approach was used for the uMngeni Catchment in SA by Nsibirwa (2018), who found a good correlation with on-ground observations.

The objectives of our study were to assess the relative risks of (i) the production of the pollutants of nutrients and suspended solids by identifying CSAs (generation risk); (ii) the connectivity between the generation site and thus the potential of delivering the generated pollutants to the river channel network (connectivity risk); and (iii) the pollution from high nutrient concentrations in the river channel, by including a dilution factor (channel nutrient risk). This was done for two hydrologically contrasting SA catchments, viz. the Thukela and the Breede. Results were mapped and compared in detail. This allowed testing of the methodology and identifying various diffuse pollution risks in the two catchments.

METHODS

Study catchments

The study catchments selected are two contrasting catchments in SA, the ~ 29 000 km^2 Thukela Catchment in the summer rainfall region in the east of the country, and the ~ 13 000 km^2 Breede Catchment in the winter rainfall region in the south-west of SA, with locations shown in Fig. 2.

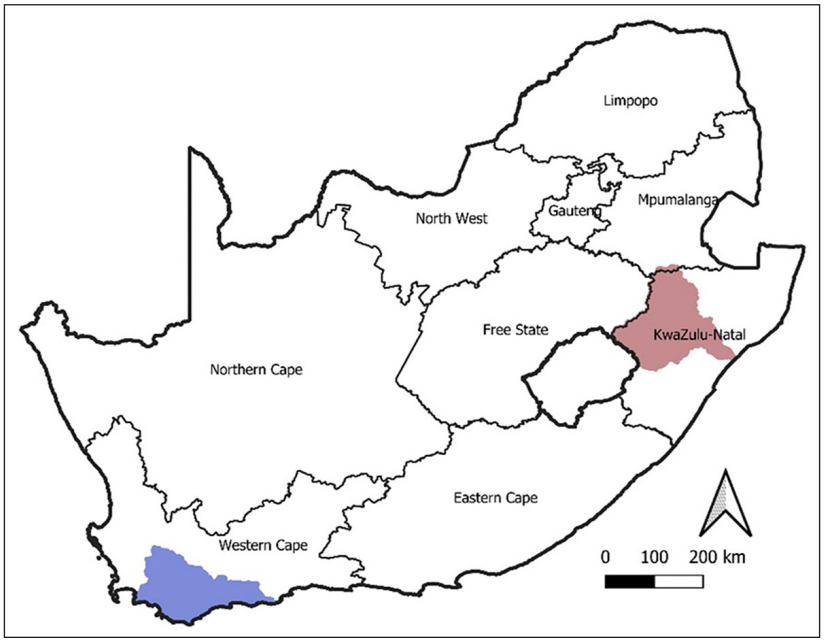

Figure 2. The locations of the Thukela Catchment (in red) in the KwaZulu-Natal Province and the Breede Catchment (in blue), in the Western Cape Province, South Africa

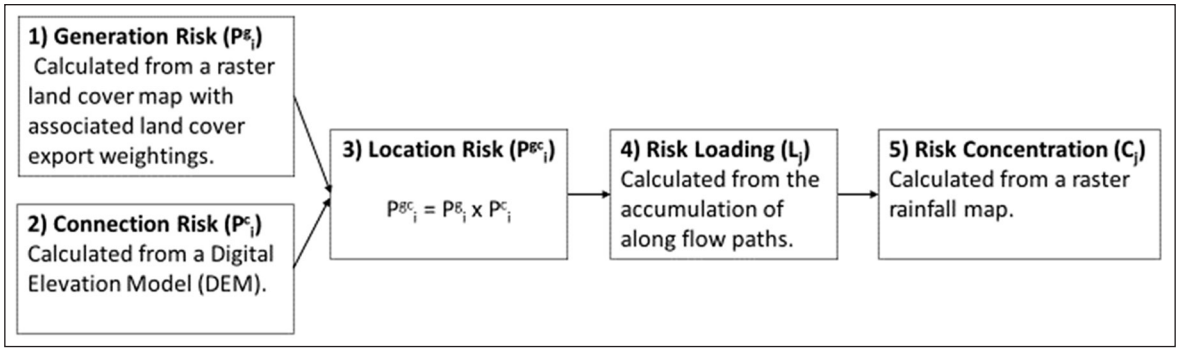

Figure 3. The processing structure of the SCIMAP model (after Milledge et al., 2012)

Sensitive Catchment Integrated Modelling Analysis Platform (SCIMAP)

For this study, the risk-based SCIMAP approach was selected, with the selection criteria being that (i) it can identify catchment hydrological connectivity and CSAs of diffuse pollutants without requiring additional development; (ii) it can be applied across a wide range of spatial scales, from hillslope of field scale to catchment scale, with the output scale being determined by the input scale (Milledge et al., 2012); (iii) the datasets for the two catchments under review are easily accessible; and (iv) the software is simple to download and free to use (from http://www.scimap.org.uk).

Using SCIMAP, (i) generation risk can be calculated, i.e., the likelihood of production of pollutants from a location, by associating land cover export weightings with land cover spatial units derived from land cover maps (Milledge et al., 2012). Thereafter, (ii) connection risk of areas to the network of rivers is calculated by formulating a saturated flow path from a digital elevation model (DEM). Flow pathways and upslope contributing areas are calculated from the filled DEM, while the catchment slope, including natural sinks and areas of disconnection, is calculated from a non-filled DEM layer (Reaney et al., 2011). Then, combining this, (iii) the locational risk is determined, with that being the risk of generated contaminants being delivered to the drainage network. Then (iv) routing and accumulating risk is calculated, to determine risk loading, and lastly (v) the risk of concentration is determined from risk loading, by taking into account the diluting potential of rainfall information (Lane et al., 2006; Reaney et al., 2011) from mean annual precipitation raster maps. The processing structure of the SCIMAP model is shown in Fig. 3. A more detailed review of the SCIMAP model is given in Nsibirwa (2018).

The three main data layers required as inputs into SCIMAP, viz. (i) land use-based likelihoods of pollutant production, (ii) a fine resolution DEM, and (iii) rainfall data layers, will be described next.

Land cover datasets

In this assessment, the South African National Land Cover dataset for the year 2000 (NLC2000) was used, as described by Fairbanks et al. (2000). Although more recent national land cover maps are now available and should be used for future work, the NLC2000 was selected at the time of doing the study, as it corresponds to the available climate input data and in order to link with previous associated work undertaken by the Institute of Natural Resources, who used the NLC2000 categories.

NLC2000 has a 20 m x 20 m spatial resolution. Using ArcMap 10.4, the national dataset was clipped, using the catchment boundaries, and thereafter converted to ASCII format. In order to later relate the land use groupings used in SCIMAP to the NLC2000 land cover classes, the land uses of the two

catchments selected are shown in Fig. 4. Key land use features of the two catchments in regard to the SCIMAP approach, other than the various natural vegetation types, are as follows: In the Thukela Catchment they are cultivated temporary subsistence dryland farming (predominantly maize); cultivated temporary commercial dryland farming (predominantly maize); forest plantations; and various forms of urbanisation. In the Breede catchment they are cultivated temporary commercial dryland farming (predominantly winter wheat); and cultivated permanent commercial irrigation (various fruit types).

The SCIMAP approach requires weightings for land use–based risk of pollutant production on a scale from 0, meaning the risk of generating pollutants is low, to 1, implying a very large pollutant generating risk. For SA, the Automated Land-based Activity Risk Assessment Method (ALARM) was developed by the Institute of Natural Resources, resulting in (i) land use groupings and (ii) diffuse pollution export potential estimates per land use grouping (DWA, 2014), based on National Land Cover maps from the year 2000 (NLC2000), with relative scores of 0 to 1 (Table 1). This gave each land use classification within NLC2000 a risk score.

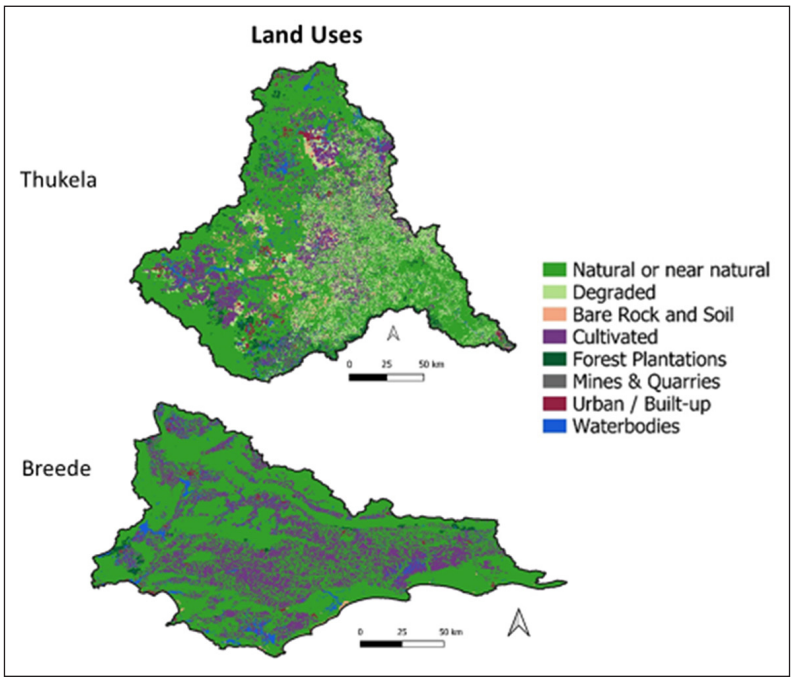

Figure 4. Land uses (simplified from NLC2000; Fairbanks et al., 2000) of the Thukela (top) and Breede (bottom) Catchments as the basis for land use classes used in the SCIMAP approach

Table 1. Land use classification based on ALARM groupings (DWS, 2014) of NLC2000, and export potentials of these groupings for generating nutrients and suspended solids, with a relative score of 0 signifying a very low and 1 a very high relative risk of generating pollutants

Land use group	NLC (2000) land cover classes	Nutrients	Suspended solids
Natural unimpacted	Forest and woodland; forest, thicket and bushland; shrubland and fynbos; herbland; unimproved grassland; barren rock	0.010	0.002
Natural degraded	Dongas & sheet erosion scars; degraded forest and woodland; degraded thicket and bushland; degraded unimproved grassland; degraded shrubland and low fynbos; degraded herbland	0.015	0.974
Wetlands	Wetlands	0.200	0.194
Plantations	Forest plantations	0.020	0.400
Dams and Rivers	Waterbodies	0.001	0.006
Irrigated commercial agriculture	Cultivated permanent – commercial irrigated; cultivated temporary – commercial irrigated	0.005	0.140
Dryland commercial agriculture	Cultivated permanent – commercial dryland; cultivated permanent – commercial sugarcane; cultivated temporary – commercial dryland	1.000	0.302
Subsistence agriculture	Cultivated temporary – semi-commercial/subsistence	0.800	0.214
Sparse settlement	Urban/built-up land residential (smallholdings: woodland), urban/built-up land residential (smallholdings: bushland), urban/built-up land residential (smallholdings: shrubland), urban/built-up land residential (smallholdings: grassland)	0.600	0.600
Urban open space	Improved grassland	0.400	0.006
Urban residential	Urban/built-up land residential	0.500	0.257
Urban commercial	Urban/built-up land commercial	0.500	0.084
Urban industrial	Urban/built-up land industrial/transport	0.900	0.200
Mines and quarries	Mines and quarries	0.200	1.000

Table 2. Ranking of ALARM export potentials from relatively highest to relatively lowest potential for nutrients (middle column), suspended sediments (right column)

Rank	Nutrient export potential ranking land use category	Suspended solids export potential ranking land use category
1	Irrigated commercial agriculture	Mines and quarries
2	Urban industrial	Natural degraded
3	Dryland commercial agriculture	Subsistence agriculture
4	Subsistence agriculture	Plantations
5	Sparse settlement	Irrigated commercial agriculture
6	Urban commercial	Sparse settlement
7	Urban residential	Dryland commercial agriculture
8	Urban open space	Urban industrial
9	Mines and quarries	Urban open space
10	Plantations	Wetlands
11	Natural degraded	Urban commercial
12	Natural unimpacted	Urban residential
13	Wetlands	Dams and rivers
14	Dams and rivers	Natural unimpacted

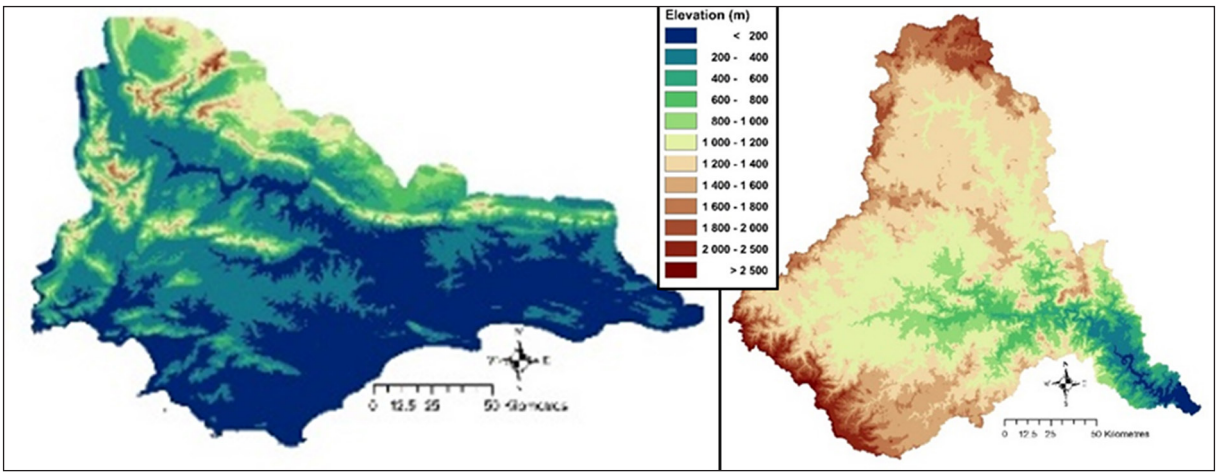

Figure 5. Comparisons between the Breede (left) and the Thukela (right) Catchments, of elevations from which the connectivity risk is calculated, with this used to derive the movement/travel of pollutants and likelihoods of connectivity to the stream network

These export coefficients do not have a connectivity score embedded; the ALARM is thus suitable for the use with SCIMAP. The 49 land cover classes of the NLC2000 were grouped into 14 categories of land use, based on the ALARM method. The maps of the land use groups based on the ALARM categories for the respective study catchments are shown later in the results section.

Ranking of the relative scores from the maximum of 1.0 to the lowest scores for nutrients and suspended solids is shown in Table 2. For nutrients, the highest export potentials are from 'irrigated commercial agriculture', 'urban industrial land' and then from 'dryland commercial agriculture', followed by 'subsistence agriculture', whereas for suspended solids, 'mines and quarries' top the list, followed by 'natural degraded lands' and 'subsistence agriculture'. Regarding nutrients, by implication from Table 1, 'irrigated commercial agriculture' would export 1.25 times as many nutrients as 'dryland commercial agriculture', 1.67 times as many as 'subsistence agriculture' and twice as many nutrients as 'sparse settlements'. similarly, 'natural degraded' areas would export 1.62 times as much suspended sediment as 'subsistence agriculture', 3.23 as much as 'irrigated commercial agriculture' and 4.55 times as much as 'dryland commercial agriculture'.

Digital elevation model (DEM)

To improve predictability and reliability in the SCIMAP approach, high-resolution DEMs are required (Lane et al., 2003). The high-resolution 20 m x 20 m DEM used in this research was the National Geo-Spatial Information Photogrammetric Compiled DEM obtained from the South African Department of Rural Development and Land Reform. The DEM was clipped to the boundaries of the Breede and Thukela Catchments using ArcMap. SCIMAP requires data in the American Standard Code for Information Interchange (ASCII) file format. Therefore, outputs were transformed to the ASCII format. The DEMs of the two catchments are shown in Fig. 5. The DEM for the Breede Catchment shows low elevations along the coast in the south and along the mainstem of the Breede River, with highest elevations, reaching a maximum of 2 232 m, in the mountain belt along the northern border of the catchment. For the Thukela Catchment, the digital elevation model shows low elevations from the east towards the coast, with higher elevations up to 3 445 m in the Drakensberg in the west.

Rainfall dataset

Surface runoff can be used to determine possible dilution of pollutants in the river. Because of the general unavailability of detailed runoff, SCIMAP uses mean annual precipitation (MAP) as an index of runoff. The raster dataset of MAP accessed for SA was by Lynch (2004) for the period 1950–1999. It contains a quality-controlled daily rainfall time series from over 1 200 rain gauges across SA, with missing values infilled. The means from the

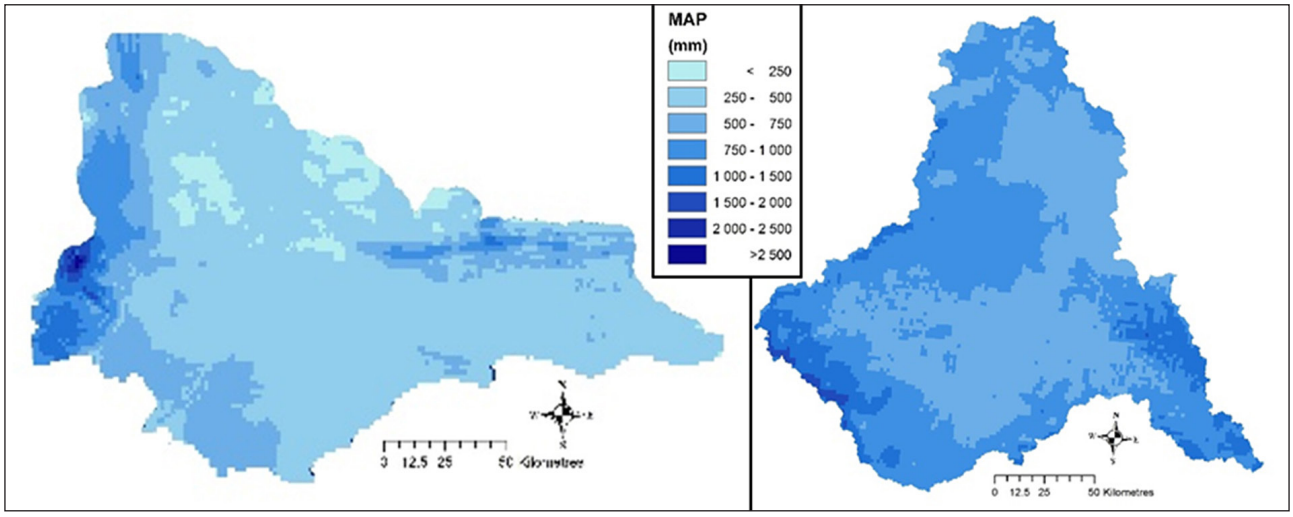

Figure 6. MAPs for the Breede (left) and Thukela (right) Catchments (Lynch, 2004), as an indicator of the dilution potential of risk concentration of diffuse nutrients

50-year dataset were considered suitable indicators of the dilution potential. Lynch's raster grid resolution of 1.7 km was re-sampled in ArcMap to 20 m to match the DEM resolution. In the review of this paper it was suggested to rather upscale the DEM resolution to the coarser rainfall resolution, as the rainfall downscaling might introduce a false precision and could thus potentially misrepresent spatial variability of MAP. This was, however, in retrospect not feasible, but is suggested going forward. Thereafter, the re-sampled rainfall raster was clipped, using the Breede and Thukela Catchment boundaries, and lastly was converted to the required file format, ASCII. MAP for the two catchments is shown in Fig. 6. MAP across the Thukela Catchment ranges from 503 mm to a high of 1 923 mm in the western Drakensberg Mountains (Lynch, 2004), with much of the more central parts of the catchment receiving between 500 mm and 750 mm/a. Of the two catchments under study, the Breede displays the higher range of MAP, from a low of 66 mm to a high of 3 198 mm in the western mountain belt, with much of the more central parts of the catchment receiving only 250–500 mm/a.

RESULTS

Five types of pollutant risk maps are shown for each catchment, viz. a 'land use–based potential of nutrient generation' map, a 'connectivity' map, a 'landscape nutrient risk' map highlighting the CSAs, a 'channel nutrient risk' map highlighting high concentration risks for nutrients in the channel, and a 'landscape suspended solids risk' map.

Thukela Catchment

Risk generation of diffuse nutrients, based on land use attributes

In the Thukela Catchment 36 land use categories are present out of the possible 49 in the land use (NLC2000) classification (cf. Fig. 4). As mentioned, other than the various natural vegetation types (shades of green), land uses of importance are cultivated temporary subsistence and commercial dryland farming, forest plantations (mixed genera) and urban clusters, as well as dams. Figure 7 (top) displays the land used groups based on the ALARM categories (Table 1) and Fig. 7 (bottom) shows the entire spectrum of diffuse nutrient generation risk from values of < 0.1 to > 0.9, displaying clearly the areas with higher risk, in a shade of red/purple e.g. from 'natural degraded', 'dryland commercial agriculture' and 'subsistence agriculture' areas. Figure 7 (bottom) corresponds to Step 1 in the SCIMAP process (cf. Fig. 3).

Connectivity risk of the movement of pollutants

The connectivity risk, which is used to derive the movement/travel of pollutants and the likelihood of pollutants getting into the river channel, is calculated from a network index derived from the DEM. This corresponds to Step 2 in the SCIMAP process (cf. Fig. 3). It needs to be mentioned that dams and other impoundments have only been considered in terms of their export potential, not with regards to actual dam releases. This is a limitation of the SCIMAP process and could be addressed going forward. The hydrological connectivity map for the Thukela Catchment (Fig. 8) has values ranging from 0.53 in the mountainous regions in the west and the incised valleys in the east to a value of 1.0 in the flatter areas of the centre and north of the catchment, with 1 implying high connectivity.

Nutrient risk from the landscape component of the Thukela Catchment

Step 3 in the SCIMAP process (cf. Fig. 3) is the nutrient risk from the landscape component. This step combines the previous two steps. It shows locations with a combined relatively high or low likelihood of (i) producing pollutants, and (ii) delivering generated pollutants to the network of rivers. Mapped for the entire catchment, Fig. 9 (left) does not display distinct differences in nutrient risk from the landscape component of the catchment, although relative nutrient risk ranges from zero to 0.81. Nutrient risk is a localised phenomenon, highly dependent on local land use. When highly scaled up, Fig. 9 (right) shows relative risks at high values where the land use map (cf. Fig. 4) shows commercial and subsistence dryland agriculture in Quaternary Catchments V13C and V13D. A map such as this is useful to water managers who want to improve water quality with respect to nutrients. It allows one to backtrack highly likely sources of that pollution within the specific catchment. This is a way of identifying otherwise not easily identifiable sources of diffuse pollution. For example, the areas shown in red in Fig. 9 (right) in Quaternary Catchment V13C could be further investigated, e.g., with field visits.

Nutrient risk in the channel component of the Thukela Catchment

Step 5 of the SCIMAP process (cf. Fig. 3), i.e., the accumulated and diluted nutrient risk concentration in the channel, is shown for the Thukela Catchment in Fig. 10. This brings together the CSA and connectivity from the DEM-derived channel component, as

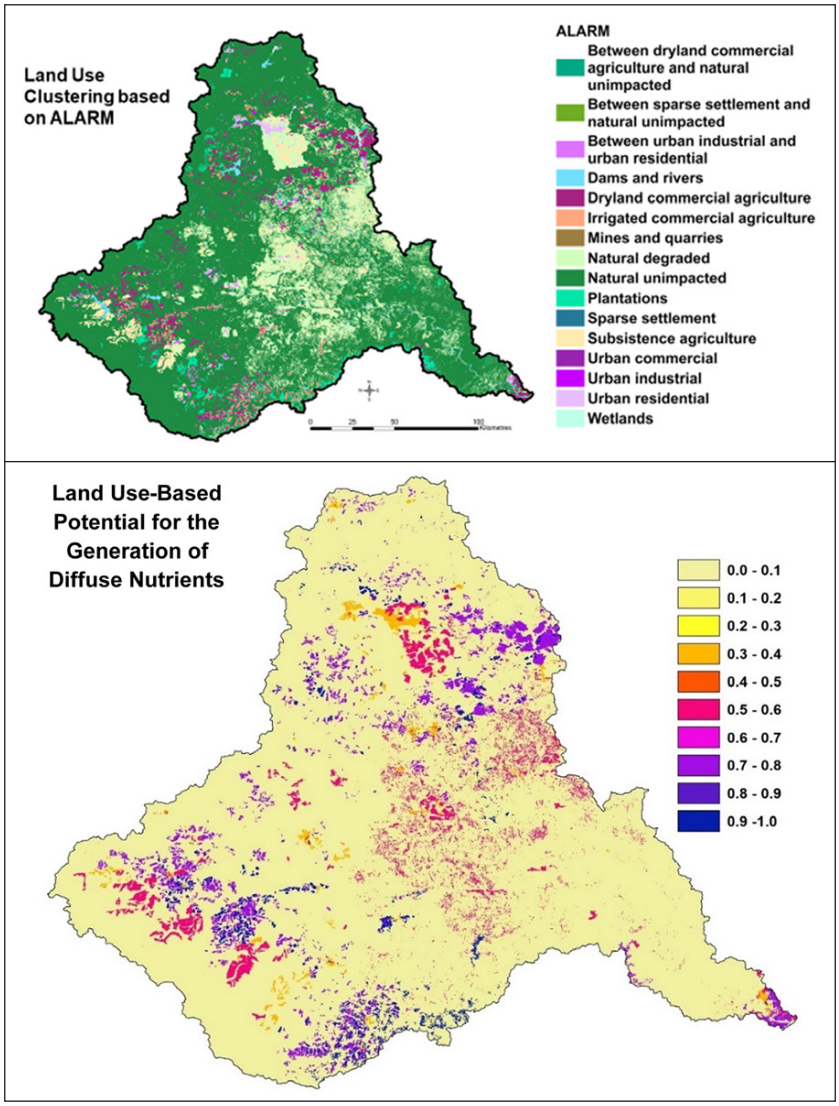

Figure 7. Land use–based ALARM groupings (top) and generation risk: relative land use–based potential for the generation of diffuse nutrients (bottom) in the Thukela catchment

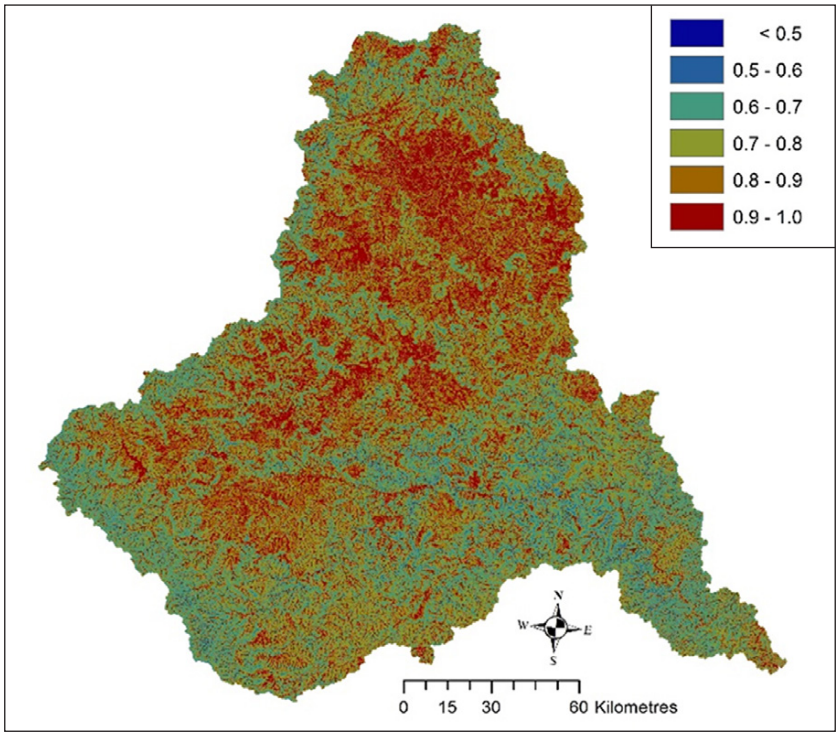

Figure 8. Connectivity risk: hydrological connectivity in the Thukela Catchment

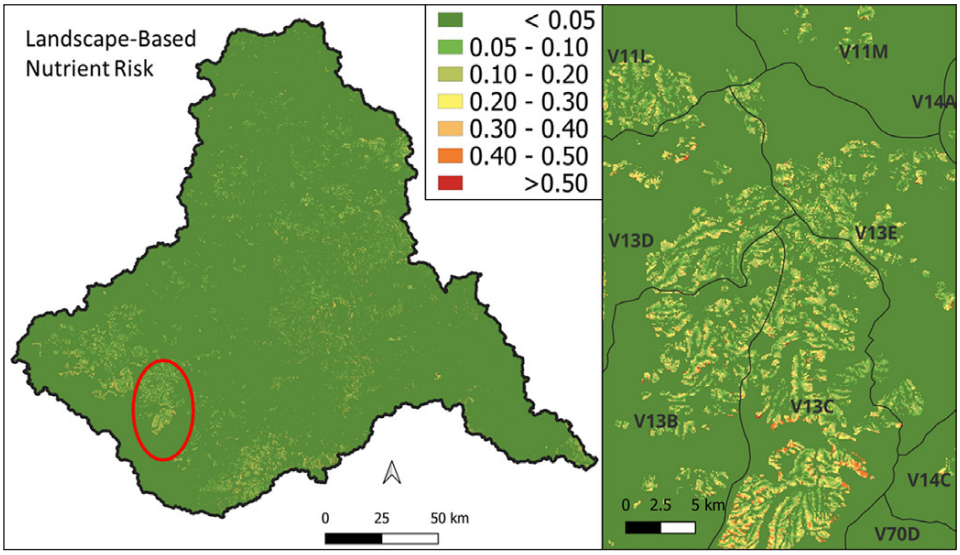

Figure 9. Landscape-based relative nutrient risk in the entire Thukela Catchment (left), with a focus (right) on Quaternary Catchment V13D and surrounding quaternaries

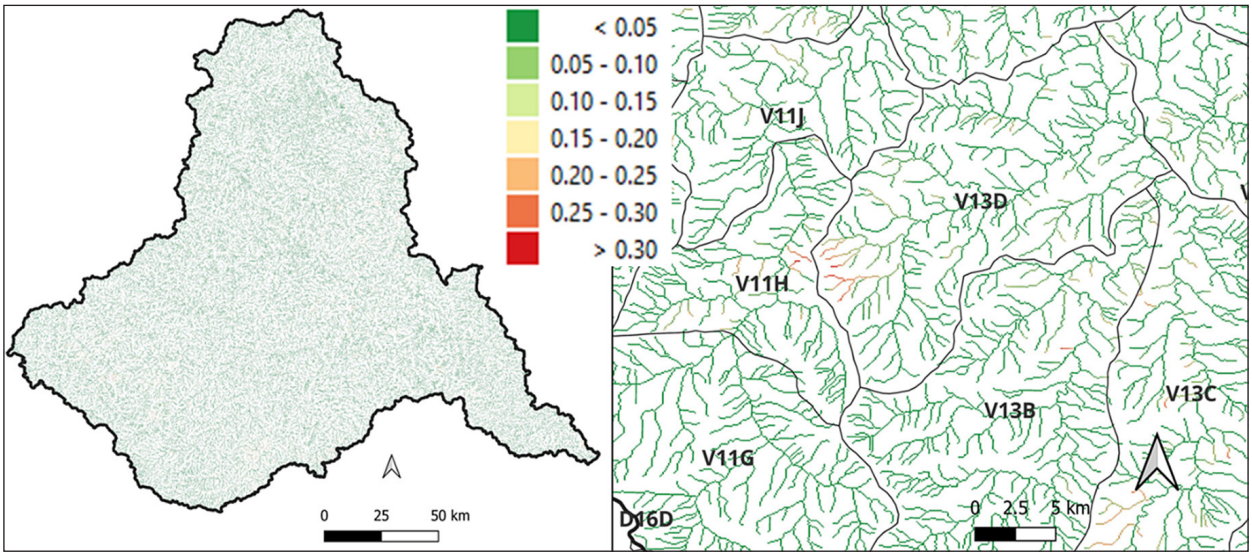

Figure 10. The Thukela Catchment (left) and a scaled-up section (right), showing local highs of the channel nutrient risk in Quaternary V13D and surrounding quaternaries

well as including a dilution factor. The results are again highly localised, with a catchment-scale map not displaying significant spatial patterns (Fig. 10, left), but scaled-up areas showing up some local variations, as Fig. 10 (right) shows.

This map showing local highs of channel nutrient risks can be useful to water managers when water bodies with high nutrient loads are encountered. It allows one to backtrack to stream sections that are likely sources of that pollution within the specific catchment, either for inspection or for further water quality testing. For example, the streams shown in red in Fig. 10 (right) in Quaternary Catchment V13D could be further investigated, if there is a nutrient pollution problem within the main stream.

Suspended solids risk from the landscape component of the Thukela Catchment

Referring back to Table 2, 'degraded areas' have a relative suspended solids risk potential of 0.974, 'subsistence agriculture' of 0.600, 'dryland commercial agriculture' of 0.214 and 'unimpacted natural vegetation' (with its aerial and surface protective cover) a risk potential of only 0.002. Based on the above, the link between the spatial distribution of diffuse suspended solids risk derived from land use potential within the Thukela catchment in Fig. 11 and the catchment's land use clusters (Fig. 11, insert), also shown previously in Fig. 7 (top), is clearly evident.

As with nutrients (cf. Fig. 9), the combined landscape-based sediment risk was determined (not shown), which allows for further investigation of, and, if necessary, intervention at areas with a combined high risk of sediment generation and transportation to the river network.

Breede Catchment

Risk generation of diffuse nutrients, based on land use attributes

In the Breede Catchment, 23 land use categories, out of a possible 49 in the NLC2000 classification, are present. As a reminder, other than the various types of natural vegetation, land uses of importance in the Breede Catchment are cultivated permanent commercial irrigated areas (mainly vineyards and deciduous fruits) and cultivated temporary commercial dryland farming (predominantly wheat), as well as some forest plantations (predominantly pines) and dams.

The land use–based ALARM grouping for the Breede Catchment is shown in Fig. 12 (top). When expressing these land use categories as export potentials for generating nutrient contamination using the ALARM system, Fig. 12 (bottom) displays the entire spectrum of diffuse nutrient generation from values of < 0.1 to > 0.9, showing clearly the 'irrigated commercial agriculture' (mainly viticulture) in dark blue and 'dryland commercial agriculture' areas (mainly wheat) in purple.

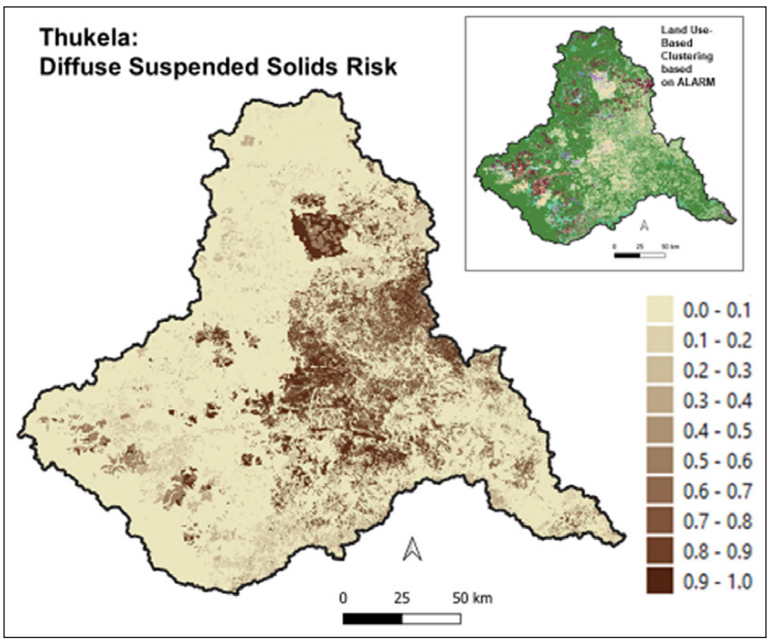

Figure 11. Diffuse suspended solids risk in the Thukela Catchment based on land use potential (bottom), and its link with actual land use (top)

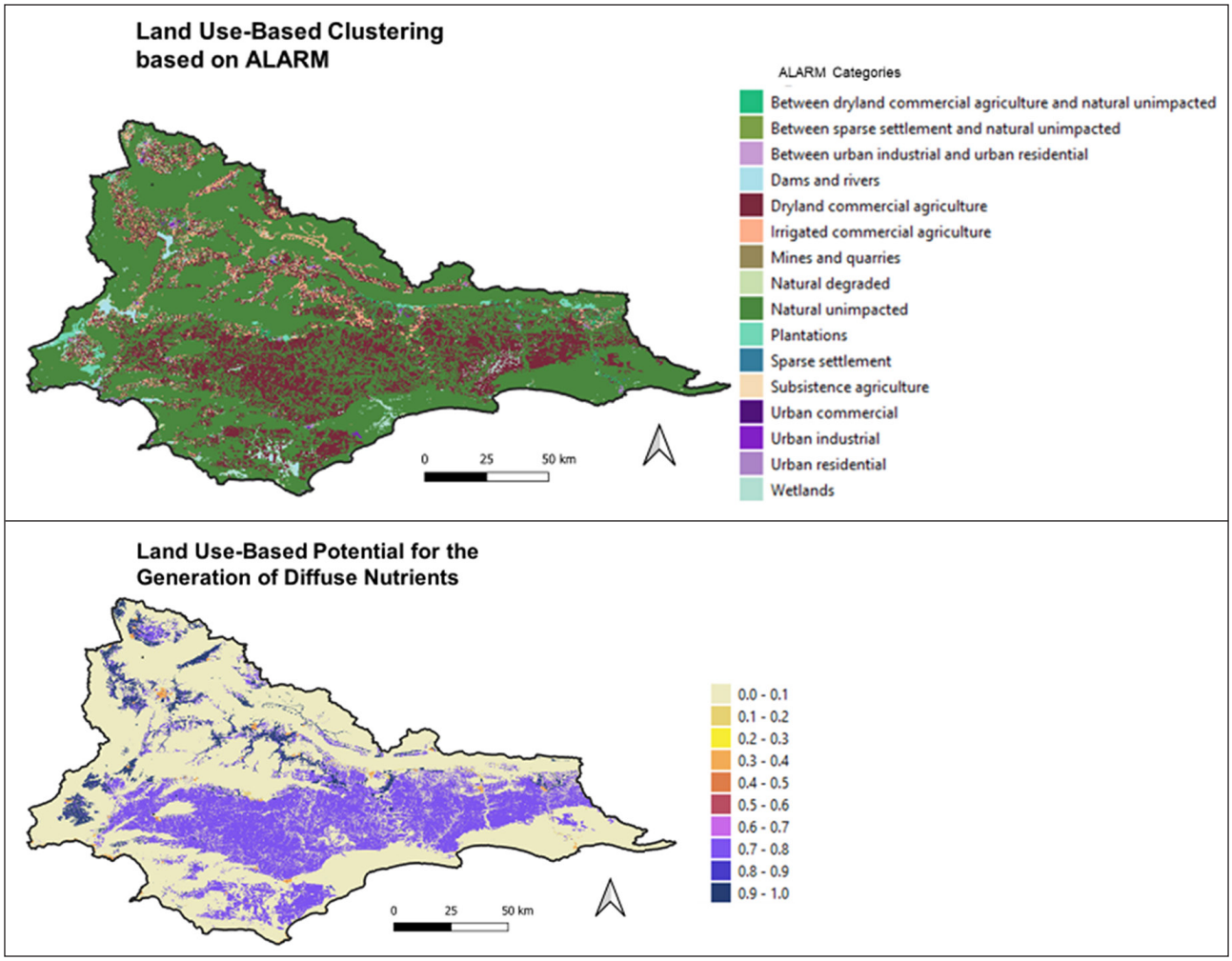

Figure 12. Land use–based ALARM groupings in the Breede catchment (top) and relative land use–based potential for the generation of diffuse nutrients (bottom), with 1 being a relatively high generation potential and 0 a relatively low potential

Connectivity risk of the movement of pollutants

The connectivity risk, used to derive the movement/travel of pollutants and the likelihood of connecting to the streams, is calculated from a network index derived from the DEM. SCIMAP outputs an index of hydrological connectivity, shown for the Breede Catchment in Fig. 13, with values ranging from 0.29 (low connectivity) to 1.0 (high connectivity) in parts of the north-west and the south. High connectivity risk implies that if pollutants are produced in an area they will likely find their way into the river network.

Nutrient risk from the landscape component of the Breede Catchment

The nutrient risk from the landscape map shows areas with a relatively low or high likelihood of delivering generated pollutants to the network of rivers (Fig. 14). Unlike the Thukela catchment which, when viewed from the perspective of the entire catchment, did not display distinct differences to the naked eye in nutrient risk from the landscape component, there is clear distinction of nutrient risk levels within the Breede catchment (left), with this clearer in the scaled-up example (right). Again, if there is a problem of high nutrient loads within this catchment, the areas with a high nutrient risk shown in red in Fig. 14 should be investigated first by water/pollution managers.

Nutrient risk in the channel component of the Breede Catchment

The Breede Catchment's channel nutrient concentration risk is shown in Fig. 15. This brings together the CSAs, the connectivity from the DEM-derived channel component, accumulation within streams and a dilution factor. Marked spatial patterns are visible even to the naked eye when mapped (Fig. 15, left), which was not the case in the Thukela Catchment. The channel component's nutrient risk, expressed via the standard deviation approach (see Methods), is illustrated when scaled up in Fig. 15 (right) for the area around Quaternary Catchments G50G and H50A.

Suspended solids risk from the landscape component of the Breede Catchment

The Breede Catchment (Fig. 16) displays generally lower suspended solids risk, mostly in the range below 0.30 where wheat is grown (area in pink in the inset), and around 0.01 where natural vegetation still prevails (cf. shades of green in the inset).

Comparisons between the Breede and Thukela Catchments

Catchment land uses from the NLC2000 classification (Fairbanks et al., 2000) were used to derive land use–based export potentials of the diffuse pollution generation of nutrients according to the ALARM system (DWA, 2014). Overall, within the two catchments, the dominant land uses (other than the various classes of natural vegetation shown in shades of green in Fig. 4), were dryland subsistence and commercial agriculture, urban clusters as well as patches of afforestation in the Thukela, and dryland wheat as well as irrigated crops (viticulture) in the Breede Catchment.

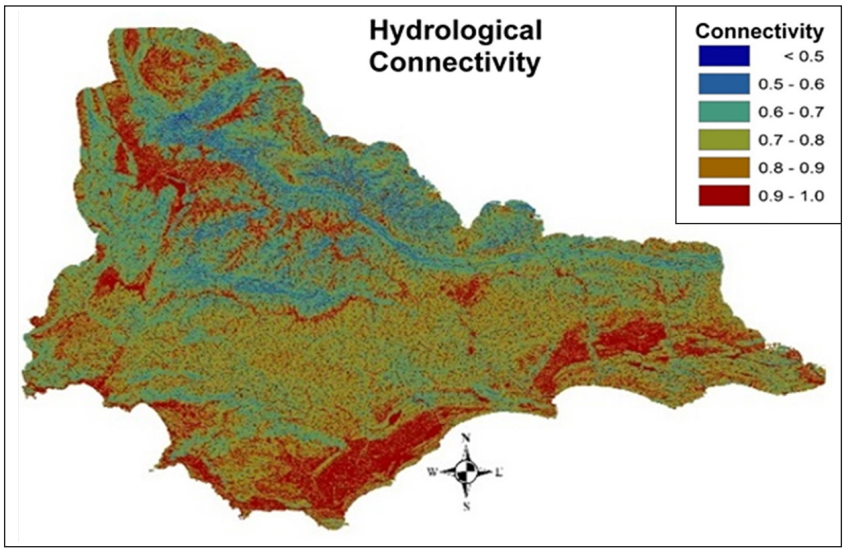

Figure 13. Connectivity risk: hydrological connectivity in the Breede catchment, with 1 implying high connectivity risk

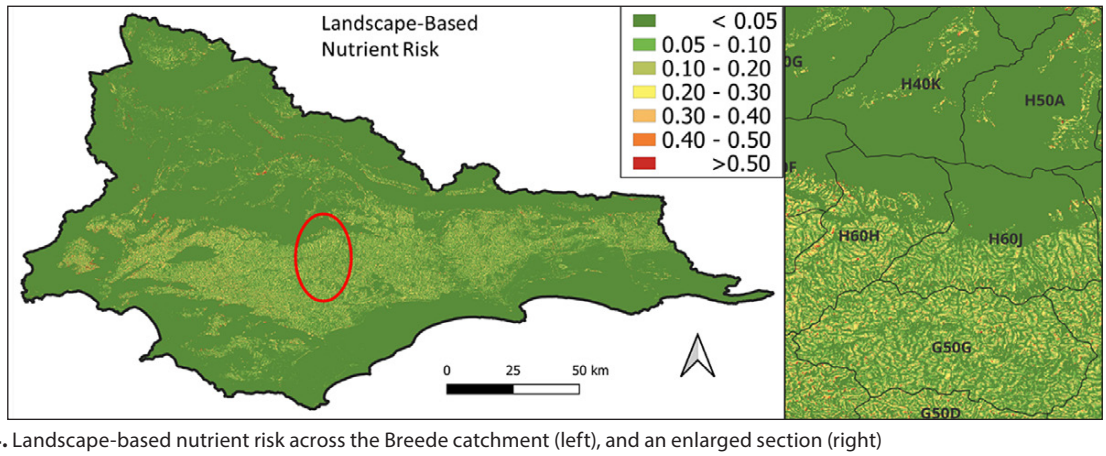

Figure 14. Landscape-based nutrient risk across the Breede catchment (left), and an enlarged section (right)

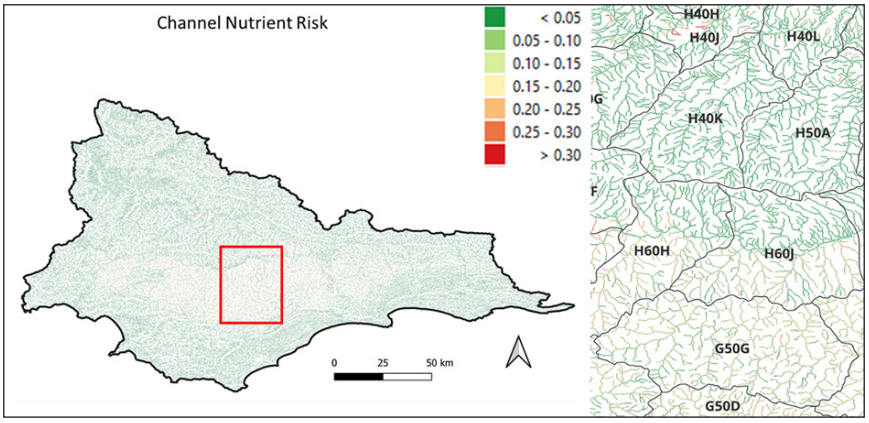

Figure 15. Nutrient risk in the channel component in the Breede Catchment (left), with (right) a scaled-up section around Quaternary G50G, derived from the standard deviation approach

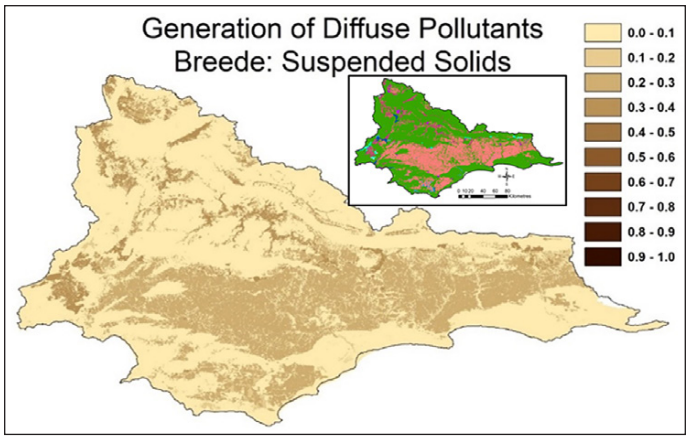

Figure 16. Diffuse suspended solids risk in the Breede Catchment based on land use potential, with the land use link shown in the inset

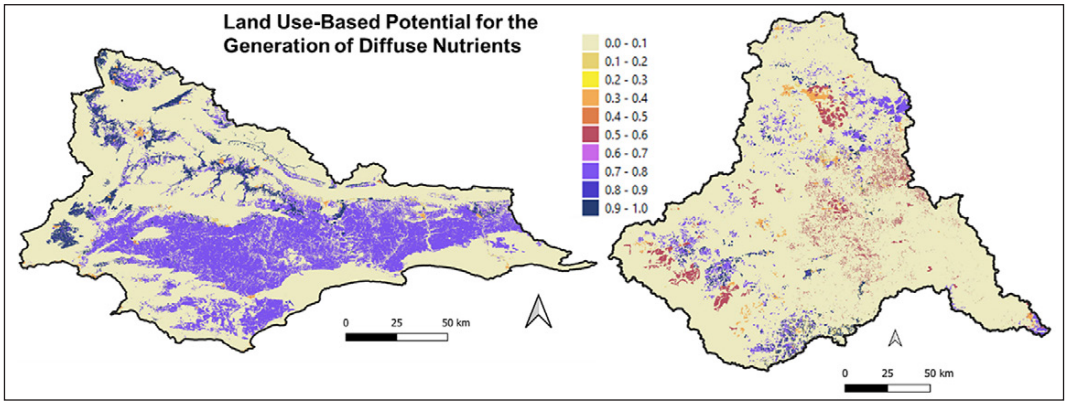

Figure 17. Comparison, between the Breede (left) and the Thukela (right) Catchments, of land use–based export potentials for the generation of diffuse nutrient pollution according to the ALARM system

Figure 17 shows considerable overall land use–based export potential differences between the Breede Catchment, where various types of dryland (mainly wheat) and irrigated (mainly viticulture) commercial agriculture dominate, and the Thukela Catchment, where considerable areas, either under subsistence farming or that are degraded, stand out.

MAP, used in SCIMAP as an indicator of the dilution potential, displays differences in spatial patterns and in overall magnitudes between the east coast summer rainfall Thukela Catchment, which experiences frequent convective events, and the Breede Catchment which has lower overall MAPs (cf. Fig. 6). A further distinction, not picked up in the SCIMAP risk concentration approach, is that the Breede is in a winter rainfall region of generally low intensity multi-day frontal rainfall events.

The DEM-derived hydrological connectivity, which expresses the connectivity risk for pollutant movement, is in the relative range of < 0.5 to 1.0 in both catchments, with each displaying relatively high to medium connectivity risks (Fig. 18), but with the high or medium connectivity ratios clustered geographically.

Linking the above in order to map nutrient risk from the landscape presented a spatially very detailed picture at the whole catchment level, with few outstanding patterns discernible in the Thukela Catchment (Fig. 20, top right), while spatial patterns were quite distinct in the Breede system (Fig. 20, top left). This is partially so because different land uses were defined literally at field scale, with differences not really discernible to the naked eye at whole-catchment resolution in the case of the Thukela. It was only when scaled up considerably (Fig. 19, bottom maps) that more local patterns became clearly defined.

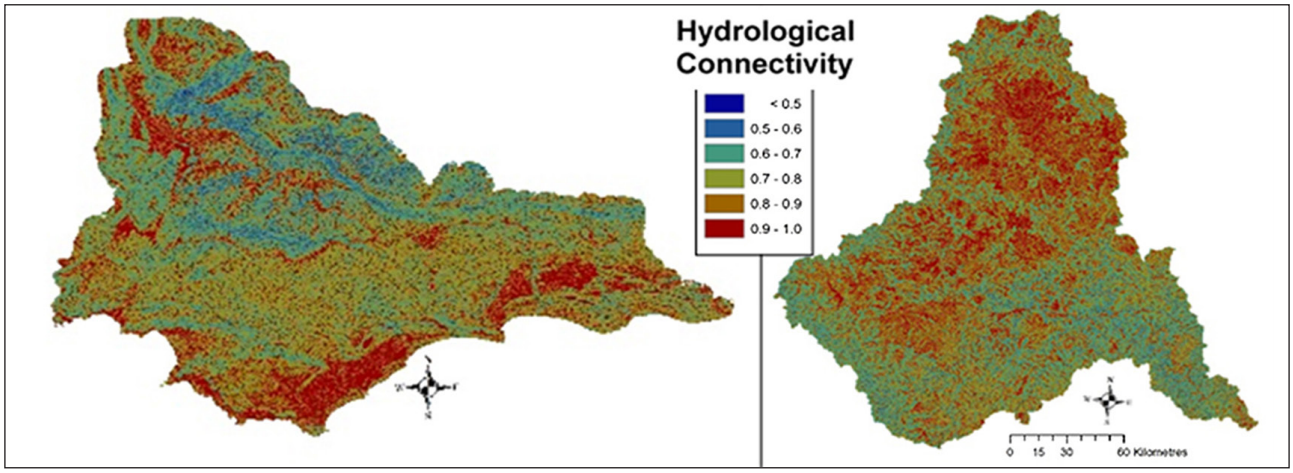

Figure 18. Comparison, between the Breede (left) and Thukela (right) Catchments, of the DEM-derived hydrological connectivity which expresses the connectivity risk for the travelling pollutants

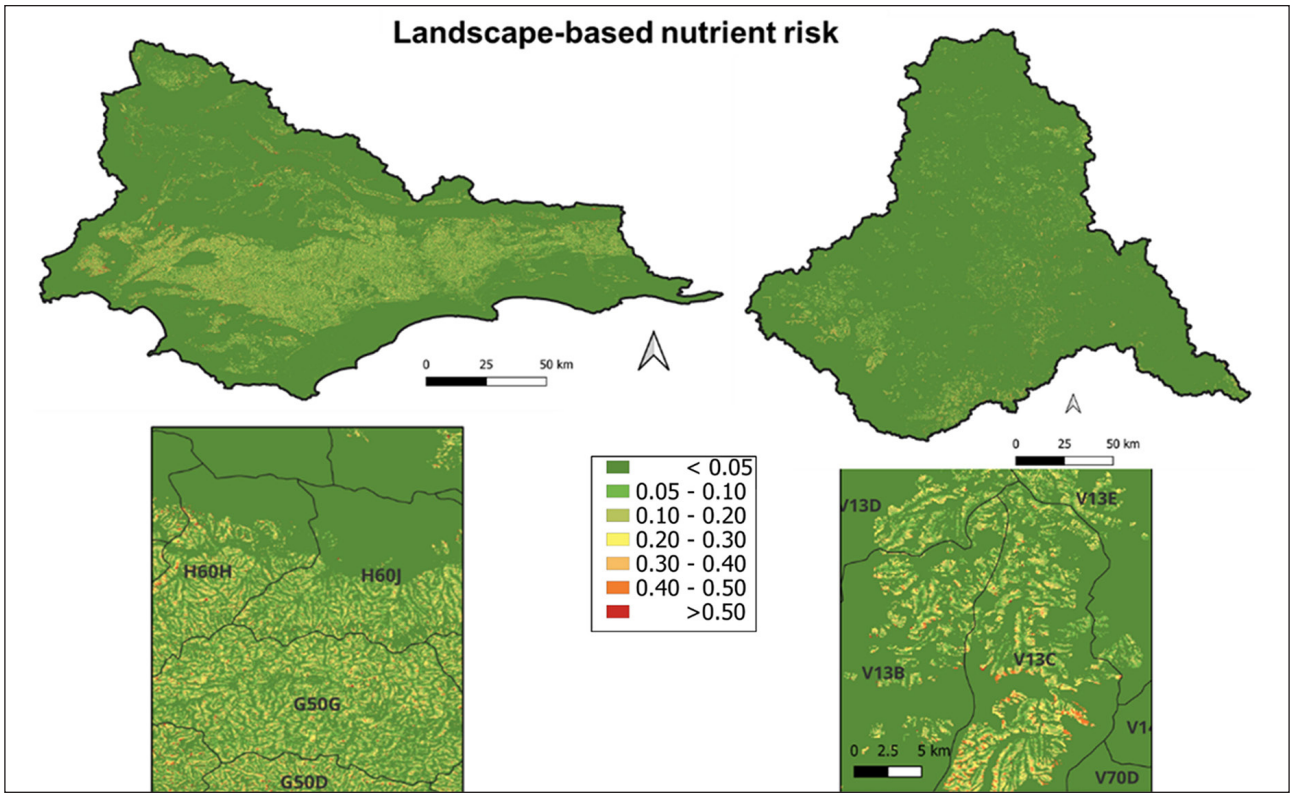

Figure 19. Comparison, of the nutrient risk from the landscape component (top) at whole catchment scale, with scaled-up representations (bottom) from the Breede (left) and Thukela (right)

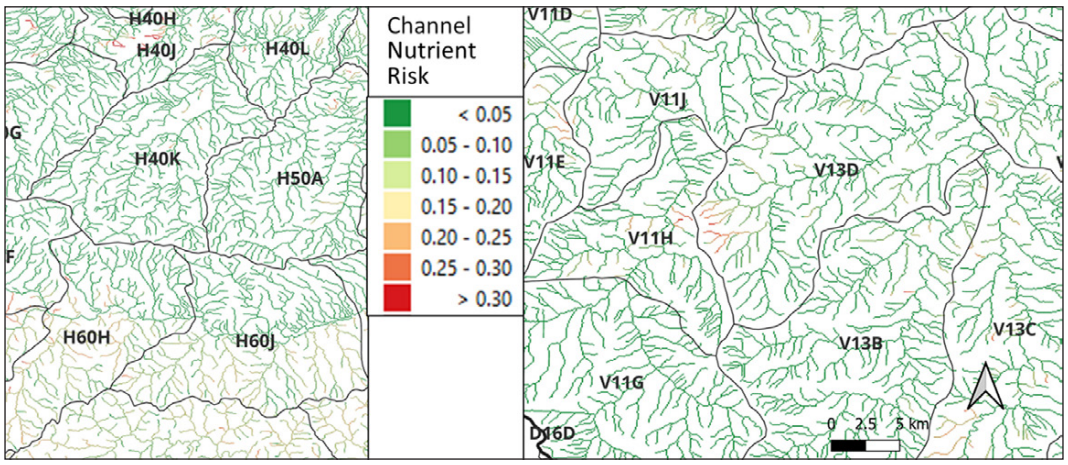

Figure 20. Differences in channel nutrient risks in scaled up areas of the Breede (left) and Thukela (right) Catchments

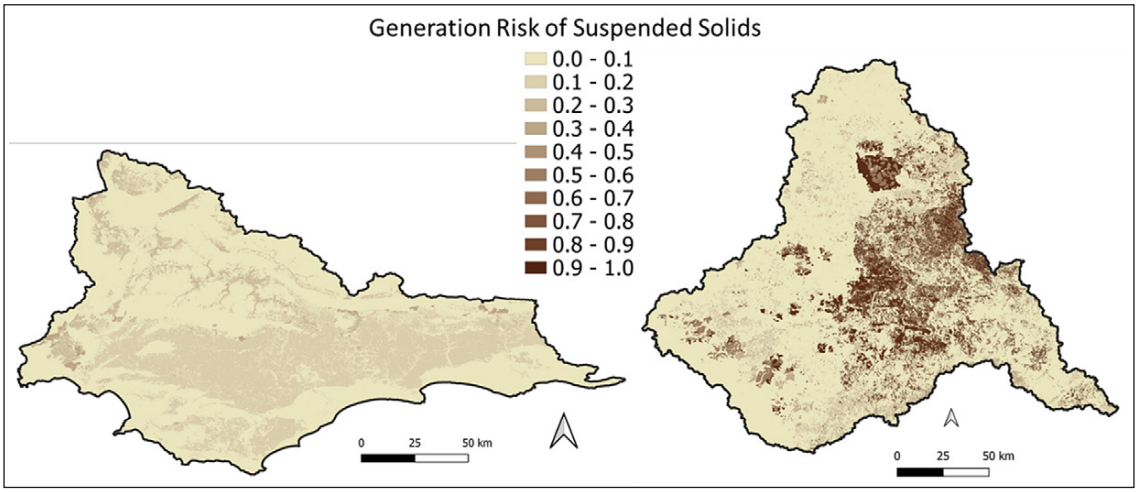

Figure 21. Comparison of the diffuse suspended solids risk between the Breede (left) and the Thukela (right) Catchments

As was the case with nutrient risk from the landscape, nutrient risk from the channel component at whole catchment level displayed no discernible patterns, in this case because of the high density of channels identified from the DEM. Only when scaled up to small areas, as in the examples from the Breede and Thukela systems in Fig. 20 (left and right, respectively), did the different channel segments display some marked differences in nutrient risks, and then more so in some catchments than in others.

Lastly, in regard to diffuse suspended solids risk, mapped values spanned the entire range from 0 to 1, with the Thukela displaying patterns of lows under undisturbed natural vegetation to highs where degradation and subsistence farming dominated the landscape, while the Breede Catchment showed much more muted differences with various forms of commercial farming dominating (Fig. 21).

DISCUSSION AND CONCLUSIONS

This study assessed the relative generation and connectivity risks of nutrients and suspended solids, by identifying CSAs in two hydrologically contrasting catchments, the Thukela and Breede catchments, using the SCIMAP approach. This was achieved by creating 'landscape nutrient risk' maps which highlighted the CSAs for nutrients, as well as 'channel nutrient risk' maps which highlighted channel sections with risks of high concentration of nutrients, and also 'landscape suspended solids risk' maps which highlighted the CSAs in regard to suspended solids. These maps can be used by water managers to first identify areas of high risk, and then to facilitate the intervention and management, or reduction, of diffuse pollution at source.

Nutrient risk maps from the landscape component (cf. Fig. 9 for the Thukela and Fig. 14 for the Breede) show locations with combined relatively high likelihoods of (i) producing pollutants as well as (ii) delivering generated pollutants to the network of rivers. These maps can be useful to water managers who want to improve water quality with respect to nutrients. They allow managers to backtrack highly likely sources of nutrient pollution within the specific catchment. This is, therefore, a way to identify likely sources of otherwise not easily identifiable sources of diffuse pollution, allowing for targeted further investigations, e.g., through field visits, and then recommending mitigating management options.

Channel nutrient risk maps (cf. Fig. 10 for the Thukela and Fig. 15 for the Breede) are useful to water managers when water bodies with high nutrient loads are encountered. It allows managers to backtrack to stream sections that are likely sources of that pollution within the specific catchment, for inspection and/or further water quality testing.

The application of this risk-based methodology is useful where there is a concern about water quality. An example would be where water bodies are found not to meet water quality standards (fit for use), and direct or non-point pollution sources are not known, or where only limited water quality sampling exists currently. A focus should then be on intervention measures for the critical source areas identified with this modelling approach, which was also suggested by Milledge et al. (2012). This type of diffuse pollution assessment supports a management process which might need to evolve, as greater clarity and understanding is gained, as was also noted by Pegram and Görgens (2000). Once river sections with a high risk of pollution have been identified, water quality sampling can then be focused on these areas, as well as the upstream areas, to identify actual pollution source areas and allow for intervention at the source.

Being at a large catchment scale, the modelling approach was found to be very useful in this study, compared to smaller scale studies where direct measurements might be more suitable, as was also found by Cherry et al. (2008). The approach that was outlined in this paper is highly applicable in SA, where many rivers have high pollution levels and where the links to the sources of this pollution might not be clear, which often allows for only very limited mitigation steps.

When compared with the comprehensive guide on non-point-source assessments in SA by Pegram and Görgens (2000), which includes a section on risk-based assessments, Step 1 described in this paper on the 'relative land use–based potential for the generation of pollutants' is similar to the 'potential maps' approach suggested by Pegram and Görgens (2000). However, we believe that our work, using the ALARM classification in conjunction with national land cover maps, provides more detail and a clearer methodology than the 'potential maps' approach. Furthermore, when compared to the Pegram and Görgens (2000) 'hazard maps', our 'landscape-based pollution risk maps' fulfil the requirements of the 'hazard maps', but give clearer methods for applications. We thus believe that our approach enhances the risk-based section within the Pegram and Görgens (2000) guide.

The SCIMAP methodology, together with the ALARM land use–based weightings, has been found to be a valuable tool for identifying CSAs of diffuse pollution in catchments in SA, which supports the findings of Nsibirwa (2018).

For areas with high pollution production as well as connectivity risk, local best management practices can reduce this risk.

This can be achieved by various approaches, such as mitigating land use management practices which reduce wash-off of contaminants, or by engineering structures which intercept and treat this wash-off. More details on these approaches can be found in Pegram and Görgens (2000).

Limitations of the present study

Within this study, pollution risk, and not actual pollution, was determined, which is a limitation of this approach. For example, nutrient losses from individual farming operations can be mitigated or worsened by management practices, as was described by Cherry et al. (2008), and the risk might therefore not reflect what is actually happening on the ground.

Furthermore, in the peer review of this paper, it was suggested to rather upscale the DEM resolution to match that of the coarser MAP resolution, as the rainfall downscaling might introduce a 'false precision' and potentially misrepresent spatial variability. This is another limitation of this study. However, retrospective rectification of this is not feasible. It should be remembered that MAP only comes into play in the final step, Step 5, of the SCIMAP process, where the dilution factor is included, and not in the initial 4 steps, those being the 'generation risk', 'connection risk', 'location risk' and 'risk loading' (cf. Fig. 3).

Dams are only considered through their export potential in the SCIMAP methodology. The impact of dams and their water releases on the connectivity was not included in this SCIMAP methodology, which is a further limitation.

Recommendations for future research

The following are suggestions to take the findings presented in this paper further in future research:

- In addition to nutrient and suspended solid risks, which were assessed in the two catchments in this paper, ALARM export potentials (DWA, 2014) also exist for the generation of toxins, dissolved salts and microbiological contamination risk for the various land use categories used in this research. These should be assessed in a future project. Furthermore, regarding suspended solids, only the generation risk was determined in this research, whereas the river concentration risk could be determined in future work.
- Mapping and interpretation of nutrients, suspended solids, toxins, dissolved salts and microbiological contamination risks should be extended beyond the two catchments which were the focus in this research, to ideally cover the entire country.
- In line with the approach taken by the developers of the SCIMAP technique, in this research MAP was used as the indicator of risk concentration of diffuse nutrients. Investigations should, however, be initiated, possibly in collaboration with the SCIMAP developers, to see whether other more appropriate hydrological indicators such as local runoff or accumulated streamflow volumes down a catchment system, or soil water content and movement, might not be better indicators of risk concentration of diffuse nutrients.
- Furthermore, in the present approach in SCIMAP in which MAP is used as the indicator of risk concentration of diffuse nutrients, no distinction was made as to whether the same amount of rain falls in summer or in winter or throughout the year, or whether it falls as low-intensity frontal rain or as high-intensity convective events. These characteristics should be taken into account for more accurate analysis.
- Currently, dams are only considered through their export potential in the SCIMAP methodology. Dams and their water releases impact on the connectivity and this could be included going forward, to improve the methodology.
- In similar vein, the 14 land cover classes used in the present research might be too broad, as there are different types of 'natural unimpacted' vegetation types (e.g., fynbos vs. tall grassveld vs short grassveld), 'natural degraded' areas (e.g. gully vs. sheet erosion) and 'dryland commercial agriculture' (e.g. with summer vs. winter crops; cultivation with or without contour banks). Refining these aspects would greatly enhance results on a local level.
- So as not to introduce false precision, it is suggested to rather upscale the DEM resolution to the coarser rainfall resolution, compared to the other way around, as was used within this study. However, this is only applicable to Step 5 in this process, where the dilution factor is introduced.
- Finally, the fractional risk values per land use should be re-visited, in consultation with experts in the field.

AUTHOR CONTRIBUTIONS

SS and RES designed the study; SS collected the data and conducted the modelling. SS and RES analysed and interpreted the results. SS and RES wrote the paper.

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