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Influence of basin connectivity on sediment source, transport, and storage within the Mkabela Basin, South Africa

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Abstract

The management of sediment and other non-point source (NPS) pollution has proven difficult, and requires a sound understanding of particle movement through the drainage system. The primary objective of this investigation was to obtain an understanding of NPS sediment source(s), transport, and storage within the Mkabela basin, a representative agricultural catchment within the KwaZulu-Natal Midlands of southeastern South Africa, by combining geomorphic, hydrologic and geochemical fingerprinting analyses.

The Mkabela Basin can be subdivided into three distinct subcatchments that differ in their ability to transport and store sediment along the axial valley. Headwater (upper catchment) areas are characterized by extensive wetlands that act as significant sediment sinks. Mid-catchment areas, characterized by higher relief and valley gradients, exhibit few wetlands, but rather are dominated by a combination of alluvial and bedrock channels that are conducive to sediment transport. The lower catchment exhibits a low-gradient alluvial channel that is boarded by extensive riparian wetlands that accumulate large quantities of sediment (and NPS pollutants).

Fingerprinting studies suggest that silt- and clay-rich layers found within wetland and reservoir deposits are derived from the erosion of fine-grained, valley bottom soils frequently utilized as vegetable fields. Coarser-grained deposits within both wetlands and reservoirs result from the erosion of sandier hillslope soils extensively utilized for sugar cane, during relatively high magnitude runoff events that are capable of transporting sand-sized sediment off the slopes. Thus, the source of sediment to the axial valley varies as a function of sediment size and runoff magnitude. Sediment export from the basin was limited until the early 1990s, in part because the upper catchment wetlands were hydrologically disconnected from lower parts of the watershed during low- to moderate flood events. The construction of a drainage ditch through a previously unchanneled wetland altered the hydrologic connectivity of the catchment, allowing sediment to be transported from the headwaters to the lower basin where much of it

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was deposited within the riparian wetlands. The axial drainage system is now geomorphically and hydrologically connected during most events throughout the study basin. The study indicates that increased valley connectivity partly negated the positive benefits of controlling sediment/nutrient exports from the catchment by means of upland based, best management practices.

1 Introduction

Athough the impacts of point source pollution on aquatic ecosystems have been greatly reduced, the management of non-point source (NPS) pollution has proven to be extremely difficult, and is a leading cause of surface water degradation (USEPA, 2000). Non-point source pollutants are of particular concern in agricultural areas where sediment, nutrients, and pesticides have been shown to negatively impact water quality. Attempts to control NPS pollution generally rely on the development and application of best management practicies which balance the economic value of land-use activities with methods to reduce the production and influx of NPS pollutants to water resources. To be cost-effective, such management strategies require a sound understanding of the primary NPS pollutant sources, how pollutants are delivered to and transported through aquatic systems, and how various management senarios will influence NPS pollutant loadings. While conceptually simple, development of quantitative tools upon which to base management decisions and strategies is complicated by multiple and diffuse sources of pollutants, their movement as both solutes and particulates, and differences in pathway transport dynamics over varying temporal and spatial scales. Fine-grained sediments serve as a particularly important component of the NPS pollutant problem because of their direct impact on biota, and the sorption of nutrients and other contaminants onto particle surfaces such that many hydrophobic contaminants are predominantly dispersed through river systems in the particulate form (Miller and Orbock Miller, 2007). It follows, then, that any attempt to effectively address NPS pollution requires a highly sophisticated understanding of the spatial and causal linkages

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among human activities, fine-grained sediment production, and sediment transport and storage processes over a range of time scales.

Historically, sediments (and associated pollutants) eroded from upland areas of a catchment were assumed to move semi-systematically through the drainage system to the basin mouth. This classical continuum view has begun to be replaced in recent years by a segmented, heirarchical perspective of a drainage network in which channel and valley floor environments that can be subdivided into progressively smaller units (Frissell et al., 1986; Kishi et al., 1987; Grant et al., 1990; Montgomery and Buffington, 1993; Grant and Swanson, 1995; Brierley and Fryirs, 2001, 2005; Miller et al., 2012). Each unit, of a given scale, are morphologically homogeneous with respect to landforms, processes, and other controlling factors such as geology, vegetation, and substrate (Gant and Swanson, 1995). Common scales of study range from localized channel units (defined on the basis of various river bed features such as pools, riffles, bars, etc.), reach-scale units (defined according to the nature of both the channel and valley floor), and larger units ranging up to and beyond the entire drainage basin. Application of the hierarchal approach for management purposes has focused on reach-scale units, often referred to as process zones.

Inherent within the hierarchal systems approach is the perception that process zones (as well as units defined at other scales) differ in their ability to produce, transport, and store sediment. Process zones therefore represent a fundamental unit of watershed management that allows distinct strategies to be developed for specific parts of the drainage network.

A closely related concept to the hierarchal view of a river system is connectivity. Connectivity, as used here, refers to the degree to which water and sediment can be transferred from one process zone to the next downstream zone (Hooke 2003). The geomorphic and hydrologic connectivity of the system are highly dependent on the time scale under consideration. For example, drainage systems located in areas characterized by seasonal rainfall may be hydrologically connected during the wet period, but disconnected during the dry months when the channel possesses both perennial and

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ephemeral reaches (Miller et al., 2012). Over longer-time scales (years to decades), sections of the drainage network may become incised, thereby increasing the surface connectivity between the zones, or become filled, creating a discontinuous drainage system with decreased connectivity between process zones.

In light of the above, the movement of NPS pollutants through a drainage system will not only depend on existing hillslope conditions and management practices, but on the hierarchal structure (morphometry) of the watershed and the connectivity between process zones and other hierarchal units. The primary objective of this paper is to describe spatial variations in the source(s), transport, and storage of sediment over annual to decadal time scales within the Mkabela drainage basin, a representative catchment within the KwaZulu-Natal Midlands of Eastern South Africa. The utilized analysis integrates field and cartographic data of fluvial landforms and processes with detailed geochemical analyses of sediment provenance. The latter analyses allow for the quantification of long-term (decadal-scale) changes in sedimentation rates and basin connectivity along the axial drainage system.

2 Study area: geologic, geographic and climatic characteristics

The Mkabela Catchment is located within the KwaZulu-Natal Midlands of Eastern South Africa, approximately 25 km from Pietermaritzburg (Fig. 1). The Mkabela River basin was selected for study because (1) it is representative of catchments in the region, (2) exhibits a wide range of land-uses, and (3) is a tributary to the much larger Mgeni River which drains most of the Midlands, and for which a decline in water quality, by means of eutrophication, has been an increasing concern. Important nutrient sources include direct waste water inputs, broken sewer lines, animal wastes, and non-point source inputs, particularly sediment-associated nutrients from agricultural lands.

Climatically, the Mkabela Basin is characterized by semi-arid conditions, receiving on average 890 mm of precipitation per year, greater than 80 % of which falls during the summer months of October to March. Ecologically, the basin and surrounding area are

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characterized by savannah type vegetation (referred to as the Savannah Ecoregion; WRC, 2002), although land cover has been dramatically altered during the past century. Current land-use is dominated by agriculture, and varies between three morphologically distinct catchment areas, referred to here as the upper, middle, and lower subcatchments (Fig. 1). Land-use within the upper subcatchment is dominated by sugar cane on hillslopes, and pasture, maize and other vegetables on valley floors, whereas the middle subcatchment is dominated by sugar cane on hillslopes and pastures on the valley bottom. Valley bottom wetlands are common within the upper catchment, and are replaced in mid-catchment areas by channelized alluvial valleys periodically interrupted by dams and reservoirs. The lower catchment is characterized by forested riparian wetlands on the valley floor and hillslopes that are predominantly covered by sugar cane vegetation. The basin as a whole is underlain primarily by shales, siltstones, and red sandstones of the Natal Sandstone and, to a lesser degree, the Dwyka Groups.

3 Methods

3.1 Process zone mapping and characterization

Field and cartographic observations indicated that the catchment could be subdivided into process zones and subcatchment areas (Fig. 2), the latter corresponding to the noted differences in land-use. Subcatchment areas were defined according to changes in hillslope and valley morphology whereas the processes zones represent stream reaches defined on the basis of their position on the landscape, their dimensions and cross-sectional form, the composition and nature of the bounding materials (bedrock vs. sediment; sediment size, stratification, etc.), and the relief/gradient of the channel and surrounding terrain. It is important to recognize that while zone types were defined geomorphically, each type exhibits specific traits with regards to geomorphic processes (including erosion and deposition) operating within the channel, and hydrologic sources and sinks (Table 1).

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Delineation and mapping of process zones utilized an iterative approach where distinct reaches of the drainage network were classified and mapped on 2007 georectified SPOT images, with the aid of stereoscopic viewing of 2004, 1:10 000 aerial photographs. Once mapped, the geo-rectified and field checked data provided spatial information on the type and distribution of the process zones and the ability of the drainage network to transfer water, sediment, and any nutrients that they carry down catchment.

3.2 Upland sediment sampling and analysis

The use of geochemical fingerprinting methods to elucidate sediment provenance from non-point sources have increased significantly during the past two decades (Slattery et al., 1995; Collins, 1995; Collins et al., 1997a,b, 1998; Walling et al., 1999; Bottrill et al., 2000; Russell et al., 2001; Douglas et al., 2003, 2005, 2010; Miller et al., 2005; Foster et al., 2007, 2012). With regards to non-point source pollutants, the basic premise underlying the use of geochemical fingerprinting methods is that the processes involved in the erosion, transport, and deposition of sediment ultimately result in a deposit that represents a mixture of material derived from multiple source areas within the catchment. It is then possible to characterize the sediments within the source areas and the downstream alluvial/lacustrine deposits for a suite of parameters and statistically compare their parameter characteristics to unravel the relative proportion of sediment that was derived from each source type (Miller and Orbock Miller, 2007). In this study, geochemical fingerprinting and tracing methods were applied to a series of sediment cores extracted from wetland and reservoir deposits to determine changes in sediment provenance through time at selected locations along the valley floor. In addition, selected cores were dated using ^{210}Pb methods to estimate sedimentation rates and determine how these rates varied with changes in sediment provenance. An assumption inherent in the analysis is that a comparison of the variations in sediment provenance and depositional rates along the valley floor provides insights into both the movement of sediment through the basin and the geomorphic connectivity of the drainage network for a specific time interval.

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Sediment sources within a catchment have been defined in geochemical fingerprinting studies in different ways (e.g. by land-use category, geological unit, or tributary basin) depending on the primary intent of the analysis. For this investigation, a total of 73 samples were collected from upland areas in May, 2008 in order to characterize sediment sources (Fig. 3). The utilized sampling strategy was developed to allow the data to be stratified (categorized) in two different ways to determine the relative contribution of sediment from six land-use categories and seven soil types. The sampling scheme, then, allows an assessment of how both land-use and soil type influence sediment production and availability (Table 2). The number of randomly collected samples in each land-use category roughly corresponds to the area that it covers within the catchment. Road samples were not used to calculate statistical properties of specific soil types because of the degree to which the soils were disturbed. All of the sampled upland soils were obtained from approximately the upper 2 cm of the ground surface. The sediments therefore represent the material most likely to be eroded during a runoff event. Erosion of sediment from hillslopes or valley deposits by gullies was not observed to be significant within the catchment. In order to reduce field variance in elemental concentrations, subsamples were collected from about 10 locations within a 5 m radius of the sampling site and composited to create a single sample.

All of the upland samples were loaded into pre-cleaned sampling containers, which were subsequently placed in plastic sampling bags, and shipped to the Nevada Bureau of Mines and Geology in the USA for analysis. The samples were analyzed using a Micromass Platform ICP-HEX-MS for major elements (e.g. Si, Al, Fe, Ca, Mg, Mn, Na, K, Ti, and P), total acid-soluble trace metals and metalloids (e.g. Pb, Zn, Cd, Cu, Au, Ag, Se, As), selected rare earth elements (e.g. Ga, Nb, La, Lu, Hf), and selected isotopes (e.g. ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb). Analysis involved the digestion of 200 mg of dried and homogenized sediment, < 2 mm in size, in 125 ml polypropylene screw-top bottles containing 4 ml of aqua regia. These were sealed and held in a 100 °C oven for 60 min. The leachates were then transferred to 200 ml volumetric flasks, brought up to volume with ultra-pure water and stored until analyzed by ICP-MS. With respect to total elemental concentrations, the Platform was calibrated using USGS, NIST, and in-house standard reference materials (SRMs). Reagent blanks and the analyte concentrations for the SRMs were plotted against blank-subtracted integrated peak areas. A regression line was fitted to this array of calibration points and the equation of the line was used to quantify unknown sample concentrations. Deviation of standards from the regression line was used to estimate analytical accuracy, which was generally ± 3 to 5 % of the amount present when determining total concentrations. Replicate analyses were used to determine analytical precision, which was generally $< \pm 5$ % for most elements. With respect to Pb isotopic analyses, precision when comparing data from individual digestions was 0.2 to 0.3 % relative deviation (one sigma) for ^{206}Pb, ^{207}Pb, and ^{208}Pb. Instrumental precision was better. Accuracy of isotopic measurements was assessed with the NIST 981 lead isotope standard. Accuracy was typically better than ± 0.5 %, and systematic instrumental bias was corrected. Given the limited abundance of ^{204}Pb, precision and accurracy values were much higher; thus, ^{204}Pb was not used as a potential tracer.

3.3 Collection, sedimentology and analysis of sediment cores

Four cores were collected in 2008 from the upper and middle subcatchments, including one core from the margin of the upstream most reservoir (R1-C1), and three cores from the wetland (WT1-C1, WT-C2, and WET) (Fig. 3). Three additional cores were collected in 2009 from sites along the axial drainage system. Two of these were located in areas within the upper catchment (TB-1, PB-1; Fig. 3). A third core (B2WTC1) was collected from a riparian wetland located along the channel in the lower catchment (Fig. 4). All of the cores were shipped to the Nevada Bureau of Mines and Geology and subsequently described, photographed, and sampled for geochemical analyses. Samples from selected cores were then analyzed for the same elements as the upland samples by ICP-MS as described above.

Selected cores were dated by means of ^{210}Pb (^{137}Cs levels were determined to be too low to yield useful results). The analyses were carried out by Flett Research Ltd.

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located in Winnipeg, Canada. Flett Research was also contracted to use the raw ^{210}Pb data to model the age-depth relationships within the cores. The results were then used to determine sedimentation rates at the site. Depth-age curves were modeled using the constant rate of supply (CRS) method (Appleby and Oldfield, 1978).

3.4 Source modeling procedure

Determination of the relative contribution of sediments from the source areas relies on the use of a sediment mixing model. Such models have been increasingly utilized in recent years to determine sediment provenance from NPS pollutants (Yu and Oldfield, 1989, 1993; Foster and Walling, 1994; Collins et al., 1997a,b,c,d, 1998; Kelley and Nater, 2000; Miller et al., 2005). During this investigation, the original model used by Miller et al. (2005) was modified using the approach provided by Rowen et al. (2000) to estimate sediment source contributions from the hillslopes to the cored deposits.

Constraints on the mixing model require that (1) each source type, contributes some sediment to the mixture, and thus the proportions (x_j, $j = 1,2,\ldots,n$), derived from n individual source areas must be non-negative ($0 \le x_j \le 1$), and (2) the contributions from all of the source areas must equal unity, i.e.:

$$\sum_{j=1}^{n} x_j = 1. \qquad (1)$$

In addition, some differences (error) between the values of the m measured parameters, in the source area, a_{ij} ($i = 1,\ldots m, j = 1,\ldots,n$) and the mixture, b_i ($i = 1,\ldots,m$) must be allowed. The residual error corresponding to the ith parameter can be determined as follows:

$$\varepsilon_i = b_i - \sum_{j=1}^{n} a_{ij} x_j \qquad (2)$$

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for $i = 1, 2, \ldots, m$, where a_{ij} ($i = 1, 2, 3, \ldots, m$, $j = 1, 2, \ldots, n$) are the measurement on the corresponding ith parameter within the jth source area and x_j is the proportion of the jth source component in the sediment mixture. When the number of measured parameters is greater than the number of source areas ($m \geq n$), the system of equations is over-determined, and a "solution" is typically obtained using an iterative computational method that minimizes an objective function using a gradient search, thereby obtaining a best fit solution to the entire data set (Yu and Oldfield, 1989). There are several ways to obtain a best fit, but in previous studies, the objective function, f, has taken the form of the sum of the relative errors (Yu and Oldfield, 1989) where

$$f(x_1, \ldots, x_m) = \sum_{i=1}^{m} \left| \varepsilon_i / b_i \right| \tag{3}$$

or (Collins et al., 1997a)

$$f(x_1, \ldots, x_m) = \sum_{i=1}^{m} \left(\varepsilon_i / b_i \right)^2 \tag{4}$$

However, in the case where f is relatively "flat", the gradient near zero may halt an iterative search method prematurely.

We take an alternative route, following Rowan et al. (2000) and Nach and Sutcliffe (1970), whereby we create the efficiency function

$$E(x_1, \ldots, x_m) = 1 - \frac{\sum_{i=1}^{m} (\varepsilon_i)^2}{\sum_{i=1}^{m} (b_i - d_i)^2} \tag{5}$$

where d_i ($i = 1, 2, 3, \ldots, m$), is the mean of the ith parameter over all source regions. An ideal solution would result in $E = 1$ or 100 % efficiency. We then create a partition of all possible combinations of non-negative n-tuples $(x_1, \ldots, x_n)$ satisfying the

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unity constraint, Eq. (1), by increments of $\Delta x = 0.05$. By evaluating E at each of the n-tuples, we are able to determine the specific combination of the source contributions $\hat{x} = (x_1, \ldots, x_n)$ yielding the maximum efficiency on the partition.

As Rowan et al. (2000) pointed out, the efficiency function E has a maximum value at $\hat{x}$, but there may be a range of n-tuples having an efficiency within a specified tolerance of the maximum efficiency. That is, there are a number of solutions that are statistically equivalent. For example, using the data from sample WT1-C1-1, the optimal efficiency value was 0.9963 when 50 % of the contribution was from cane, 25 % from corn and vegetable, and 25 % from wattle groves. Yet we see that there is a small range of proportions for each source that yields efficiency levels at the 0.95 level or above.

4 Results and discussion

4.1 Drainage network characteristics

Field and cartographic data show that the drainage network within the Mkabela Basin can be subdivided into nine distinct process zones on the basis of their position on the landscape, valley dimensions and form, the underlying geological deposits in which they are developed, and the degree to which they have been affected by human activities (Simon et al., 2011) (Fig. 2). Each of these defined process zones are dominated by a suite of geomorphic and hydrologic processes as described in Table 1, and occur with different frequencies within distinct segments of the catchment referred to as the upper, middle, and lower subcatchments (Fig. 4).

Upper subcatchments comprise the upstream most (heardwater) areas of both axial and large tributary drainage systems (Fig. 4). Within these upper subcatchments, hillslope drainage has often been significantly modified by cultivation, particularly in areas of sugar cane, in part to reduce the removal of sediment from the cultivated slopes. However, hillslopes are locally traversed by a relatively high density (approximately 2.5 km km^{-2}) of man-made, low-gradient, u-shaped “waterways” that are

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oriented perpendicular to topographic contours (Fig. 5a, Table 1). Hillslope runoff and flow along contoured features primarily deliver sediment to these waterways that is then feed into larger, incised channels, referred to as "upland ditches" (Figs. 5b, 4) (Note that due to their small scale, lines of drainage parallel to contours were not considered here as a type of process zone). The upland ditches represent heavily modified or relocated upland channels, or entirely man-made features. In either case, upland ditches are more incised and v-shaped than the u-shaped waterways. Farther downstream, upland ditches and waterways deliver water and sediment to wetlands, or more frequently, an "axial ditch" (Figs. 5c, 4). The largest axial ditch within the upper subcatchment was cut into unconsolidated valley fill deposits that comprise the axial valley. Until recently (∼ 1990), this portion of the axial valley was dominated by a natural wetland, but after the creation of the axial ditch upstream areas of the wetland were drained and converted to pasture (Fig. 4). Farther downstream, however, the axial ditch decreases dramatically in size and depth as it enters a less disturbed area of wetland formed upstream of a bedrock constriction in the valley floor (Fig. 4). This wetland defines the downstream limit of the upper subcatchment. The mouth of a tributary entering the axial valley from the south west (Fig. 4) also exhibits an extensive wetland devoid of an integrated network of surface channels. Field observations indicate that the water table within the wetland is below the ground surface during the dry season, but is at or near the ground surface during wetter months. The extensive wetlands found within the axial valley system of the upper catchment are dominated by relatively low channel and valley gradients and depositional processes.

The middle subcatchment begins downstream of the bedrock constricted wetland (Fig. 4). Hillslopes within this portion of the basin are also dominated by sugar cane fields that possess numerous waterways (Fig. 4). However, many of the waterways along the western side of the catchment are short, drain relatively small areas, and are disconnected geomorphically from the axial valley, limiting their ability to directly deliver sediment to the axial channel. Perhaps of more importance with respect to sediment transport, the axial drainage system within the middle subcatchment is characterized

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by a continuous, relatively shallow, but high gradient ($\sim 0.008\,\mathrm{m\,m^{-1}}$) alluvial channel. The channel is disrupted by four separate farm dams and their associated reservoirs (Fig. 4). Water flows over the top of the dams throughout most of the year, but during wet season storms the movement of water through the reservoir and over the dam can be particularly intense. Immediately below the fourth dam, the stream consists of a bedrock channel locally characterized by a series of knickpoints (Fig. 5e). The river then enters the lower subcatchment.

The lower subcatchment is dominated by a low gradient, alluvial channel boarded by extensive and forested riparian wetlands (Figs. 4, 5f). The wetlands are intermingled with areas of sugar cane that also occur locally on hillslopes. In marked contrast to the upstream subcatchments, upland areas within the lower subcatchment exhibit very few waterways, axial ditches, or upland channels, in spite of the fact that valley floors are incised well below the surrounding terrain. The low gradient nature of the axial channel, and the broad alluvial valley consisting of extensive riparian wetlands, forms a highly depositional environment that allows for the store of large volumes of sediment (as described below).

4.2 Sediment provenance analyses

4.2.1 Delineation of geochemical fingerprints

Geochemical fingerprinting methods were used to determine the predominant source of sediments to wetland and reservoir deposits located along the drainage network. Two separate analyses were carried out, one in which sediment sources were defined on the basis of soil type (Fig. 6), and the other for which sources were defined on the basis of land-use. An inherent assumption in the use of such geochemical tracers is that the elemental fingerprints are conserved during transport (i.e. there is no loss in elemental mass). A comparison of the average concentrations and mass within the upland soil samples collected from the wetland sediment revealed that a number of the ~40 analyzed parameters (e.g. Ca, Mn, P, Cu, and Zn) were not conserved (i.e.

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elemental mass was lost from the system, presumably in the aqueous phase). Thus, these elements could not be utilized in the mixing models. The remaining elements were subsequently utilized in a stepwise discriminate analysis to determine which parameters were effective at differentiating sediment sources. The results suggest that effective fingerprints can be developed for sediment sources when defined according to either soil type (Table 3a) or land-use category (Table 3b).

With respect to the soil type, eight elements were identified as fingerprints, including Ti, Cr, Ga, Nb, La, Ce, Lu, and Hf. The majority of these are Rare Earth Elements which are known to be highly immobile in freshwater systems with normal Eh and pH conditions. The eight elements correctly classified 79 % of the samples (Table 3a). The most incorrectly classified samples were obtained from Cartref and Glencoe soils, both of which are found on steep slopes and possess sandy-textured horizons.

A stepwise discriminate analysis was also carried out for sediment sources defined by land-use. The selected parameters were the same as those used to differentiate soil types (Ti, Cr, Ga, Nb, La, Ce, Lu, and Hf) (Table 3b). Sediments collected from specific land-use categories were incorrectly classified about a third of the time. The difficulty of correctly identifying a particular land-cover may be related to two factors. First, crop rotations, although not extensive in cane fields, may potentially produce a mixed geochemical signal with regards to land-use. Second, a given land-use category may be underlain by several soil types, complicating its geochemical signature. In fact, when soil type is added to the discriminate analysis as a numeric value the ability to correctly classify land-cover increases significantly (to 86 %).

4.2.2 Provenance modeling results

The location and general characteristics of cores collected, geochemically analyzed, and modeled to assess sediment provenance within the Mkabela Basin are provided in Fig. 4 and Table 4, respectively. The soil source modeling (in which provenance was defined on the basis of soil type) shows that three distinct intervals are present in WT1-C1 (Fig. 7). Samples 10–16 (69.5–107 cm) are composed exclusively of Clovelly (CV)

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and Katspruit (Ka) soil types. The relative contributions of Clovelly range from 10 to 70 %, and average 40.1 %; Katspruit ranges from 40 to 90 %.

Samples 7–9 (41.5–69.5 cm) are dominated by Katspruit (> 60 %), with minor contributions of Westleigh (We), Avalon (Av), Catref (Cf), and Longlands (Lo), in three of the samples. The upper part of the core (samples 1–4) primarily consist of Avalon (30–60 %), Katspruit (10–70 %, and Longlands (10–40 %) soil types, with minor contributions of Glencoe (Gc) and Westleigh.

Boundaries between two of the major source type intervals within the core roughly correspond to stratigraphic unit boundaries. The boundary between the mid-interval (samples 7–9) and the lower interval (samples 10–16) imprecisely correlate with a gradational stratigraphic boundary within the core.

Core WT1-C1 can also be subdivided into three distinct intervals with respect to modeled land-use sediment sources (Fig. 8). The three intervals correlate with the intervals denoted for soil type. Samples 10–16 are composed predominantly of sediment from cane (15–75 %) and vegetable (30–80 %) fields. The samples also contain minor amounts of sediment from pastures (< 10 %). The intermediate interval (samples 7–9) is dominated by sediment from vegetable fields (generally > 70 %). However, in comparison to the lower unit, the interval exhibits a notable increase in sediment from pastures (∼ 10–25 %), and localized, minor amounts of material from roads and wattle-covered terrain. With the exception of sample 5, the upper 6 samples contain a wider range of source inputs. The dominate sources for these samples include sediment from vegetable fields, pastures, and cane fields, with lesser amounts of sediment from wattle-covered terrain (Fig. 8).

Core WT1-C2 (from upper catchment wetland) can be subdivided into three intervals on the basis of sediment provenance with respect to soil types (Fig. 7). The lower most interval ranges from 78–90 cm (samples 13–14), consists of a medium sandy loam, and possesses sediment from a variety of soil types including Longlands (10–60 %), Glencoe (20–40 %), Cartref (0–30 %), Katspruit (0–30 %), and Clovelly (0–10 %). This lower most interval is overlain by a unit ranging from 62–78 cm (samples 11–12) that

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is dominated by sediment from Clovelly (30–90 %) and Katspruit (10–60 %) soils, with minor contributions from Avalon soils (0–10 %). The majority of the core, ranging from 0–62 cm in depth, is dominated by sediment from Katspruit (80–90 %), with < 20 % coming from Catref soils, except in the lower most sample. This latter sample contains sediment from Glencoe rather than Catref soils. Changes in sediment source contributions correspond to stratigraphic unit boundaries.

With regards to land-use, sediment provenance within Core WT1-C2 can be subdivided into two intervals which closely, but not precisely, match the boundaries denoted for soils. The lower most deposits (below 55.5 cm, sample 10) contain relatively large percentages of sediment from cane fields (Fig. 8), whereas the overlying sediments are predominantly derived from vegetable fields (> 80 %) with lesser contributions from roads. Sample 10, located along the boundary between the two intervals appears transitional in terms of source, consisting of large amounts of sediment from vegetable fields (as is the case for the overlying deposits), as well as minor amounts of sediment from cane fields and pastures (as is the case for the lower deposits).

The sediments in Core WET (from upper catchment wetland) can be subdivided into two predominate intervals in terms of the soil types from which the sediments were derived (Fig. 7). The lower most sediments (37–69 cm, samples 7–10) are composed primarily of Avalon, Westleigh, and Katspruit soils, with minor amounts (10 %) of Catref and Longlands in sample 7. The upper most part of the core (from 0–30 cm) consists primarily of sediment from Longlands soils, with lesser (∼ 10 %) from Catref soils. Sample 6, which separates the two intervals and which is found at the top of a stratigraphic unit, is highly anomalous, consisting exclusively of sediment from Clovelly soils.

Changes in sediment provenance modeled with respect to land-use closely parallel noted changes in provenance assessed by soil type. The lower most sediments (37–69 cm, samples 7–10) are composed primarily of sediment from pastures (15–70 %), and in decreasing order, vegetable fields (5–70 %), wattles groves (5–15 %), pine groves (0–15 %), cane (5–20 %) and roads (0–10 %). The upper most part of the core (from 0–30 cm) consists primarily of sediment from cane fields (10–100 %)

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and wattles (45–85 %), with small amounts (5 %) from vegetable fields and pastures in sample 5. Sample 6, which separates the two intervals and which is found at the top of a stratigraphic unit, consists exclusively of sediment from cane fields.

Core R1-C1was obtained from the margin of reservoir located within the middle catchment. The majority of sediment within the reservoir was derived from Longlands soil, with the exception of five, notable, but thin horizons. Sampling intervals 18 and 21 at the bottom of the core (126–140 cm) are composed exclusively of sediment from Katspruit type soils. The sampling interval from 60–73 cm (samples 13–14) contains 30–50 % Covelly soil material, in addition to Longlands. Thin loamy fine sand to loam layers between 29.5 and 39 cm contain no definable sediment from Longlands soils, but are dominated by Katspruit (sample 6) or a mixture of Katspruit, Glencoe, and Clovelly (sampling interval 7). The upper most sediments also contain significant amounts of Clovelly type materials as well as Glencoe and Katspruit in the case of sampling interval 1.

With regards to land-use, the majority of the sand dominated sediment within Core R1-C1 appears to have been derived from cane fields. Fine-grained, loamy sediments (e.g. found in sampling intervals 1, 6, 7, 18, and 19) appear to have been derived primarily from vegetable plots. Figure 8 also shows that there is a notable increase in the contribution of sediment from wattle groves within and above sample 11 (55.5 cm), as well as vegetables and roads, at and above sample 8 (39 cm) following a period of input primarily from cane fields between samples 12 and 16 (55.5–106 cm).

4.2.3 Sediment dating

Based on their stratigraphy and location, samples from two cores (WT1-C1 and R1-C1) were analyzed for ^{210}Pb to (1) determine the age of the deposits as a function of depth, and (2) estimate sedimentation rates for specific time intervals. ^{210}Pb in the relatively fine-grained sediment of Core WT1-C1 was measurable, but low (Fig. 9). The single ^{226}Ra measurement of 0.82 DPM g^{-1} in the deepest section (at 112–122 cm depth), which based on stratigraphic data represent pre-historic sediment, is similar

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to the ^{210}Pb measurement of 0.60 DPM g^{-1} in the same section. This suggests that background levels of ^{210}Pb have been attained at 105 cm. Although the ^{226}Ra and ^{210}Pb values diverge slightly, backgound may have been attained at the shallower depth of 70 cm depth (R. Flett, personal communication).

Age-depth relations were modeled using the constant rate of supply (CRS) method for background values at both 105 and 70 cm, generating two age-depth curves (Fig. 9). Both curves are presented to provide the range of age-depth relations that may exist, depending on the background depth that is utlized. The two analyses yield similar results for the upper 6 samples (last 20 yr), but progressively diverge after that (Fig. 9). Both analyses indicate that sedimentation rates within the wetland are relatively uniform until the end of the 1980s, at which point sedimentation rates begin to increase significantly to the present.

The ^{210}Pb content of the sediment from R1-C1 was very low and irregular, showing no consistent pattern. This pattern is presumably related to the coarse-grained nature of the reservoir deposits. In any case, it was not possible to confidently determine the date of deposition of any of the sediments within the core from the reservoir (R1-C1).

4.2.4 Controls on sediment source

A difficult question that must be addressed when using geochemical fingerprinting methods to determine sediment provenance is the grain-size of the material that should be analyzed. Many investigators focus only on the < 63 µm fraction because (1) it comprises a significant portion of the suspended sediment load in rivers, (2) it generally represents the chemically active phase, and (3) it is less effected by the dilution of chemical concentrations by relatively inert, particles composed of quartz, feldspars, and, perhaps, carbonates. Analysis of only fine-grained sediment is not, however, without its problems. Sand, in some cases, can comprise a significant part of the suspended sediment load, and may dominate alluvial and/or reservoir deposits. Such is the case in the Mkebela Catchment where the reservoir deposits are composed almost

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exclusively of sand-sized particles. Some wetland deposits, such as those found near the top of Core WET, are also composed of sand-sized materials. As a result, documentation of sediment provenance within the catchment required an analysis of both the silt- and clay-sized sediment and the sand-sized fraction.

An examination of the core data collected from the wetland and reservoir shows that the deposits exhibit significant spatial (depth, areal) variations in grain size. These variations between subcatchment areas are dramatic. The upstream most reservoir within the catchment is dominated by sand, as was mentioned earlier (Figs. 7, 8). The wetland, however (which is upstream of the reservoirs) consists primarily of loamy or sandy loam deposits. The observed variations in deposit grain size presumably reflect changes in sediment source and the nature of the source materials, hydraulic sorting of the sediment during transport and deposition, differences in flow magnitudes (owning to differences in cathcment size), or a combination of the three factors.

The utilized sediment mixing model suggests that nearly all of the sand-sized sediment within the reservoir is derived from Longlands and, to a much lesser degree, Clovelly soils. Both of these soil types exhibit sandy textures within the catchment (Table 5; Le Roux et al., 2006). They tend to be sandier than the clay-rich Westleigh or Avalon hillslope soils, and much sandier than valley bottom soils such as the clayey Katspruit soil (Le Roux et al., 2006). The geographic distribution of Longlands and Clovelly soils has been mapped in detail for only the headwaters of the Mkabela Catchment (Fig. 6). Here Longlands and Clovelly soils are located along the eastern corner of the Catchment, and are shown to abut Cartref soils on the 1 : 100 000 soils map (Fig. 6). However, while the area shown as Cartref is dominated by Cartref types soils, it also includes a mixture of other soil types including Longlands and Clovelly soils. Thus, Longlands and Clovelly soils extend further south beyond the region mapped in detail (Fig. 6) and underlay a portions of the eastern hillslopes which drain into the wetland and the reservoir. It appears reasonable, then, that Longlands and Clovelly soils serve as the primary source of sand-sized sediment within the reservoir, particularly given the relatively steep slopes (4–7 %) upon which they occur. It is perhaps reassuring to note

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that near surface sediment from a hillslope near Core WET underlain by Longlands was modeled to consist of Longlands derived sediment.

The hillslopes underlain by Longlands and Clovelly soils are primarily covered by sugar cane fields. This is also consistent with the land-used based mixing model results which indicate that the majority of the sand-sized sediment was derived from cane fields.

Several loam textured layers occur within the reservoir core (R1-C1) (Figs. 7, 8). These finer-grained units were modeled to consist of sediment primarily derived from Katspruit, and to a much lesser degree, Cartref, Glencoe, and Avalon soils. As would be expected, Katspruit soils are rich in clay as are Avalon and Glencoe soils (although not to the degree of Katspruit soils) (Le Roux et al., 2006).

The Katspruit soils are primarily covered by vegetable fields on relatively flat sections of the valley bottom, and the land-use based modeling suggests that the loamy deposits within the reservoir are primarily derived from vegetable fields, with minor contributions from roads (with a clay-plinthic base) and cane fields (presumably underlain by Avalon or other clayey hillslope soil).

Similar texture, soil type, land-use associations occur with all three of the cores obtained from the wetland. These are particularly apparent for the lower portions of the historic deposits. For example, sediments within Core WT1-C1 below approximately 69.5 cm (sample 10 and below) exhibit a fine sandy loam texture. Modeling suggests the sediments were derived from Katspruit soil (fine component) and Clovelly soils (sand component), covered primarily by vegetables and cane, respectively (Figs. 7, 8). Finer grained deposits (loam textured) between 41.5 and 62.5 cm (samples 7–9) were derived, according to the model, from Katspruit and Weistleigh soils (both fine grained) overlain by vegetables (including corn, which can be found on Weistleigh hillslopes).

A detailed examination of the modeling results indicates that a significant change in sediment source near the middle to top of the wetland and reservoir cores is superimposed on the texture, soil type, land-use association. In Core WT1-C1, the change in source begins at a depth of approximately 55 cm (sample 8) with a progressive increase in the contribution of sediment from pastures, wattles, and, to a much lesser degree, roads. Avalon and Longlands soil contributions also become more prevalent. The top of Core WET (above sample 6) also exhibits an increase in the contribution of sediment from wattle groves, and an increase in Longlands and Cartref soil types (the latter of which underlies wattle groves). In Core WT-C2, sediment above 62 cm (sample 10) is derived almost exclusively from areas composed of Katspruit soils and vegetable fields, with a rather abrupt input of material from roads. Further downstream in the reservoir, the change in source is characterized by an increase in sediment from wattle groves, and an increase in sediment from Glencoe soils.

Interestingly, changes in sediment source coincide with a notable increase in sedimentation rates from approximately 0.67 cm yr^{-1} to 2.21 cm yr^{-1} as determined using ^{210}Pb data in Core WT1-C1. The ^{210}Pb data suggest that the change occurred between approximately 1988 and 1992.

The noted changes in sediment source and sedimentation may be related to (1) changes in land-use and crop type through time, both in terms of the absolute area covered and their position on the landscape, and (2) changes in management strategies. It is more likely, however, that the alterations are associated with a major alteration in the geomorphic connectivity of headwater drainages to the wetland and reservoir further downstream in the catchment. Discussions with a local sugar cane farmer revealed that in the early 1990s, the lower half of his fields were changed from maize to sugar cane. This would have involved contouring and water way development associated with cane, in order to limit off-site sediment yields.

At the time of the conversion of corn fields to sugar cane, the valley bottom upstream of the cored wetland also consisted of a wetland that was consistently flooded, resulting in the deposition of sediment in an area which the farmer was attempting to pasture. Thus, a ditch was excavated through this wetland immediately upstream of the large tributary entering from the west (and which drains the wattle grove). The net result was an increase in geomorphic and hydraulic connectivity that allowed drainage from the fields within the headwater areas of the catchment and the western tributary

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to be transported further downstream. The change appears as (1) an increase in sedimentation rates in Core WT1-C1, and (2) an increase in sediment from the wattles and Cartref soils from the tributary, as well as a road that previously limited downstream drainage. The increased contribution of sediment from pastures, present in Core WT1-C1, is probably due to bank erosion along the excavated ditch.

Core WT1-C2 exhibits a significant increase in sediment from vegetable fields underlain by Katspruit soils, at the expense of sediment from cane fields. Given the conversion of corn fields to sugar cane around 1990, the change in sediment provenance is surprising. However, it may be related to better sediment control practices on the cane fields which allowed a larger proportion of the sediment to be derived from the vegetable plots. It is also important to remember that sediment source is texture dependent, so that the contribution of sand-sized sediment from the cane fields was shown to increase within Cores WET and WT1-C1 as a result of the drainage alteration.

4.2.5 Insights from other geochemical tracers

Several trace elements were excluded from use in the geochemical mixing models because of their non-conservative nature, but provide useful information regarding the downvalley transfer of sediment within the catchment. The two of most importance are copper (Cu) and zinc (Zn). Both elements are contained in fertilizer known to have been used on vegetable fields within the catchment. In fact, the utilized fertilizer is reported (on its bag) to contain 2.5 % Zn. The potential impact of the fertilizer on Zn concentrations in the soil is illustrated by comparing the amount of Zn within pasture and vegetable fields underlain by the same soil type (Katspruit). The pasture samples exhibit a mean Zn concentration of 3.58 $\mu g\,g^{-1}$, compared to a concentration of 139 $\mu g\,g^{-1}$ for the vegetable plots, the latter higher by two orders of magnitude (Fig. 10). In addition, Zn concentrations within soils of the vegetable plots are much higher than is generally observed for uncontaminated bedrock (16–105 $\mu g\,g^{-1}$) or soils (60 $\mu g\,g^{-1}$), (Turekian, 1971; Buonicore, 1996; Miller and Orbock Miller, 2007). Similar trends are found for Cu,

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although differences between background materials and the vegetable plots are not as significant (Fig. 10).

Cu and Zn concentrations within the wetland cores vary systematically with depth, but the trends are distinctly different (Fig. 11). Variations in observed trends can be explained, however, by differences in sediment provenance. In Core WT1-C1, for example, both Cu and Zn concentrations increase from the bottom of the core toward the surface (from samples 16 to 7). The concentrations then abruptly decrease by a factor of 5 before remaining relatively constant until reaching the ground surface. The change in concentration is coincident with the observed increase in sedimentation rates (discussed early), and a change in sediment source. More specifically, Zn and Cu concentrations tend to increase as contributions from vegetable fields increase, and decrease as contributions from pastures and cane fields increase (compare Figs. 11, 8). The influence of sediment provenance on Cu and Zn concentrations within the cores is illustrated more directly in Fig. 12. With the exception of three outliers (discussed below), there is a weak tendency for Zn and Cu concentrations to increase as the modeled contribution of sediment from vegetable fields increases. In contrast, indirect relations exist for cane and pasture. The dramatic decrease in concentration above sample 7 in Core WT1-C1 can therefore be explained by (1) increasing contributions of sediment from pasture and cane fields, and (2) higher rates of sand-sized particle sedimentation which presumable exacerbated the effects of dilution on Cu and Zn concentrations.

In contrast to Core WT1-C1, contributions of sediment from vegetable fields in Core WT1-C2 increase toward the surface (decreasing age) above sample 12 (Fig. 11). As expected from the paragraph above, concentrations of Cu and Zn increase as the contributions of sediment from vegetable fields increase. It is also notable that the lowest Cu and Zn concentrations are associated with sample 12 which the source model suggests contain the most sediment from the cane fields.

The indirect relationship between Cu and Zn concentrations and the relative contribution of sediment from pastures is understandable given the limited use of fertilizer on pastures. However, the indirect relationship between Cu–Zn concentrations and sediment from cane fields is surprising given the relatively high mean concentrations of the two elements in cane field samples (Fig. 10b). This indirect relationship may be related the use of fertilizers on corn and vegetable fields which were later converted into cane fields. This hypothesis is supported by (1) highly variable Cu and Zn concentrations within samples collected from the cane fields, and (2) Cu and Zn concentrations that exceed those typically found in soil and bedrock (Fig. 10). The hypothesized influx of sediment to the wetland from previously fertilized cane fields with high Cu and Zn concentrations would also explain the outliers on Fig. 12 (high Cu and Zn with no significant input of sediment from vegetable fields, and high Cu and Zn with high input from cane fields and pastures).

The difference in Cu and Zn concentrations in Longlands soils is interesting as the parent material for it is thought to be the same as that for the other soil types in the catchment (Natal Group Sandstones). Moreover, if the high Cu concentrations consistently observed for Longlands soil samples were related to fertilizer, high Zn concentration would also be expected as shown on Fig. 11. It is unclear at this time why such large differences exist, when they do not for the other soil types. It is possible, however, that the sandy nature of Longlands soils, combined with their occurrence on relatively steep slopes, allowed the more mobile Zn to be leached from the sampled surface sediments.

Figure 13 shows that Cu and Zn concentrations are relatively low from the bottom of Core R1-C1 (sample 21 to sample 9). Concentrations of both elements above sample 9 are generally 3 to 5 fold higher. The change in concentrations is roughly coincident with the modeled change in sediment provenance that was attributed earlier to the construction of a drainage ditch through an upstream wetland. In other words, higher Cu and Zn concentrations appear to result from an increase in system connectivity and the capacity for sediment derived from headwater vegetable fields and other sediment sources to be transported downstream through the wetlands and to the reservoir.

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Interestingly, Cores WT1-C2 and B2WTC1 exhibit similar variations in Cu and Zn concentrations to that observed for approximately the top third of R1-C1 (Figs. 11b, 13). Concentrations are high at the surface and then systematically decrease with depth before increasing further down the core. The primary difference is that the abrupt decrease in Cu and Zn concentrations observed at depth within Core R1-C1 is not present in the other two cores. The zone of relatively low Cu and Zn concentrations corresponds sedimentologically to layers containing significant amounts of sand-sized sediment which the source modeling indicates was derived in part from cane fields. The Cu- and Zn-enriched horizons are finer-grained and derived predominantly from vegetable plots in Cores WT1-C2 and R1-C1 (source modeling was not performed on Core B2WTC1 because it was located well downstream of the sampled upland sediment sources). The similarities in depth trends in concentration suggest that all three locations, spanning the entire study catchment, received similar contributions of sediment from the various sources since about 1990. It therefore appears that following the construction of the upstream drainage ditch through the upstream wetland, the axial drainage network was geomorphically and hydrologically connected.

4.3 Sediment sources, runoff magnitudes, and basin connectivity

Geochemical provenance studies show that the source of sediment deposited within wetlands of the upper subcatchment, and a reservoir from the middle subcatchment, varies as a function of sediment size, stratigraphic layer, and time of deposition. Fine-grained sediment within both depositional settings was primarily derived from vegetable fields underlain by fine-grained soils (e.g. Katspruit) that comprise the valley floor. It seems reasonable to assume that these sediments were delivered to the axial drainage network during relatively modest storm events when hillslope runoff over sandier soils with higher infiltration capacities was limited (Fig. 14). In other words, the lack of sandier sediments from cane fields on hillslopes within the wetland deposits suggests that the hillslopes were not significantly eroded during relatively low-magnitude events.

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Alternatively, what sediment was eroded was redeposited on the hillslopes as a result of the utilized management practices.

Very little of the fine-grained sediment from low-lying vegetable fields was deposited and stored with the first downstream reservoir of the middle subcatchment. The general lack of fine-sediment within the reservoir is presumably related to (1) the hydrologically and geomorphologically disconnected nature of the drainage network during low-flow conditions (prior to valley floor modification), and (2) the minimal impact of the dams on the storage of silt- and clay-sized particles during larger events when the system is hydrologically connected. The lack of influence of the dams on sediment storage is not surprising given that water overflows the dams during periods of high surface runoff, creating a rapidly flowing system through the reservoir, and the increase in sediment transport capacity of the middle subcatchment (as described below).

Sandier sediments within both the wetland and the reservoir were derived largely from hillslope cane fields. Presumably, these sediments were not only eroded from the valley bottom sediment sources, but from sandier hillslope soils covered largely by sugar cane during larger storm events that produced significant runoff. What is important to recognize is that the provenance of the sediment within the examined depositional environments varied as a function of both sediment size and runoff magnitude. Moreover, given the chemically reactive nature of fine-particles, and the association of nutrients, particularly phosphate, with sediment, reductions in sediment-associated nutrient loads may best be sought through practices that address the erosion of sediment from agricultural fields along the valley floor.

The above provenance studies, combined with data from the geomorphic investigations, show that the Mkabela Basin, and presumably other similar catchments within the KwaZula-Natal Midlands, can be subdivided into three geomorphologically distinct subcatchments. These subcatchments vary in relief, the nature of their drainage network (or process zones) and their ability to store and transport sediment. As a result, sediment transport and storage do not systematically vary along the axial drainage system, but are characterized by spatially abrupt changes in their nature and magnitudes.

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In headwater areas with intact valley floors, sediment eroded predominantly from low-lying areas during low-magnitude events are largely deposited within wetlands that comprise large segments of the valley floor. The general lack of fine sediment within the reservoir, prior to valley modification, suggests that while the axial drainage network may be integrated during large floods, during low to moderate events the upper catchment areas were disconnected from downstream sections of the catchment (Fig. 15). Thus, the wetlands (in their natural state) serve as reservoirs of sediment (and associated nutrients).

In contrast to the upper subcatchments, the mid-catchment areas are dominated by relatively high gradient alluvial and bedrock channels, with fewer, natural depositional zones. This portion of the catchment, then, possesses a greater ability to effectively transport sediment downstream (Fig. 15). The general lack of fine-sediment within the reservoirs indicates that once silt- and clay-sized sediment is entrained, it is transported through this section of the catchment, although at least some of the transported material may be stored on or within floodplains that are more extensive than they are upstream. The lower subcatchment is dominated by low gradient, alluvial channels boarded by extensive riparian wetlands. Storage of sediment within this zone is extensive, as illustrated by Core B2WTC1, once again limiting the downstream translation of sediment and nutrients that they may carry (Fig. 15). The natural division of the catchment into geomorphologically distinct sections suggests that previously developed watershed modeling routines that are used to predict sediment exports from a basin may need to be modified before being applied to these catchments to adequately address the abrupt changes in sediment transport processes that occur.

5 Conclusions

The source, transport, and storage of sediment was evaluated within the Mkabela catchment using a combination of geomorphic, hydrologic, and geochemical tracing analyses. The integrated approach resulted in the following conclusions.

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1. The Mkabela Basin, and other similar catchments within the Kwa-Zulu Natal Midlands, exhibit three distinct morphological areas (referred to as upper, middle, and lower subcatchments), each characterized by differences in their ability to produce, transfer, and store sediment. Upper catchment areas are characterized by extensive wetlands along the valley floor which, in their natural state, represent significant sediment sinks. Mid-catchment areas lack significant wetlands, and possess higher gradient alluvial and bedrock channels conducive to sediment transport. Lower catchment areas are characterized by lower gradient alluvial valley floors, incised into the surrounding terrain, that possess broad riparian wetlands that store considerable quantities of sediment and associated nutrients.

2. The complex interactions between runoff, soil type and characteristics, and land-use (among other factors) create temporal and spatial variations in sediment provenance. Silt- and clay-rich layers found within the wetland and reservoir deposits are derived from the erosion of fine-grained, valley bottom soils which are frequently utilized as vegetable fields. The deposits tend to exhibit elevated concentrations of Cu and Zn, presumably from the use of fertilizers which contain both elements. Coarser-grained sediments within the wetland and reservoir environments are derived from the erosion of sandier hillslope soils extensively utilized for sugar cane. Erosion of these upland cane fields presumable occurs during relatively high magnitude runoff events that are capable of transporting sand-sized sediment off the slopes. Therefore, sediment source varies as a function of particle size and runoff magnitude.

3. Sediment source determination, carried out on multiple cores from the wetland, demonstrated that sediment partitioning by particle size occurs during transport producing deposits of varying sedimentological and chemical characteristics. While general provenance characteristics (e.g. the fact that fine sediment was derived from specific soils used primarily for vegetable fields) were similar between the cores, differences in sediment provenance as a function of depth (time) exist.

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As a result, within highly variable depositional environments, multiple cores should be collected and analyzed to fully determine sediment provenance from non-point sources.

4. Comparison of sediment provenance between sites and through time revealed that the construction of a drainage ditch through the upstream most wetland significantly altered the geomorphic and hydrologic connectivity of the catchment. Prior to its construction, sediments (and the nutrients that they carry) were largely deposited within wetlands which encompassed a majority of the valley floors within the upper catchment. Thus, upper catchment areas were disconnected from mid- and lower-subcatchment areas during most flood events. Following construction of the ditch, sediments from the upper catchment were transported to and through mid-catchment areas and were subsequently accumulated to significant thicknesses within riparian wetlands of the lower catchment.

5. The construction of the drainage ditch through the wetland appears to have negated some of the effectiveness of best management practices that are used on the cane fields to limit sediment and nutrient losses from the hillslopes.

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Table 1. Summary of Process Zones and their general characteristics.

	Process zone	Morphology	Sediment storage	Dominant process(es)
Process Zones in Low Order Valleys	Waterway	Wide, shallow, often u-shaped man-made channels; channel oriented parallel to slope; bed and banks typically covered in vegetation	Minimal sediment storage in bed of waterway	Minor sediment production; dominated by sediment transport over "rough" bed; Hydrologically, a zone of recharge
	Upland ditch	Man-made, trapezoidal channel; deeper than waterways, with less vegetation on channel bed; local depositional bars present; channel is semi-parallel to slope	Minimal sediment storage as bars on channel bed	Dominated by sediment transport through low gradient, but efficient channels; hydrologically dominated by recharge
	Upland channel	Natural, single-thread channel bound by alluvium; channel may locally be modified by human activities	Moderate storage within channel as bars and on floodplain	Dominated by sediment transport, but local overbank deposition occurs during floods; channel may exhibit both influent and effluent conditions, depending on season
Process Zones within Bedrock Valleys	Bedrock channel	Well-defined, often rectangular channel bound by bedrock; locally, banks may consist of alluvial sediments; channel gradients are relatively steep	Very little, if any, sediment storage	Dominated by bedrock erosion and the transport of sediment delivered to the channel from upstream reaches and adjacent hillslopes
	Axial ditch	Narrow, deep trapezoidal channel excavated into alluvial valley fill and wetlands; often low gradient	Minimal sediment storage	Dominated by sediment transport
	Alluvial channel	Natural, meandering channel developed in alluvial sediments along relatively wide valleys	Moderate quantities of sediment are stored within channel bars and as overbank deposits on floodplain	Dominated by a combination of sediment transport and deposition, depending on flow conditions
Process Zones within Alluvial Valleys	Alluvial channel with wetlands	Single thread, meandering channel developed in alluvial sediment; found in wide valleys with riparian wetlands adjacent to stream	Significant sediment storage as bars in channel and overbank deposits on floodplain and within riparian wetlands	Dominated by sediment deposition, although some sediment is transported through channel; localized zones of groundwater discharge
	Wetlands	Wide, flat valley area with water table at or near the ground surface; shallow channel(s) are locally present	High quantities of sediment stored across the wetland	Dominated by sediment deposition and groundwater discharge
	Reservoir	Perennial bodies of open water formed by downstream dam	Significant sites of sediment storage	Dominated by deposition; fine sediments may be transported through reach during high flow events

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Table 2. Summary of samples collected in May 2008.

Land-Use Category	# Samples	Soil Type	# Samples
Pasture	10	Avalon	10
Pine Forest	2	Cartref	12
Roads	10	Clovelly	3
Sugar Cane	35	Glencoe	18
Vegetables	10	Katspruit	6
Wattles	6	Longlands	5
		Westleigh	9
Total	**73**	**Total**	**63**

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Table 3. Discriminate Analysis Classification Matrix; (A) Soil Type; (B) Land-Use.

(A) Soil Type	Number of Samples Classified per Soil Type Av	Cf	Cv	Ka	Gc	Lo	We	% Correct
Av	9	0	0	1	0	0	0	90
Cf	0	9	3	0	3	0	0	75
Cv	0	0	3	0	0	0	0	100
Ka	0	0	1	5	0	0	0	83
Gc	3	0	1	0	11	1	2	61
Lo	0	0	0	0	0	5	0	100
We	0	0	0	0	1	0	8	89
Totals	12	9	8	6	12	6	10	79
(B) Land-Use	**Number of Samples Classified per Soil Type Sc**	**Veg**	**Wt**	**Pine**	**Rds**	**Past**		**% Correct**
Sc	22	3	9	0	1	0		63
Veg	0	8	2	0	0	0		80
Wt	0	0	5	1	0	0		83
Pine	1	0	0	1	0	0		50
Rds	0	0	2	0	6	2		60
Past	0	0	2	0	1	7		70
Totals	23	11	20	2	8	9		67

Av – Avalon; Cf – Cartfer; Cv – Clovelly; Ka – Katspruit; Gc – Glencoe; Lo – Longlands; We – Westleigh.
Sc – Sugar Cane; Veg. – Vegetables; Wt – Wattles; Pine – Pine Grove; Rds – Roads; Past – Pasture.

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Table 4. Summary of Collected Cores.

Core	Location	Characteristics
Core WT1-C	Located within an extensive wetland approximately 40 m from its downstream terminus. The area is dominated by a relatively flat surface about 1 m above a small channel that traverses the wetland. At the time of coring, the water table was about 20 cm below the surface, but based on the vegetation, periodically rises to ground level.	Total length is 122 cm. Stratigraphic relationships, including the presents of a buried paleosol consisting of a light brown, very sticky, gravelly clay loam, suggests that historic sediment is 107 cm thick. A total of 17 samples, collected at 7 cm increments were obtained from the core for geochemical analyses. Sixteen of the samples were taken from historic deposits. No sample was collected across a stratigraphic unit boundary.
Core WT1-C2	Obtained from a flat surface about 1 m above the wetland channel, about 250 m upstream of the wetland's downstream terminus. The location was located about 15 m from the channel edge. The water table was about 20 cm below the surface at the time of coring.	Total length is 112.5 cm. Sediments below 90 cm in depth have been interpreted to pre-date historic deposition; they are heavily weathered, and exhibit significant accumulations of clay. A total of 16 samples were collected at 7 cm increments. As was the case for the other cores, samples did not cross stratigraphic boundaries.
Core WET	Obtained from a flat surface about 1 m above the wetland channel, about 250 m upstream of the wetland's downstream terminus.	Total length is 130 cm. The upper 69.5 cm of is thought to be of historic age based on stratigraphic and geochemical data. A total of 18 samples were collected at 7 cm increments, with the exception of the last stratigraphic unit, which was sampled at 11 cm increments. None of the samples cross stratigraphic boundaries.
Core R1-C1	Collected from the edge of the first reservoir along the main drainage in a low-lying area that is inundated during flood events.	Total length is 140 cm. The core was sampled at 7 cm increments for Pb-210 dating, generating a total of 20 samples. A total of 21 samples were collected for geochemical analyses. Two samples of similar thickness were collected for units more than 5 cm thick. All of the sediment appears to be of historic age.
BW2TC1	Riparian wetland within lower catchment	Total length is 179 cm. All sediment appears to be of historic age. A total of 21 samples were collected at 8 cm intervals.

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Table 5. Brief description of the primarily soil types found in the study area (after le Roux et al., 2006).

Soil Type	General Characteristics
Avalon (Av)	The Avalon soil type surveyed to 120 cm depth and consists primarily of soft plinthic B horizons which is a sandy yellow-brown B horizon underlain by hard plinthic horizons.
Cartref (Cf)	Shallow, sandy soils with very little water holding capacity found on steep, short, convex hillslopes.
Clovelly (Cv)	Associated with, and similar to, Longlands soil type.
Glencoe (Gc)	Similar to Avalon soil type, but dominated by hard plinthic sub-horizon; found on steeper slopes of higher relief. Parent material is thought to be the Natal Group Sandstone (NGS).
Hutton (Hu)	Found near crest and midslopes of high relief, steep hillslopes. Moderately drained, underlain by NGS.
Katspruit (Ka)	Clayey, strongly gleyed soils found on low-relief (10–15 m) terrain, particular valley bottoms.
Longlands (Lo)	The Longlands soil type was surveyed up to 120 cm depth and consists of soils that are sandier than the Avalon soils with similar profile of soft plinthic B horizons well developed underlain by hard plinthic horizons.
Westleigh (We)	The Westleigh soil type was surveyed up to 110 cm depth and consist a poorly drained hydrosequence dominated by clayey soils with prominent mottling and deep, clayed subsoils.

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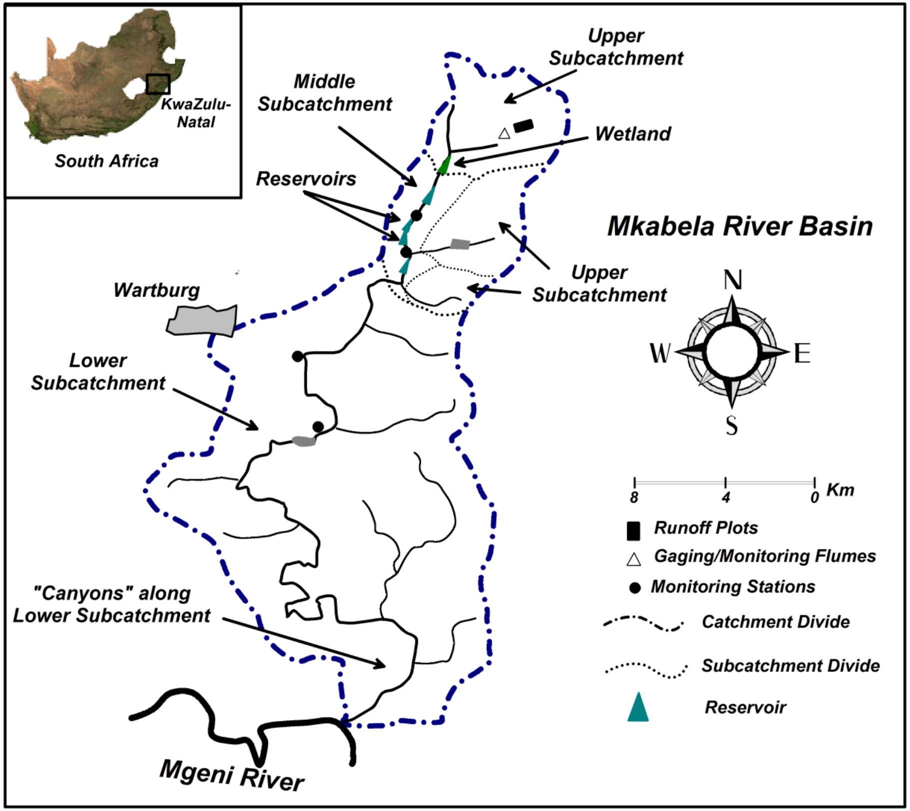

Fig. 1. Map showing the location of the Mkabela Catchment in South Africa and the position of the defined subcatchments within the basin.

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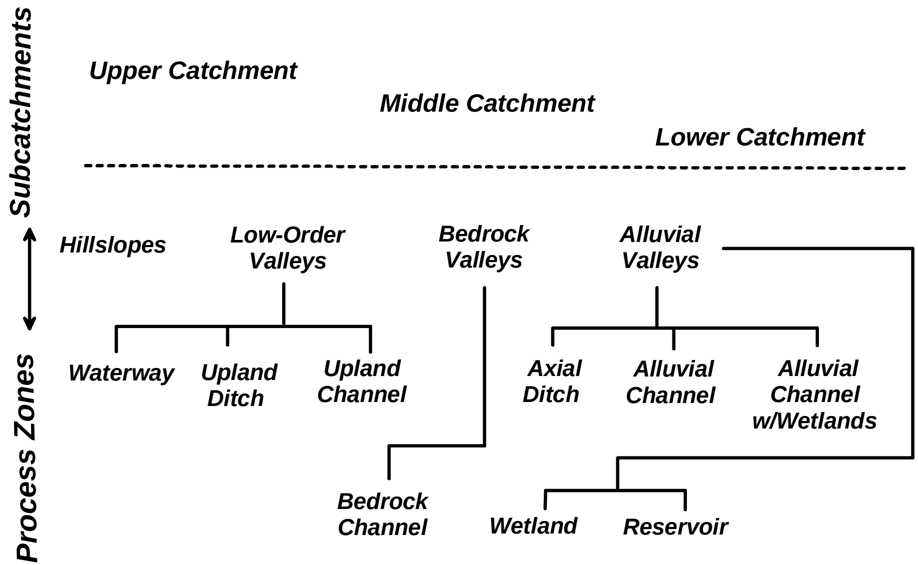

Fig. 2. General overview of subcatchment and process zone types recognized within the Mkabela Catchment.

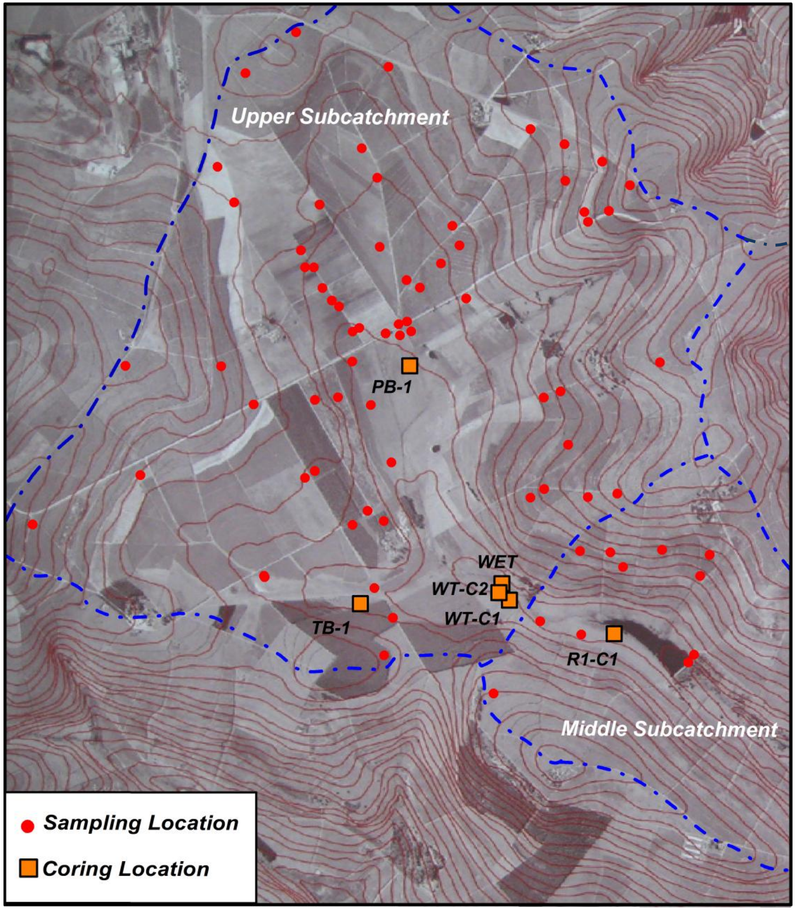

Fig. 3. Sampling and coring locations within the Mkabela Catchment.

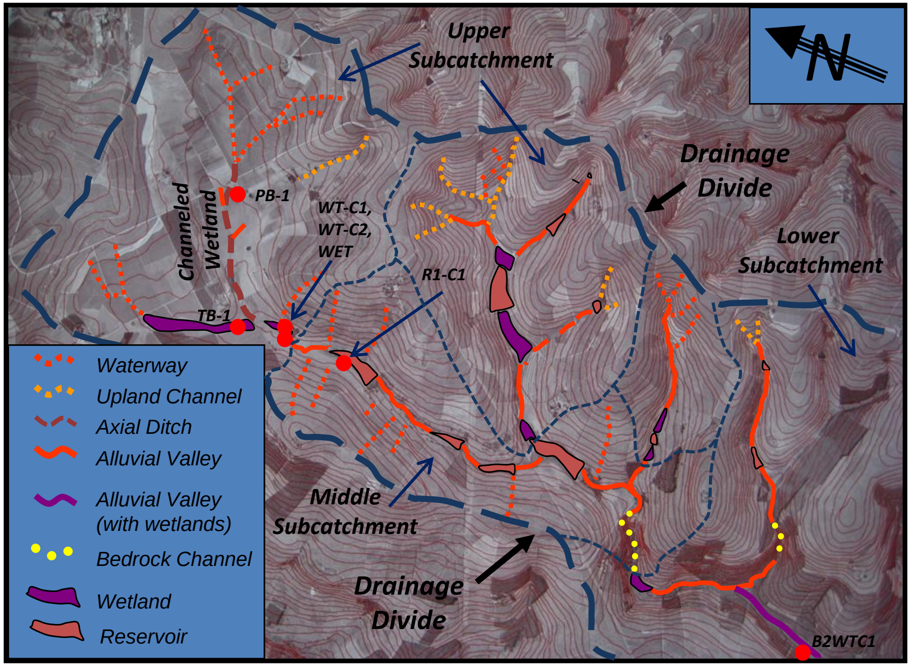

Fig. 4. Delineation of process zones and subcatchment areas within the upper and middle subcatchments.

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Fig. 5. Photographs of selected process zones types defined within the Mkabela Catchment.

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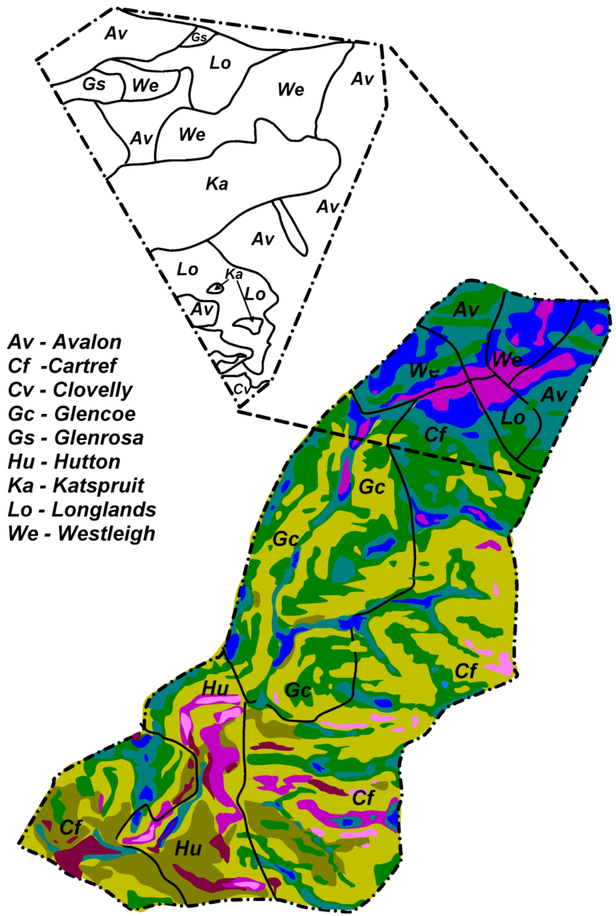

Fig. 6. Soil types found in Mkabela catchment (after le Roux et al., 2006).

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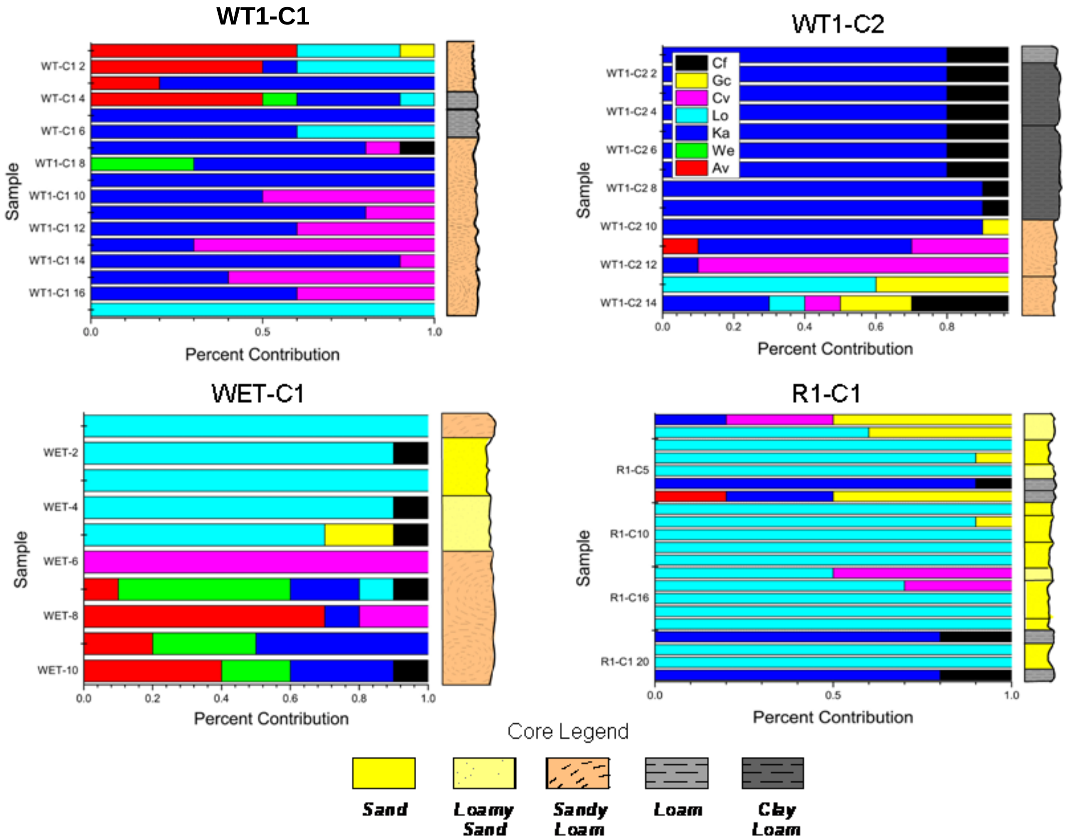

Fig. 7. Relative percent of sediment derived from specific soil types within the catchment. Av – Avalon, Cf – Cartref, Cv – Clovelly, Gc – Glencoe, Ka – Katspruit, Lo – Longlands, We – Westleigh.

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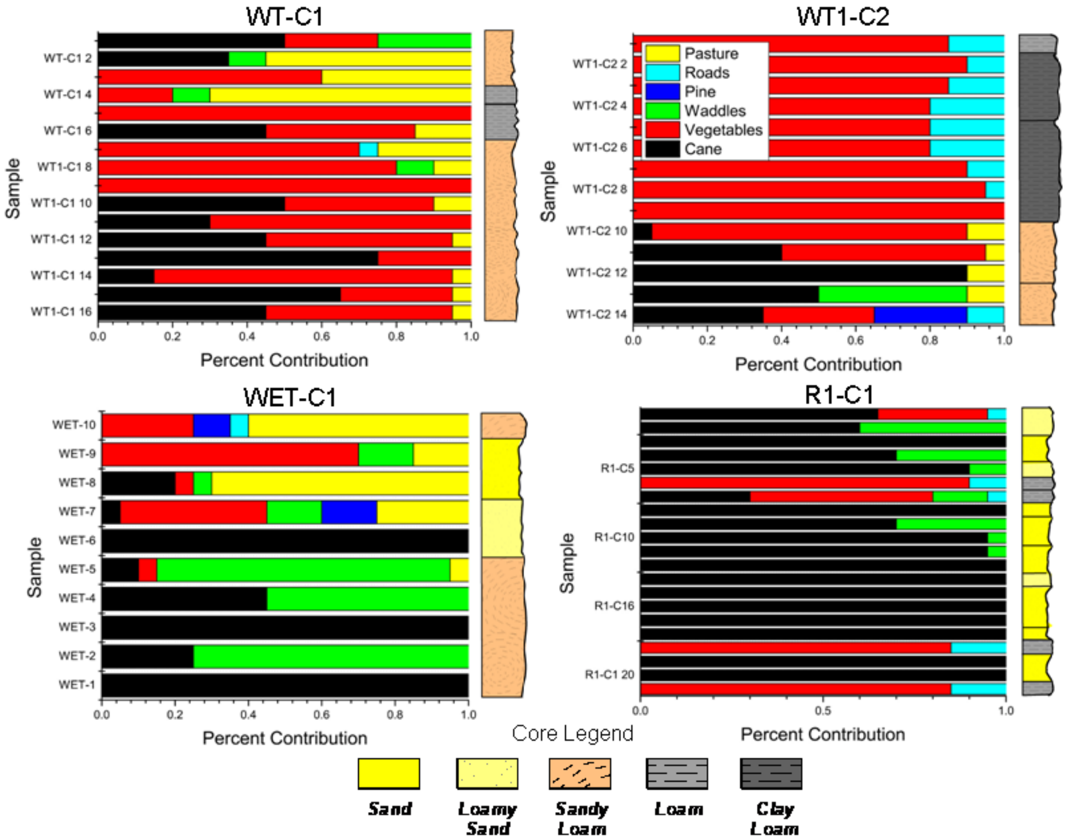

Fig. 8. Relative percent of sediment derived from specific land-use types within the catchment.

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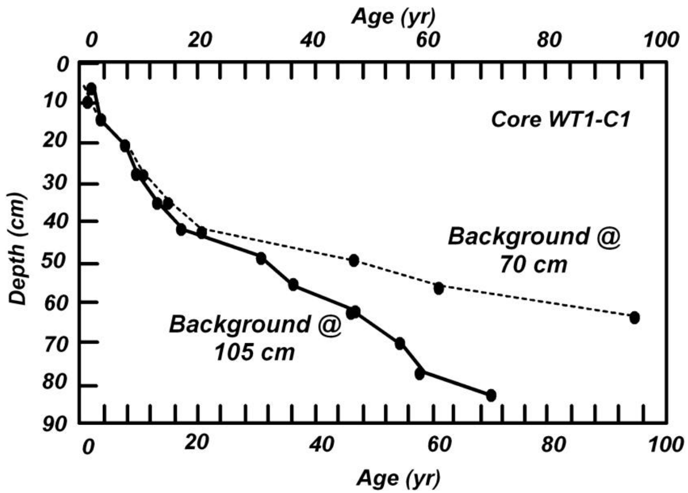

Fig. 9. Estimated age of the sediments in Core WT1-C1 as determined by ^{210}Pb analysis. The slope of the line in age-depth plot represents the sedimentation rate. Sedimentation rates increase above 41.2 cm, or after about 1992.

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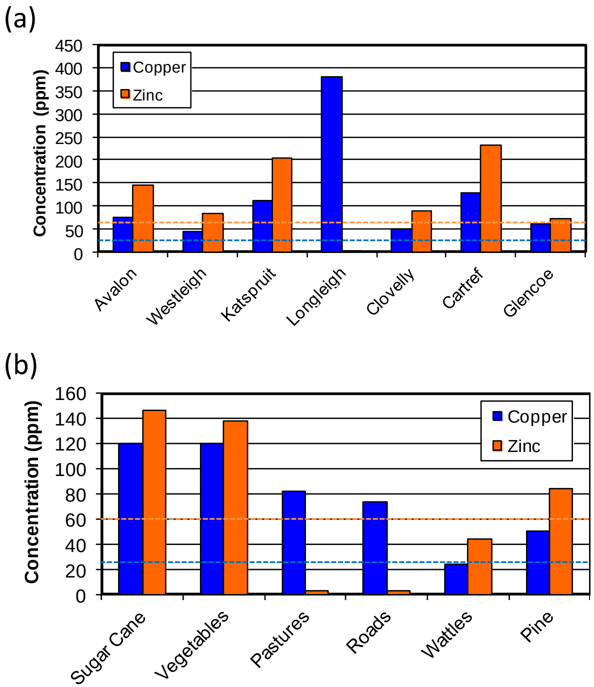

Fig. 10. Mean concentrations of Cu and Zn calculated for upland soil **(a)** and land-use **(b)** types. Dashed lines represent global average Cu (blue) and Zn (orange) concentrations within soil reported by Buonicore (1996).

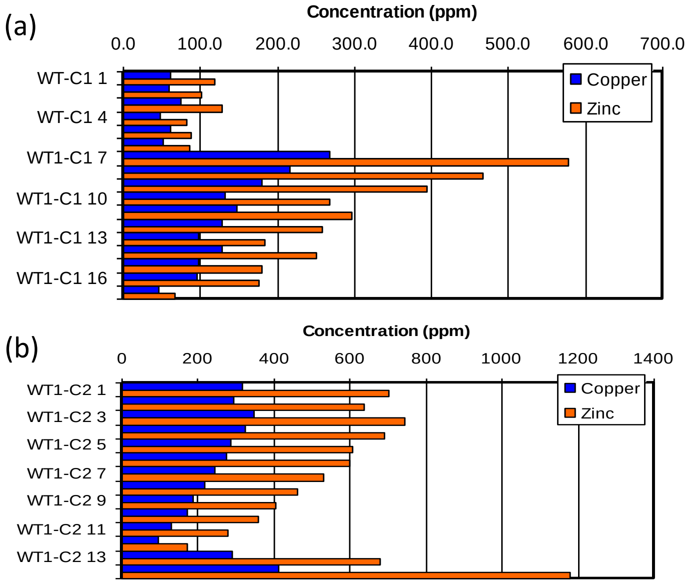

Fig. 11. Variations in Cu and Zn concentrations with depth in wetland Cores WT1-C1 **(a)** and WT1-C2 **(b)**.

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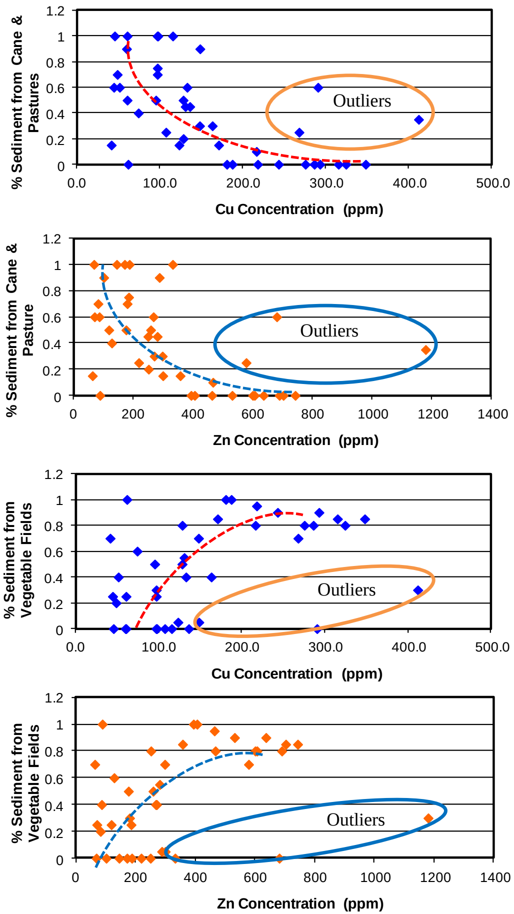

Fig. 12. Relationship between Cu and Zn concentrations and % relative contribution from vegetable and pasture + cane fields.

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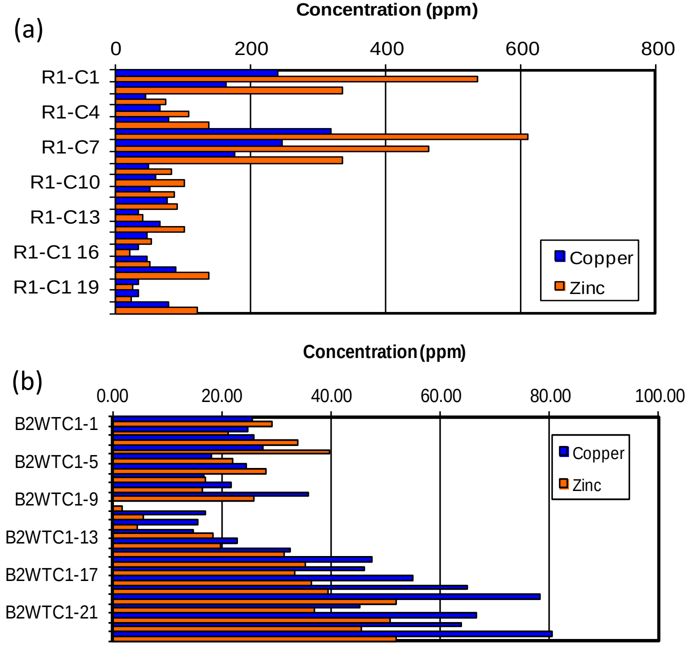

Fig. 13. Variations in Cu and Zn concentrations with depth in wetland Cores R1-C1 **(a)** and B2WTC1 **(b)**.

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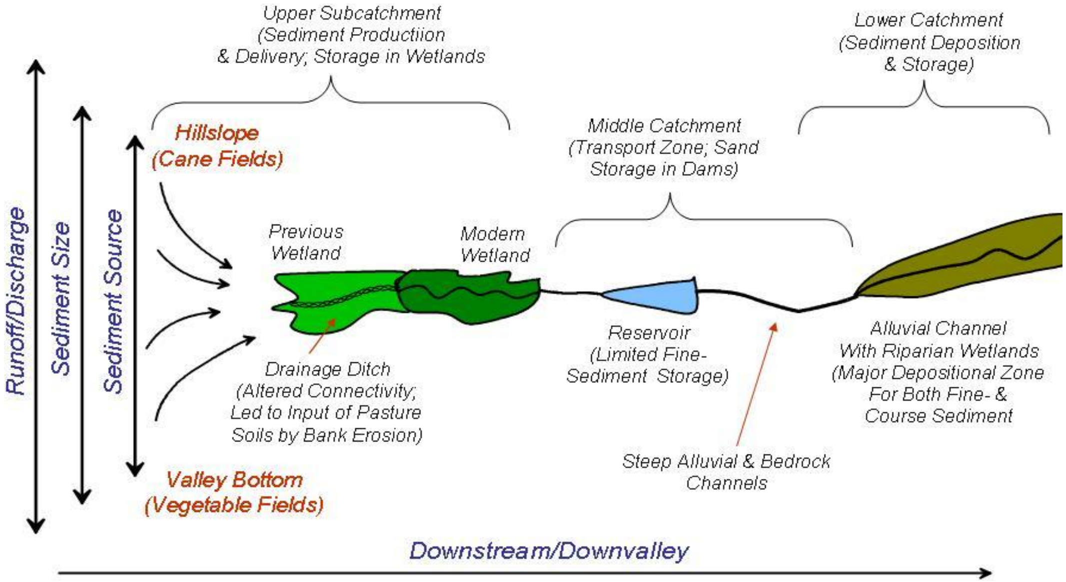

Fig. 14. Schematic diagram of the primary processes occurring in each of the three delineated subcatchments, and the variations in sediment size and source from varying runoff magnitudes.

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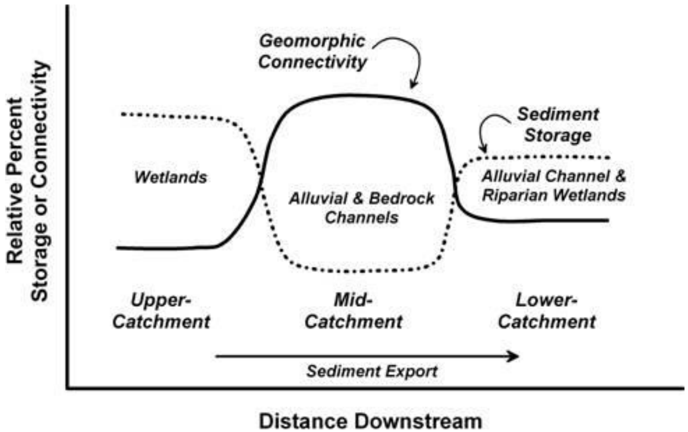

Fig. 15. Schematic diagram illustrating differences in geomorphic connectivity and sediment storage between subcatchment zones of the Mkabela Basin.

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