Implementing contour bank farming practices into the J2000 model to improve hydrological and erosion modelling in semi-arid Western Cape Province of South Africa

Thomas Steudel, Richard Bugan, Holm Kipka, Björn Pfennig, Manfred Fink, Willem de Clercq, Wolfgang-Albert Flügel and Jörg Helmschrot

ABSTRACT

Contour bank farming is a well-known agricultural management technique in areas which are characterised by intensive and erosive rainfalls. Contour banks are designed to reduce the flow velocity of overland flow and to intercept water before it concentrates in rills, thereby reducing the risk of soil erosion and land degradation. By their structure, contour banks noticeably impact surface runoff pattern both temporally and spatially. Also subsurface flow may be affected by contour banks. For example, if contour banks intersect the A- and B-horizon of the soil, it can cause significant infiltration of water into the C-horizon, which if saline, can generate saline interflow to downslope areas. Although these aspects have been highlighted in previous research efforts, the quantitative and qualitative impacts of contours on runoff generation and associated erosion dynamics or salinisation are rarely considered in process-based hydrological modelling approaches. In this study an approach was developed to improve distributed hydrological and erosion modelling by integrating contour banks in the delineation and routing of Hydrological Response Units. Applying the distributed and process-based hydrological model J2000 which was modified with a contour bank and erosion module it could be shown that the implementation of contour banks improved the model performance significantly.

Key words | contour bank farming, flow pattern, hydrological and erosion modelling, J2000, Sandspruit, South Africa

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INTRODUCTION

Due to low annual precipitation volumes and the high spatio-temporal variability in precipitation, semi-arid areas are often challenged by limited water resources. In addition population growth, increasing per capita water demand and large scale irrigation practices result in further pressure being placed on water resources. This occurs particularly in areas which experience inadequate land management practices and the combined effect of these factors often causes severe environmental problems such as desertification and droughts, soil erosion and salinisation and the loss of biodiversity (Hughes 2008; Wheater 2008). To better understand and assess such impacts, innovative tools are required, which aim to sustainably manage the limited land and water resources. Integrated hydrological models have the potential to support management decisions by providing information on system dynamics and change impacts (Abbott *et al.* 1986; Wheater 2008; Biondi *et al.* 2012). To sufficiently address land management practices

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and environmental conditions, the underlying model concept of such models needs to be process-based, i.e. needs to represent the processes controlling lateral as well as vertical fluxes (Hughes 2004; Arnold & Fohrer 2005).

One of the most significant environmental problems occurring within the semi-arid south-western Cape region of South Africa is the process of soil erosion (Meadows 2003). According to Meadows & Hoffman (2002) the mean annual soil erosion caused by water in South Africa ranges from 0.8 to 4 tonnes per hectare ($t\,ha^{-1}$), which may lead to severe land degradation. To prevent and reduce land degradation, contour bank farming (also called contour banking) is commonly practised as a management instrument of water and soil conservation works within the agricultural areas of the Western Cape Province. These earthen structures are constructed perpendicular to cultivated slopes, as well as at pre-determined intervals down slopes in order to reduce slope lengths, flow velocity of water and to intercept and prolong surface runoff before it causes erosion (Wakindiki *et al.* 2007). Contour banks also channel surface runoff into stable waterways, natural depressions or grassed areas adjacent to a paddock (Department of Environment and Resource Management (DERM) 2004; Figure 1).

Contour bank channels have a small gradient (0.1–0.4%) to prevent channel flow reaching high and erosive velocities in non-vegetated areas. The distance between contour banks is usually determined by the local slope. Other factors influencing the distance between contour banks are the soil type, the applied cropping practice and previous erosion events. According to DERM (2004) and Freebairn (2004) two different types of contour bank cross sections exist. The narrow-based type of contour bank is used on steeper cultivated slopes (5–12%) with batters which are too steep to be cultivated and are usually covered with grass. The channels of narrow-based contour banks are normally part of the contour bay and cultivated and used for crop production. Broad-based contour banks are usually built on gentle slopes (<5%), with deep soils and are often cultivated (DERM 2004).

The impact of contour bank farming on flood reduction and sediment dynamics has been studied in various semi-arid Mediterranean basins (Kingumbi *et al.* 2004; Nasri *et al.* 2004a, b; Leduc *et al.* 2007; Nasri 2007; Baccari *et al.* 2008; Lesschen *et al.* 2009; Ouessar *et al.* 2009) and in Australia (Callow & Smettem 2009; RPS 2010). Nasri *et al.* (2004a) published results from an experimental catchment in Tunisia showing that soil conservation techniques

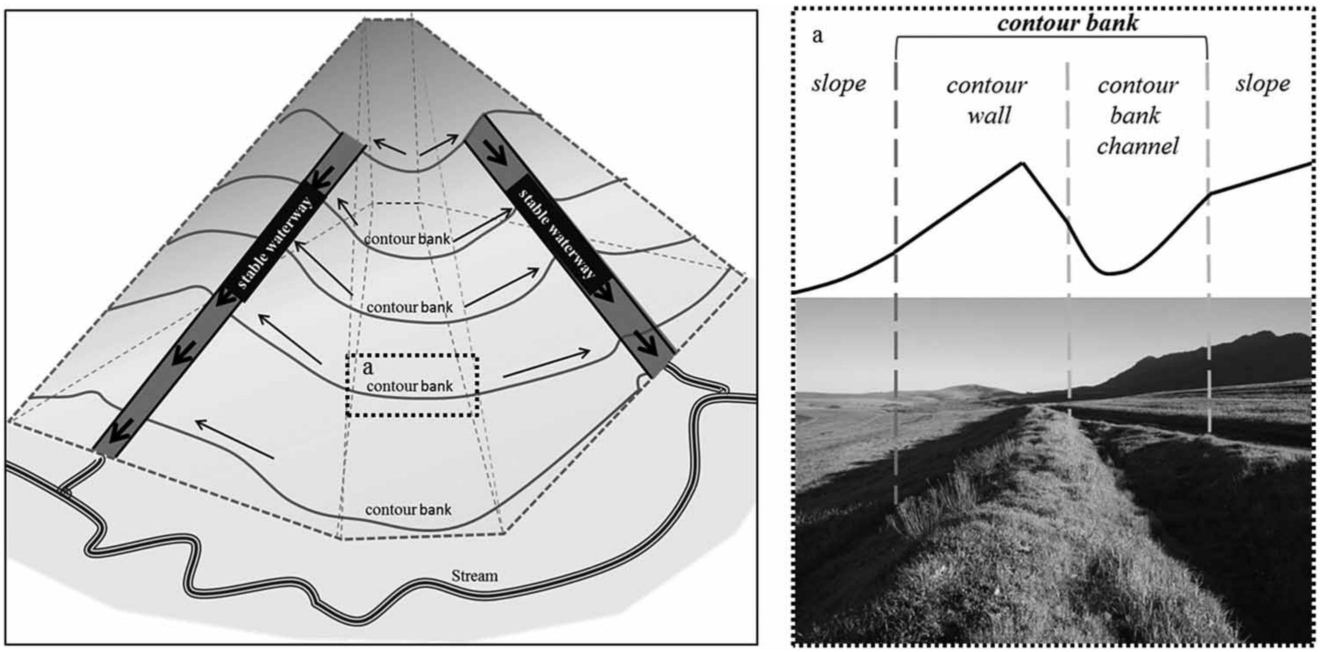

Figure 1 | Simplified impression of contour banks along a slope and waterway layout.

significantly reduce flood risks due to the reduction of surface runoff on steep slopes. At a larger scale, Nasri et al. (2004b) demonstrated that the introduction of contour ridges in a semi-arid, medium-sized (18.1 km²) basin led to a decrease of catchment outflow by 50–80%, a reduction in peak discharge by 60–90% and the virtual disappearance of observed erosion. Similar results regarding the quantification of water holding capacities and efficiencies of benches in Tunisian catchments were reported by Nasri (2007), Leduc et al. (2007) and Lacombe et al. (2008). Some studies (Nasri 2007; Baccari et al. 2008) also showed that contour banks lose their efficiency in reducing runoff as a result of sedimentation and filling of the sinks over time.

Studies from Australia indicated that contour banks have trapping efficiencies ranging from 54 to 84% (compared to areas without contour banks) and therefore reduce the direct sediment transport into the stream (RPS 2010). It was also demonstrated that 10–40% of transported material is deposited on the hillslope before reaching the contour bank channel. Furthermore, Callow & Smettem (2009) investigated the effect of farm dams and man-made earth banks on hydrologic connectivity and runoff estimation in 12 sub-catchment basins in a dryland agricultural region. Based on geomorphic and hydrologic descriptors (cumulative area distribution, hypsometric curve, simplified width function and instantaneous unit hydrograph) they have shown that the basin hydrology, in particular hillslope processes, is significantly altered by farm dams and earth banks.

Although these studies demonstrate the impact of contour banks on runoff generation and sediment fluxes, their successful implementation in distributed and process-based model exercises lacks evidence in previously published studies. However, Ouessar et al. (2009) introduced a modified version of the SWAT (Soil and Water Assessment Tool; Arnold et al. 1998) model to assess the impact of water harvesting systems (earthen dikes) on hydrological processes in semi-arid environments. The authors conclude that the model reproduces all water balance components sufficiently, but is limited in representing the spatial variability of runoff generation mechanisms. By integrating hillslope and plot features influencing the hydrologic connectivity in basin modelling, Lesschen et al. (2009) successfully applied the LAPSUS model to predict realistic values for total runoff and sediment yield at catchment scale for one single event. All studies show that there is a clear indication that contour banks change natural flow paths and inner basin hydrological process dynamics and that they have to be integrated into distributed, process-based modelling to allow for realistic assessments of water and nutrient transport dynamics in regions affected by contour bank farming. Despite those rare, but promising, model approaches, the problem of erroneous runoff and erosion modelling in areas with contour banks due to the lack of suitable modelling tools still requires research efforts (Jetten et al. 1999; Bugan et al. 2009; Lesschen et al. 2009).

This study was conducted in the Swartland region in South Africa (Western Cape), where contour banks which total approximately 25,000 km in length were constructed between 1972 and 1995 (Meadows 2003). Little is known, however, about their quantitative impact on runoff generation and erosion control. Bugan et al. (2009) concluded in their modelling studies within the Sandspruit catchment (a dryland agricultural catchment in the Swartland region) that the contour banks have a significant influence on the catchment water balance, and also that common model approaches are not capable of representing contour bank farming.

The aim of this study is to describe how contour banks may be integrated to improve distributed, process-based hydrological and erosion modelling in semi-arid environments which are affected by contour bank farming. Thus, the J2000 hydrological model has been enhanced with the implementation of contour bank and erosion modules. The contour banks have been considered in the delineation and routing of spatial model entities. The developed model tools were tested and used to simulate runoff generation and sediment transport and to assess the topological control of the contour banks in the Sandspruit catchment.

STUDY AREA

The Sandspruit catchment (152 km²) is located in the Western Cape Province, South Africa (Figure 2) and is a tributary basin of the Berg River. The region is characterised by a Mediterranean-type climate with warm dry summers and cool moist winters (Department of Water Affairs and

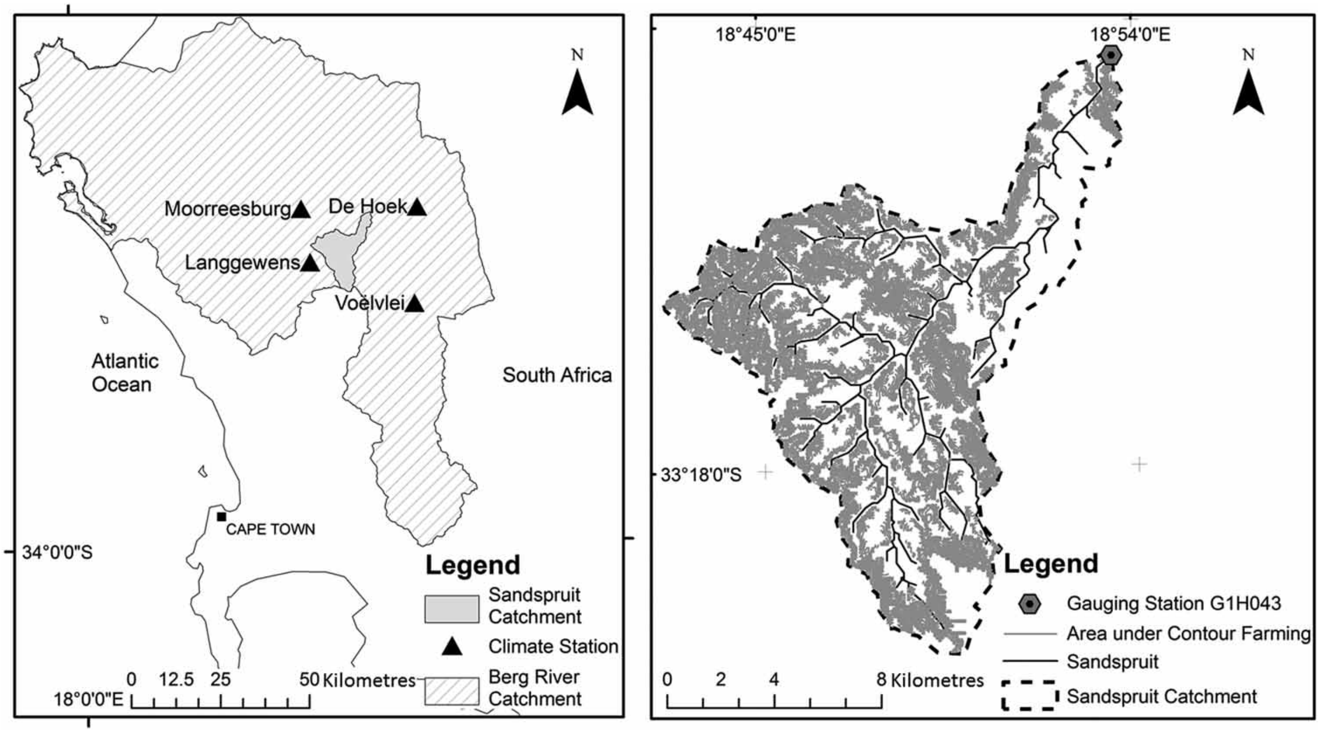

Figure 2 | Location of the study area and given climate stations in the Berg River catchment, Western Cape Province, South Africa (left) and areas under contour bank farming in the Sandspruit catchment (right).

Forestry (DWAF) 2007; Bugan *et al.* 2009). The mean annual temperature is approximately 19 °C. Precipitation dominantly occurs during the winter months (April–October) in the form of long duration and low intensity frontal rain from the north-west. Summer precipitation is predominantly convective, and thus rainfall events are generally highly variable in space and time (Meadows 2003; Kruger *et al.* 2010). The mean annual precipitation exhibits large spatial variability as shown for four stations located in the study area (Table 1, DWAF 2007; Bugan *et al.* 2009). The spatial variability of precipitation is a function of both topography and the distance from the coastline. Bugan *et al.* (2012) presented rainfall data for stations located within the Sandspruit catchment. Analysis of these data indicates that a rainfall gradient exists across the catchment, i.e. decreasing from south to north. In 2009, the annual rainfall recorded in the upper- (south), mid- and lower-parts (north) were 494, 391 and 319 mm respectively. In addition to the higher elevation, the higher rainfall in the upper parts of the catchment is also interpreted to be a result of

Table 1 | Monthly and annual average precipitation derived from station data in the study area (Figure 2) for the period of 1987–2008

		Precipitation [mm]												
Station	**Elevation [m a.s.l.]**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Yr**
De Hoek	115	14	15	21	54	83	103	99	83	64	35	29	27	627
Voëlvlei	72	10	13	14	44	70	101	101	72	49	26	22	18	540
Langgewens	177	9	10	9	38	54	69	71	60	41	22	17	14	414
Moorreesburg	158	9	10	8	36	55	74	74	61	41	24	18	14	424
Mean	131	11	12	13	43	66	87	86	69	51	27	22	18	500

orographic rainfall caused by Kasteelberg. In terms of rainfall shadowing effects, Kasteelberg is not interpreted to have any effect to its west and north as the rainfall approaches from the north-west. The area to the east and south falls outside of the Sandspruit catchment and hence was not included in this study. The Quaternary catchment G10J (including the Sandspruit catchment) is reported to exhibit a potential evapotranspiration (ET) range between 1,500 and 1,700 mm/a. (Midgley *et al.* 1994).

The topography within the catchment is undulating with elevations ranging from approximately 30 metres a.s.l. (near the confluence with the Berg River) to 950 metres at the Kasteelberg Mountain in the southern part of the catchment. The Sandspruit catchment comprises sequences of rocks of the Malmesbury Group, the Table Mountain Group and younger Cenozoic deposits. The Malmesbury Group comprises erodible, soft rocks within the mid to lower parts of the catchment which are steeply folded along a north-west striking axis. The hard and resistant quartzitic sandstones of the Table Mountain Group, which act as secondary water-bearing features, occur only in the southern parts of the catchment around the Kasteelberg. The Cenozoic sediments in the northern and north-western parts of the catchment are the result of the Tertiary sea-level transgression and regression processes and consist primarily of aeolian sands, gravel and clayey deposits (DWAF 2007). According to Bugan *et al.* (2009) the soils within the catchment are shallow and poorly developed with soil thicknesses between 0.5 and 1 m. Almost 70% of the catchment area is dominated by the lithic Glenrosa (Gs) soil form which is highly erodible. These soils appear predominantly on the substrates of the Malmesbury and Table Mountain Groups and are pre-eminently associated with convexity and the processes of divergent water flow (Görgens & de Clercq 2006; Fey 2010). Along the streambed of the Sandspruit, the Dundee soil form is dominant and covers approximately 10% of the catchment area. These soils consist of varying shallow to deep soil deposits (alluvial material). The stratified sandy layers, varying in texture, colour and thickness are the result of continuous deposition of soil material by floods. Within the northern parts of the Sandspruit streambed, the moderately deep and non-gravelly, wet saline duplex soils of the Estcourt soil form are dominant. This soil form has a low agricultural production potential especially during the wet season (Lambrechts 2007). The north-eastern parts of the catchment are dominated by the soils of the Swartland soil form, which developed above the weathered Malmesbury shales and have a higher agricultural potential with depths partially exceeding 50 cm. Furthermore there are minor occurrences of colluvial soils of the Oakleaf form with a high production potential in the northern and eastern parts of the catchment (Lambrechts 2007). The land use within the catchment is dominated by cultivated lands and pastures (approximately 145 km²) with dryland winter wheat and canola being the dominant vegetation types (Bugan *et al.* 2009). To minimise the detachment of soil particles from erosive runoff and the transport of the resulting soil material, farming utilising contour banks to prevent gully formation is applied as a land management technique within the catchment.

MATERIAL AND METHODS

Input data

Hydro-meteorological data for model input and calibration parameters were available from different sources. Since no climate station is located in the Sandspruit catchment, climate data from four nearby stations (Figure 1) were obtained from the Drysal River Basin Information System (DrysalRBIS, link: leutra.geogr.uni-jena.de/drysalRBIS/), the Agricultural Research Council (ARC) and the Department of Water Affairs (DWA) in South Africa. Daily maximum, minimum and mean air temperature [°C], precipitation sums [mm], relative humidity [%], wind speed [$m\,s^{-1}$] and sunshine duration [h] were available for the De Hoek, Langgewens, Moorreesburg and Voëlvlei stations (Figure 1). All climatological time series were edited regarding homogeneity, consistency and gaps and corrected using regression analysis. As a result, corrected data sets were available for the hydrological years from 1986 to 2010. Daily time series of river discharge [$m^3\,s^{-1}$] were available for the gauging station G1H043 (Vrischewaagd) (Figure 2). Runoff records were also tested for homogeneity and consistency and corrected using regression analysis. In addition, non-continuous records of soil water and groundwater measured at several sites across the study area were available for model calibration and validation.

Geographic Information System (GIS) data are available for the study area from different sources, i.e. soils (Görgens & de Clercq 2006), land cover (Council for Scientific and Industrial Research (CSIR) and ARC 2005) and geology (Visser 1989). A Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) with 90 m resolution was obtained from the US Geological Service (USGS 2003), providing slope, aspect, river network and watersheds. Comparing the extracted river network with existing data (e.g. Google Earth images (Google Inc. 2011)) revealed inconsistencies in the generated river network. Thus, the DEM was corrected using a river network available from topographic mapping and filling. In addition, all GIS data products, including the location of climate stations and gauges, were projected to Universal Transverse Mercator Zone 34 South.

During the analysis of the different spatial data sets, inconsistencies and discrepancies such as soils on bare rock areas or soils without hydromorphic characteristics in floodplain areas were identified. Those areas were extracted and reclassified using neighbourhood functions and cross-validation as well as visual comparisons to identify the respective class of highest probability.

The hydrological model J2000

An enhanced version of the process-oriented, spatially distributed J2000 modelling system (Krause 2001) was used for the simulation of the hydrological and erosion dynamics at catchment and model unit scales. For a better representation of spatially explicit hydrological dynamics and linkages, J2000 is following a fully distributed modelling approach. Here, the catchment is subdivided into Hydrological Response Units (HRUs) (Flügel 1996) which are delineated according to Wolf *et al.* (2009). Represented as individual polygons, the delineated HRUs are linked to each other in an explicit topology which is in contrast to semi-distributive modelling approaches as used, for example, by the SWAT (Arnold *et al.* 1998).

The J2000 modelling system allows the simulation of the energy and water balance of a watershed across temporal (hourly to annually) and spatial (micro to macro) levels of aggregation. Hydrological processes modelled include interception, ET, snow accumulation and ablation, horizontally differentiated soil- and groundwater balance, and distributed runoff generation by explicitly computed lateral flows and flood routing in the catchment's river network (Krause *et al.* 2006).

All relevant hydrological processes are implemented as individual process modules (Krause 2002). The interception module uses a simple storage approach following Dickinson (1984), which calculates a maximum interception storage capacity based on the Leaf Area Index (LAI) of the respective land use. As long as this maximum capacity is not exceeded, precipitation is stored in the actual interception storage, which is depleted by evaporation. When the maximum storage capacity is exceeded, any surplus of rainfall is treated as throughfall and passed to the next module. Potential ET is calculated using the Penman–Monteith equation. Parameters required to solve the Penman–Monteith formula are provided by input data derived from the given climate stations. In the case of missing variables, J2000 offers algorithms to calculate variables such as net radiation balance, real and saturated vapour pressure, heat fluxes and absolute humidity (Krause 2001).

The J2000 soil-water balance module (Figure 3) represents the soil zone as a regulation and distribution system and interacts with nearly all other J2000 process modules. Based on empirical equations, the module separates precipitation into Runoff Direct 1 (RD1, surface runoff), water stored in depression storages (once the maximum infiltration rate is exceeded) and infiltrating water. This separation, takes the soil infiltration capacity, maximum infiltration rate, surface conditions (structure and slope) and calibration parameters into account. To simulate water movement in the unsaturated soil zone, the module implements a unique water storage concept based on two different compartments. It divides between the middle pore storage (MPS) in which stored water is held against gravity and only drained by an active tension, and the large pore storage (LPS), which is not able to hold water against gravity. The total amount of outflow from the LPS is calculated by a nonlinear relationship taking the relative saturation of the storage into account. It is split into (1) the horizontal component Runoff Direct 2 (RD2), which is

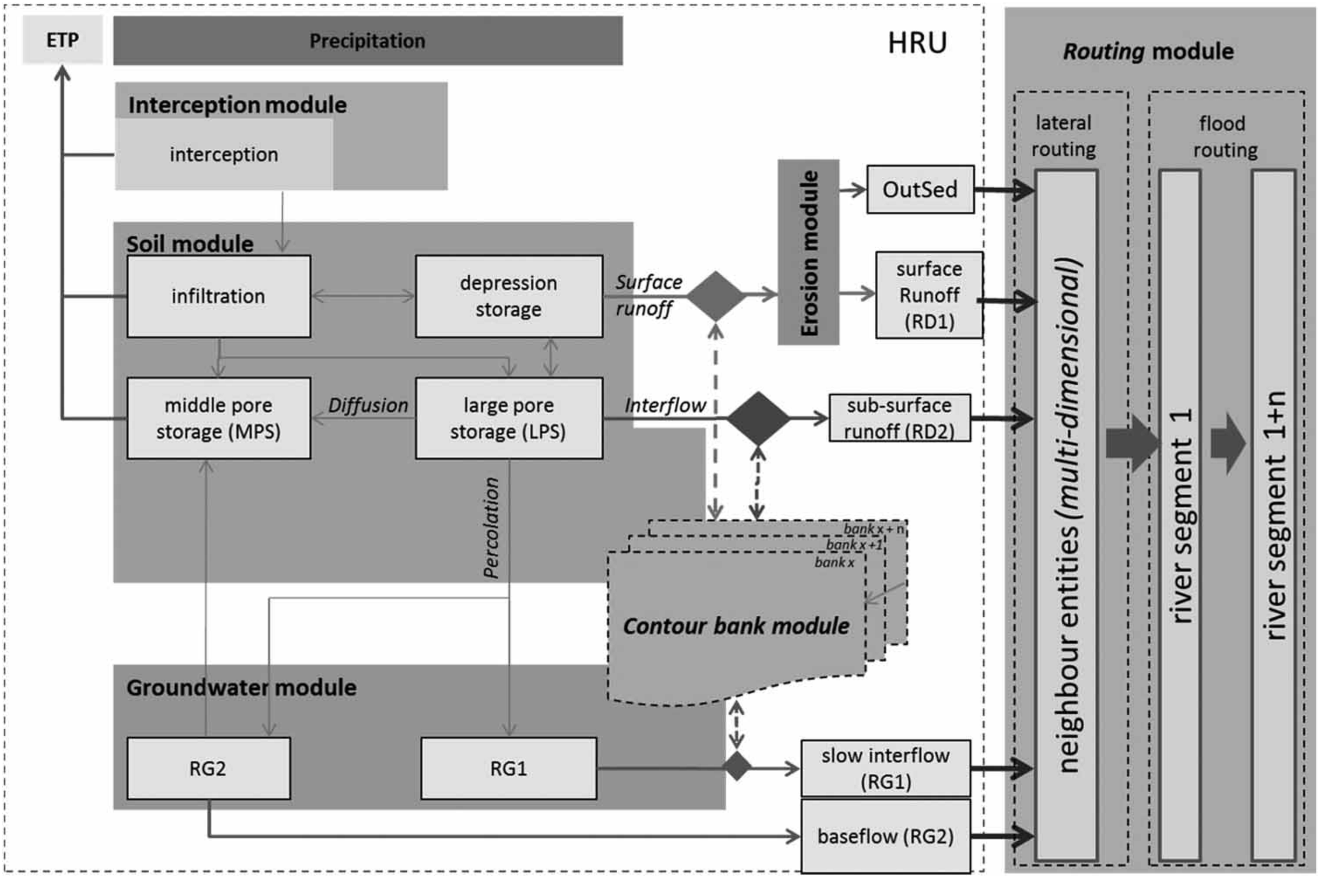

Figure 3 | Concept of the J2000 hydrological model used for the presented study (modified after Krause 2001, 2002).

interflow from the unsaturated soil zone, and (2) the vertical components (percolation, ET) with respect to topographic (e.g. slope) as well as soil (e.g. soil depths) parameters.

The groundwater module incorporates two storages representing the shallower weathering zone and a deeper aquifer (Figure 3) for each spatial model unit. The water input received from percolation into the groundwater module is distributed among the two storages based on slope and a calibration parameter. The outflow from the two storages occurs either as Runoff Groundwater 1 (RG1) which could be seen as slow interflow, i.e. water movement in the shallower weathering zone, or Runoff Groundwater 2 (RG2) which is baseflow. RG2 represents the water movement in the deeper aquifer and/or in fractures and is computed based on the actual storage content, a recession coefficient, and a global calibration parameter (Krause 2001; ILMSWIKI 2012).

Runoff is simulated at HRU level, with subsequent calculation of runoff concentration processes (through a lateral routing scheme) and flood routing in the stream channel network (Figure 2). All runoff components (surface runoff (RD1), interflow from the unsaturated soil zone (RD2), interflow from the saturated weathering layer of the underlying hydrogeological unit (RG1), and saturated baseflow (RG2)) are simulated for each HRU and for the total watershed (Figure 2). After calculation of the runoff generation processes, runoff concentration is calculated based on topological routing of the HRUs (Pfennig *et al.* 2009). The routing of water between adjacent HRUs is realised by using a multi-dimensional approach developed by Pfennig and Wolf (2007), and is an extension of the one-dimensional approach introduced by Staudenrausch (2001). Here, each runoff component generated on a single HRU is laterally connected either to a receiving HRU or to a receiving stream reach. The routing inside the stream network is simulated by connecting the reach storages, receiving the water from the topologically connected HRUs by a hierarchical storage cascade and calculating the flow velocity inside the channel using the Manning–Strickler equation. Thus, the travel time is primarily controlled by only a roughness coefficient. The outflow of each stream segment is transferred as inflow to the downstream segment. All runoff is accumulated as the basin runoff at the reference gauge at the watershed outlet.

J2000 also offers routines for the regionalisation and correction of climate data used in the process modules, based on statistical tests (regression analysis) and geostatistical approaches (Inverse Distance Weighting) (Krause 2001). Tools for sensitivity and uncertainty analysis (Fischer *et al.* 2009), accuracy assessment and output capabilities to export or visualise model results are also incorporated (Krause *et al.* 2006).

A detailed description of all process modules of J2000 is given in Krause (2001) and Krause (2002). Figure 3 gives an overview of the concept of J2000.

The original J2000 model was extended by an erosion module and a contour bank module. The erosion module calculates the sediment yield (tons per area unit) at HRU level for each time step. According to Kipka *et al.* (2010) and Pfennig *et al.* (2009), the calculation of daily potential soil loss/sediment yield is conducted by implementing the Modified Universal Soil Loss Equation (MUSLE) from the SWAT (Neitsch *et al.* 2001). Here, the original USLE (Wischmeier & Smith 1965) rainfall factor is replaced by a dynamic runoff factor, which is internally calculated by J2000. The MUSLE according to Williams (1975) and Neitsch *et al.* (2001) calculates the sediment yield (SY) from a rainfall event for each HRU by:

$$SY = R*K*L*S*C*P*\mathrm{ROKF} \text{ with } R = 11.8\,(Q_{\mathrm{surf}}*q_{\mathrm{peak}}*A_{\mathrm{HRU}})^{0.56} \quad (1)$$

where Q_{surf} is the volume of surface runoff in mm per hectare, q_{peak} is the peak flow rate in m^3 per second, A_{HRU} is the specific HRU area (ha). K is the soil erodibility factor, L is the slope length factor, S is the slope gradient factor, C is the cover and management factor, P is the support practice factor and ROKF is the coarse fragment content factor. For more theoretical information regarding the MUSLE the reader is referred to Williams (1975), Wischmeier & Smith (1965) and Neitsch *et al.* (2001). The routing of material fluxes is coupled with the water flow routing.

To incorporate the effect of the local applied land use management practice of contour bank farming a contour bank module was integrated. This incorporates the addition of contour bank storage to each HRU. The volume of this storage is dependent upon the contour length per HRU (which is calculated during the pre-processing and depends on site specific conditions) and a predefined catchment-specific mean height of the contour bank wall. The specific width of a contour bank wall is calculated as a trigonometric function of mean HRU slope (γ), bank angles (α and β) and the wall height. In addition, the depth, width and the length of the contour bank trench are taken into account for storage estimation (Figure 4). The main inflows into this storage are surface runoff (RD1) and interflow from the intermittently saturated soil zone (RD2). If the depth of the contour bank trench exceeds the depth of the soil layer, the inflow from the weathering layer (RG1) of the underlying hydrogeological unit is a further possible input component. At each time step, all simulated surface runoff is routed into the contour bank storage. The proportion of RD1 which exceeds the maximum storage capacity of the contour bank is routed as surface runoff into the next adjacent HRU by following the flow path. In contrast, the proportion of interflow (RD2), which flows into the contour bank storage during each time step is a function of actual interflow (RD2act) and a gradient (G). This gradient is calculated as the difference between the actual water level of the intermittently saturated soil zone interacting with the trench (WLT) and the total actual water level of the intermittently saturated soil zone (WLSZ). Therefore,

$$\mathrm{RD2} = \mathrm{RD2act}*\frac{\mathrm{WLT}}{\mathrm{WLSZ}}*e^{\frac{-1}{|G|}} \quad (2)$$

The thickness of the intermittently saturated soil zone at the outlet of each hillslope segment depends on the actual

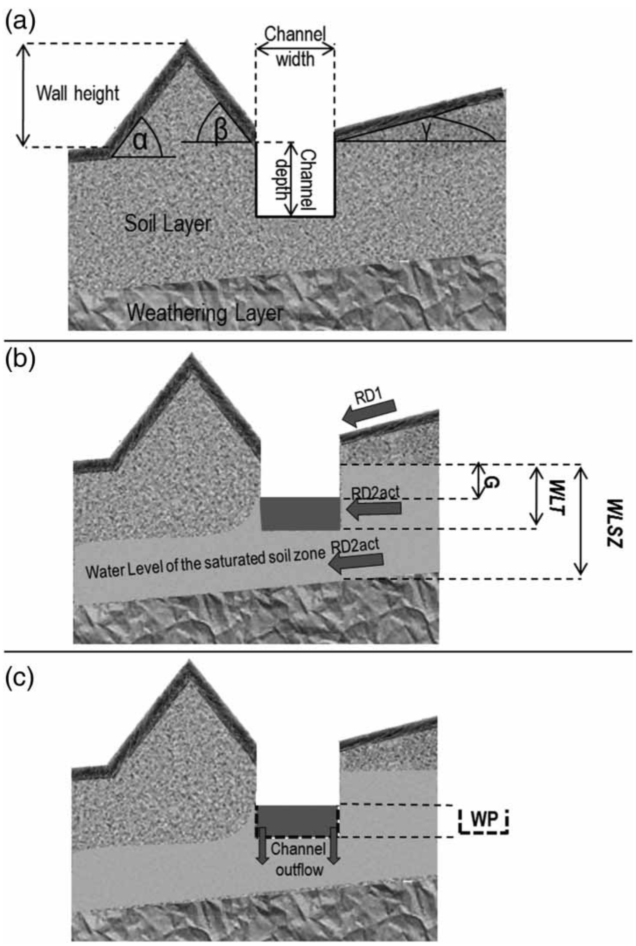

Figure 4 | (a) Simplified profile cross section of a contour bank segment and the parameters used for contour bank storage estimation. (b) Main processes of water movement within the contour bank and interaction between the contour bank storage, the runoff components of surface runoff (RD1) and actual interflow (RD2act), and the gradient (G). (c) Simplified channel outflow in dependency of the wetted perimeter (WP) between the actual water level within the trench (WLT) and the surrounding actual water level of the intermittently saturated soil zone (WLSZ).

LPS, which is the control of all vertical and lateral flows, and the mean slope of the respective HRU (γ). LPS is calculated within the soil-water module. Water in the contour bank trench infiltrates and/or percolates into the underlying soil or groundwater zone (if the contour bank depth exceeds the soil layer depth) of either the same HRU or the downslope HRU. Here, infiltration and percolation (Channel outflow) is calculated as a function of the gradient (G) between the actual water level within the trench (AW) and the actual water level of the saturated soil zone. In addition, the wetted perimeter of the trench (WP) and the specific hydraulic conductivity (K) is used to calculate a recession coefficient for determination of contour channel outflow losses ($RD2_{out}$) with

$$\text{Channel outflow} = AW * WP * e^{\frac{-1}{|G| * K}} \quad (3)$$

For channel drainage, each HRU with assigned contour banks is routed to the stream network according to the calculated flow accumulation. The fraction of water that is neither contributing to the soil or groundwater storage, nor retained back in the contour bank storage is considered as concentrated contour bank outflow. This outflow is topologically routed to the next reach (node) of the channelled flow network that is linked to the river network. Here, flow velocity in the contour trench is calculated using the Manning–Strickler equation and depends on a roughness coefficient, wetted perimeter and the channel gradient (Pfennig *et al.* 2010).

Catchment discretisation

The delineation of spatially distributed model entities, which integrate hydrological relevant characteristics of landscape features such as topography, land use, soil and geology, is based on the modification of the HRU approach (Flügel 1996). To better represent topography in the hydrological modelling, the HRU approach was modified by incorporating a clustering of selected topographic indices derived from the SRTM-DEM as shown by Wolf *et al.* (2009). The topographic indices included are the Topographical Wetness Index (TWI) (Kolberg 1997; Böhner *et al.* 2002; Wolf *et al.* 2009), the Annual Solar Radiation Index (ASR) (McCune & Keon 2002) and Mass Balance Index (MBI) (Möller *et al.* 2008; Wolf *et al.* 2009).

The TWI is used to describe the spatial pattern of depth of the water table and spatial distribution of soil moisture where a high TWI corresponds to a moist area with rapid hydrological response (Kolberg 1997; Wolf *et al.* 2009). The ASR estimates the potential direct incident radiation, which represents an improved relation to potential evaporation by integrating the slope, exposition and latitude (McCune & Keon 2002; Wolf *et al.* 2009). The MBI is a relative index for the determination of erosion-, transit- and accumulation zones. Furthermore it represents the spatial distribution of soil water (Wolf *et al.* 2009). The clustering was performed by a complete linkage cluster analysis using a program for iterative combining of homogeneous areas (IVHG) (Friedrich 1996; Metzler 2002). Here, agglomerative distance procedures are linked with a spatial neighbourhood analysis. With this approach, only grid cells having a very small displacement to each other in the multivariate space and being spatial neighbours within the data matrix are aggregated. In order to derive homogeneous relief units the distance grouping method, using the smallest Euclidian displacement, is applied (Friedrich 1996, 1998). More details on the process of clustering are documented in Pfennig & Wolf (2007). To represent the basin heterogeneity by process-oriented HRUs as described by Flügel (1996), the spatial model entities derived from clustering were merged with spatial information relating to soil, geology and land use. Here, re-classified layers of soil (Classes: Glenrosa, Oakleaf, Swartland, Estcourt and Dundee), land cover (Meadows and Pastures, Deciduous Forest, Mixed Forest, Farmland and Shrubs) and geology (Fine Sediment, Granite, Greenstone, Quartzite, Shale, Silcrete-Ferricrete), which are considered as relevant for hydrological process dynamics in the Sandspruit catchment (Flügel 1995; Bugan *et al.* 2009), were overlaid with the output of the clustering. To address relationships between runoff generation mechanisms and storage dynamics, a topological routing was performed for lateral water transport modelling between HRUs, determining the watershed spatial connections between two HRUs based on a n:m topology, or between HRUs and stream reaches, or between stream segments (Pfennig *et al.* 2009).

To model and assess the impact of contour bank farming and its effect on erosion, the contour bank storage of each HRU needed to be calculated. As there is limited information available pertaining to the distribution of contour banks in the study area, the areas with contour banks as well as the lengths of contour banks per HRU, were determined using a GIS-based approach. Since land use is the major reason for using contours, only HRUs under agriculture were considered for further analysis. Guidelines for the Western Cape region (Mathee 1984) recommend to farmers that the distance between contour banks should be calculated with

$$V = 0.25 * S + 0.5 \tag{4}$$

where V is the vertical distance between neighbouring contour banks (in metres) and S is the mean HRU slope (as a percentage). Applying this methodology to delineate the length of contour banks per HRU, revealed that the number and lengths of contours were highly over estimated in comparison to Google Earth images (Google Inc. 2011), field information and the topographical map of Porterville (Scale: 1:50000) (Staatsouteursreg 1981). This indicates that farmers rarely followed the given guidelines. However, tests in randomly selected HRUs were performed to identify the applied scheme for contour bank construction. From this information it was indicated that the highest agreement between calculated and real contour banks was reached using the formula:

$$V = 0.5 * S + 0.5 \tag{5}$$

The study also revealed that contour bank farming is widely restricted to slopes ranging between 6 and 18%. Using these criteria the contours were calculated for all HRUs. Since the mean slope length for each HRU is required for erosion modelling, the mean HRU slope length was then divided by the number of segments of contour lines crossing HRUs. Finally, the HRUs with assigned contour banks had to be routed to the adjacent stream segment by following the direction towards the steepest slope (O'Callaghan & Mark 1984). For this purpose, the stream network was extended allowing the direct linking of contour banks in areas without direct linkage to the stream network.

Model calibration, validation and accuracy assessment

J2000 parameterisation requires the generation of input parameter files and the parameterisation of the process modules. With respect to the classes used for the HRU delineation, physical parameters for each class of land cover (e.g. albedo, monthly surface resistance for water saturation, LAI, efficient vegetation height, rooting depth, sealed grade), geology (e.g. maximum storage capacities, storage coefficient) and soil (e.g. soil depth, permeability coefficient, air capacity, usable field capacity) were taken from Bugan *et al.* (2009). HRU related parameters such as position parameters, elevation, slope and aspect, class IDs (soil, geology, land cover) and routing parameters were derived from GIS analysis. Model parameter values for the process modules were also taken from Bugan *et al.* (2009), but adjusted following assessment of parameter sensitivity during the calibration process.

The initial model calibration was realised for J2000 with the contour bank module and a multi-dimensional flow routing. The model was calibrated for the period of 1989–90, in which 1989 was used for model initialisation. So as to test overall model performance with an uncalibrated model run and to allow a better assessment of model results, validation was performed for 1991. However, the year 1990 is considered as a representative year with a total precipitation of 502 mm (mean 1987–2008: 500 mm), and a mean daily runoff of 0.36 $m^3 s^{-1}$ caused by potentially erosive, low frequency high runoff events with local peaks between 7–9 $m^3 s^{-1}$ (e.g. 8.96 $m^3 s^{-1}$ on 10th July, 7.92 $m^3 s^{-1}$ on 29th June and 8.37 m^3 on 12th July; see Figure 5). Thus, the year 1990 was selected to assess the functioning of the modules rather than using the full period which would entail a change of focus from the introduction of the contour bank and erosion modules as model features to a more general discussion of the long-term hydrological dynamics. With regard to Janssen & Heuberger (1995), the calibration process was conducted combining manual and automated techniques. Initially, calibration was performed by a trial and error procedure, i.e. various model parameters ensembles were tested and evaluated regarding the representation of hydrological dynamics. A sensitivity analysis was done following the approach of Wheater (2008) and Beven (2008). Here, 10,000 Monte Carlo iterations were performed for 25 model parameters with the aim of identifying the most sensitive J2000 parameters as well as the specific parameter optimum within the manually predefined sampling interval. Based on the visual inspection of the hydrograph and objective functions, the parameters with a high sensitivity were finally re-calibrated.

Four accuracy criteria were considered for model accuracy assessments and optimisation during the calibration and validation process. In accordance with Nash & Sutcliffe (1970), Janssen & Heuberger (1995), Krause et al. (2005), Willmott (1981) and Wagener et al. (2003), the Absolute Volume Error (AvE), the Nash-Sutcliffe Efficiency (E2), Index of Agreement (IOA), and the Double Mass Gradient (DsGrad) were used to evaluate overall model performance and to iteratively optimise model parameters driving dominant hydrological processes.

RESULTS AND DISCUSSION

Hydrological modelling results and accuracy assessment

The model results derived from the calibrated model run for the year 1990 were used for the assessment of the impact of contour banks on model performance. The hydrographs representing daily simulated and observed runoff for the year 1990 (Figure 5) show a good overall representation of temporal runoff dynamics and a reasonably good correspondence between measured and simulated runoff. It is demonstrated that the model is capable of representing the ephemeral characteristics of the stream

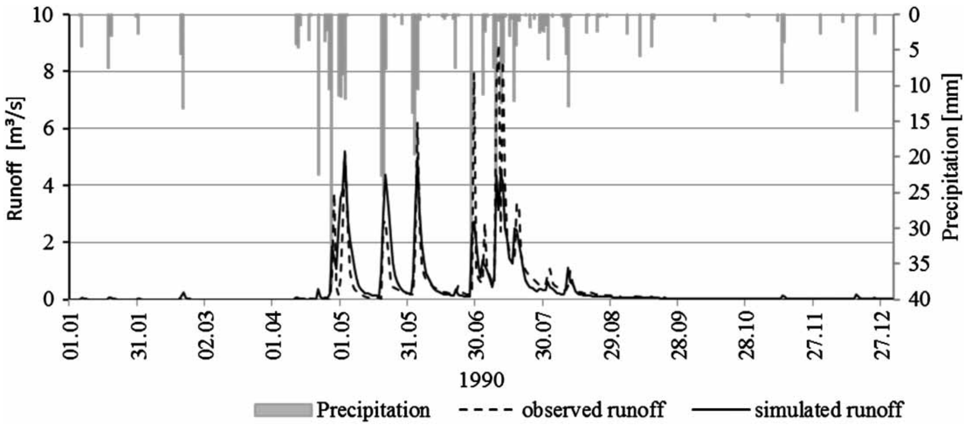

Figure 5 | Rainfall, and observed and simulated daily runoff of the Sandspruit basin for the year 1990.

during summer months with low baseflow, high ET rates and occasional runoff response resulting from convective summer rainfall events. In contrast, high runoff peaks show a good temporal agreement with rainfall events during the rainy season, even though slight over predictions occur at the beginning of the rainy season whereas the peaks in the late rainy seasons are under predicted. In terms of precipitation distribution, the west–east rainfall gradient, a result of the distance from the coastline, was accounted for by utilising data from Langgewens and Moorreesburg (west), as well as data from Voëlvlei Dam and De Hoek (east) into the hydrological modelling process. As meteorological time series data, measured within the Sandspruit catchment were not available for use in this study, the south–north rainfall gradient could not be accounted for. This was considered when evaluating the model results.

The accuracy assessment using objective functions confirms the successful modelling. An E2 of 0.65 indicates a fairly good representation of runoff response by the model. The IOA, which is proposed to resolve insensitivities of E2 to additive and proportional differences of the observed and predicted means and variances (Krause *et al.* 2005), is 0.80, which confirms the sensitivity of the model to extremes. However, the absolute volume error of 0.72 mm, showing that the annual water balance is nearly cleared, also demonstrates the good model performance. With respect to various guidelines and hydrological model assessment studies (Legates & McCabe 1999; Krause *et al.* 2005; Moriasi *et al.* 2007), all model efficiencies as well as visual interpretations and information on model-based processes (e.g. ET) met the author's criteria for a successful calibration. Thus, model results were used for the subsequent assessments of basin hydrology and the impact of contour bank farming on erosion dynamics.

Hydrological and erosion process dynamics

The good model results suggest that the integrated analysis of simulated runoff components, rainfall pattern, topography and soils, provides information on spatio-temporal dynamics of runoff generation and erosion. The separation of individual runoff components further shows that subsurface runoff, i.e. fast interflow (RD2) is the dominant runoff component throughout the year. In 1990, interflow contributed 68.58% to the annual basin runoff, whereas RG1 and RG2 contributed 13.4 and 11.45% respectively and the fraction of surface runoff (RD1) is 6.57%.

The analysis of the spatio-temporal runoff pattern and individual events also indicates that seasonal runoff generating processes are controlled by the frequency and intensity of rainfall, as well as by soil properties and topographic features. Figure 5 reflects the typical seasonal flow pattern of the Sandspruit catchment. The majority of runoff (96%) is generated during the rainy season (April–August). In the dry season, runoff is (basically) very low. During convective summer rainfall events, surface runoff (RD1) becomes a dominant runoff component in areas without contour banks when rainfall intensities exceed maximum soil infiltration capacities. Surface runoff dominated areas were identified along footslopes and floodplains, in particular in the north-eastern parts of the catchment. This is in agreement with areas characterised by Swartland and Estcourt soil forms. The tendency of these clayey-loamy soils to waterlogging due to low air capacities and low pore volume during wet conditions, as well as their tendency to crust under dry conditions (Moberly & Meyer 1984) supports the generation of surface runoff. To reduce the effect of possible surface crusting on overland flow during convective precipitation events, a parameter controlling the maximum seasonal infiltration amount was implemented. It was also possible to take into account special infiltration conditions for short duration and high intensity convective precipitation events. During dry periods, runoff is only controlled by subsurface components which are fairly balanced.

The basin runoff significantly increases at the beginning of the rainfall season in late April (Figure 5). At this time infiltration and the corresponding subsurface flow processes become the dominant controls of runoff generation. As shown in Figure 6, the fast interflow (RD2) is the major source of catchment discharge during the winter rainfall season. It correlates strongly with the observed basin runoff (Figure 5) and the storage dynamics (Figure 7). As visible in Figure 7, a higher frequency of precipitation events and significantly higher quantities of precipitation (up to 35 mm/day) results in the rapid filling of the middle pore storage (MPS) of the generally sandy-loamy and loamy

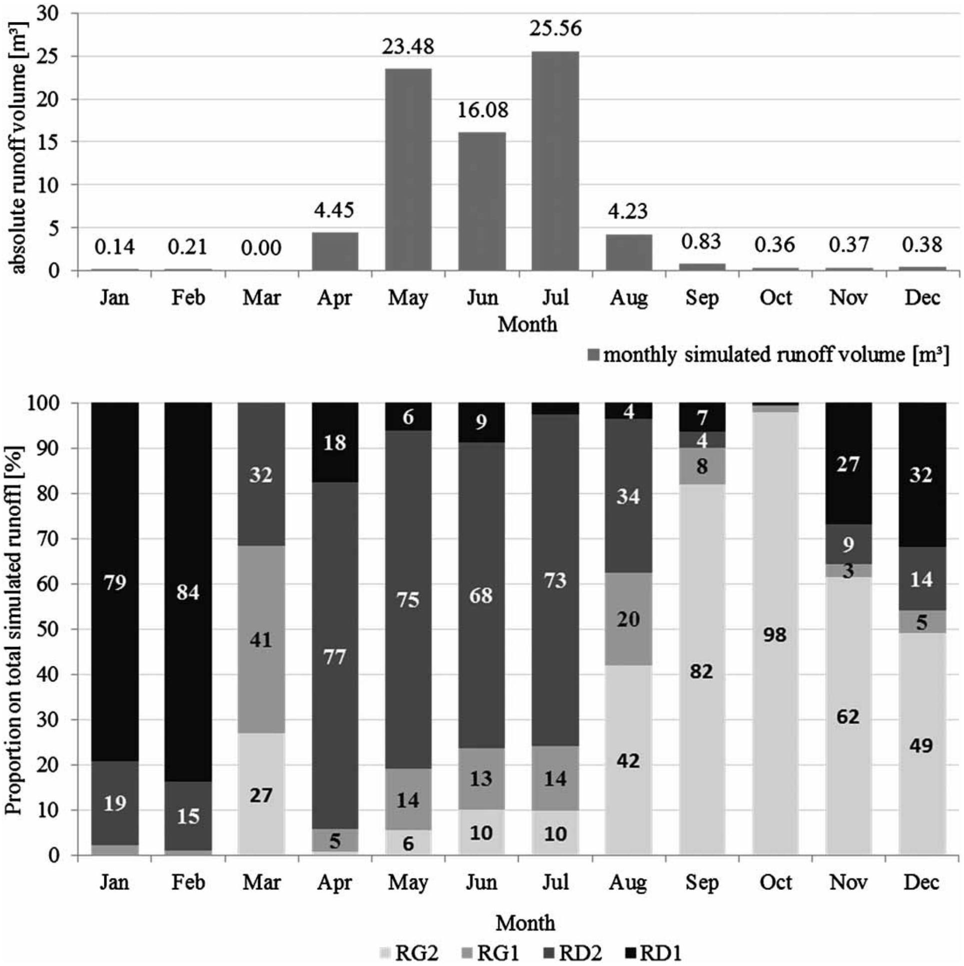

Figure 6 | Monthly simulated runoff at the catchment outlet (top) and relative proportion of single simulated runoff components on total monthly runoff volume (bottom) within the year 1990.

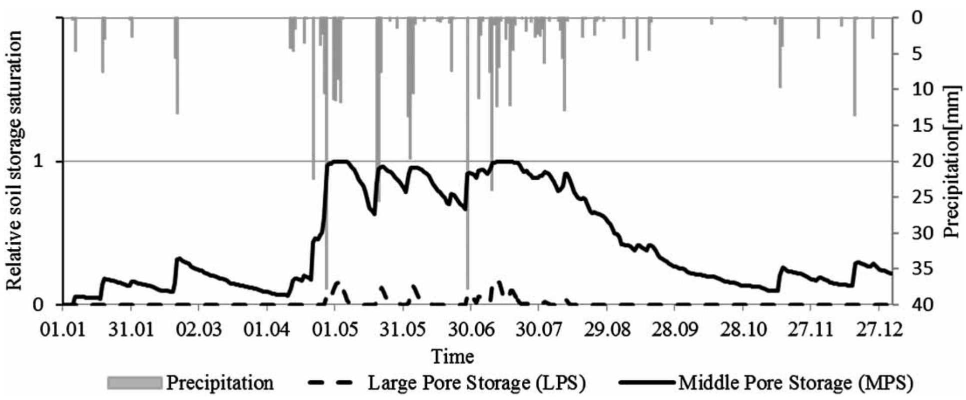

Figure 7 | Simulated relative saturation of the Large Pore Storage (LPS) and the Middle Pore Storage (MPS) during the year 1990.

sand soils with moderate available moisture capacities (Moberly & Meyer 1984), reaching saturation in late April. As a consequence of the saturation of the MPS, water is transferred to the LPS, which is the source of the lateral subsurface flow (RD2), as well as percolation into the groundwater.

It also appears that flow components generated in the saturated zone, play only a minor role due to high ET rates, infiltration excess flow, and filling of the large pore storage (LPS) during rain events that exceed 25 mm. As such, it can be stated that the relative contribution of slow interflow (RG1) and baseflow (RG2) to catchment runoff, will increase following an increase in precipitation and percolation. This increase in interflow and baseflow is therefore caused by an increased saturation of the soil-water storage during the winter rainfall season and the decrease of interflow and baseflow by the recession periods afterwards.

Applying the modified soil erosion module, a total soil loss of 5.89 t was predicted in the Sandspruit basin for 1990. The predicted sediment loss was limited to about 7% (10.6 km^2) of the basin area, in particular for those HRUs not managed by contour bank farming. The spatial assessment of the modelling results indicates that the range of soil loss varies between the HRUs depending on topography and soil characteristics (coarse fragment factor). The mean soil loss in areas without contour bank farming is 0.06 t ha^{-1} and the maximum soil loss is 0.41 t ha^{-1}. In terms of spatial distribution, the majority of erosion affected areas are located under areas of loamy sands of the Glenrosa soil form, which is dominant within the catchment (~70%), and on gentle slopes under agricultural use. The highest rates of soil loss are predicted on single model entities characterised by the Swartland and Estcourt soil form in the north-western parts of the catchment. Due to their texture, the erodibility ratings (Moberly & Meyer 1984) of these soil forms are characterised as either medium (Swartland soil form) or high (Estcourt and Glenrosa soil forms).

The seasonal assessment of erosion dynamics shows that sediment transport within the stream is strongly correlated with the runoff generation dynamics. The simulated catchment sediment yield at the outlet is 2.35 tons for the year. The highest sediment yields are predicted in May and July when surface runoff is generated due to excess infiltration flow.

Influence of the contour bank module on hydrology and erosion prediction

To assess the influence of the implemented contour bank module on hydrological modelling and soil loss prediction, the calibrated model was applied with the same parameter set and an inactive contour bank module.

Application of the model with inactive contour bank module to the year 1990 yields a significant decrease in the model performance. The Nash–Sutcliffe efficiency (0.47) and the IOA (0.77) are significantly lower than with an active contour bank module, and the absolute volume error also increased by up to 46.16 mm (see Hydrological modelling results and accuracy assessment section).

By ignoring the contour bank management practice, the fast surface runoff constitutes nearly the only runoff component during the first two months of the year. Comparing both models, it is apparent that the inclusion of contour banks significantly reduces the simulated peak flow caused by events with high precipitation input. A significant overprediction of the measured peak flow events is observed when applying the model without contour banks, in particular during the late autumn and early winter months of April and May. As a consequence, a higher simulated catchment runoff volume is predicted for this period, caused primarily by missing contour bank storages which would otherwise have retained some of the additional water. As is visible in Figure 8, both models are significantly under-predicting the high runoff event of June 29, 1990. One explanation for this is the fact that flood events in the Berg River lead to backwater effects at the gauging station (flooding the gauging station), which influence the depth of measured runoff.

During the wet winter and early spring months, the absolute value of the simulated runoff volume during peak flow events, is higher when simulated by the model version incorporating the inactive contour bank module. However by comparing the models between May and October, the differences within the composition of the simulated catchment runoff are negligible.

Application of the J2000 model with the inactive contour bank module shows a slight shift in the relative contributions of each runoff component to the annual discharge volume, compared to the results from the version with the active contour bank module. In particular,

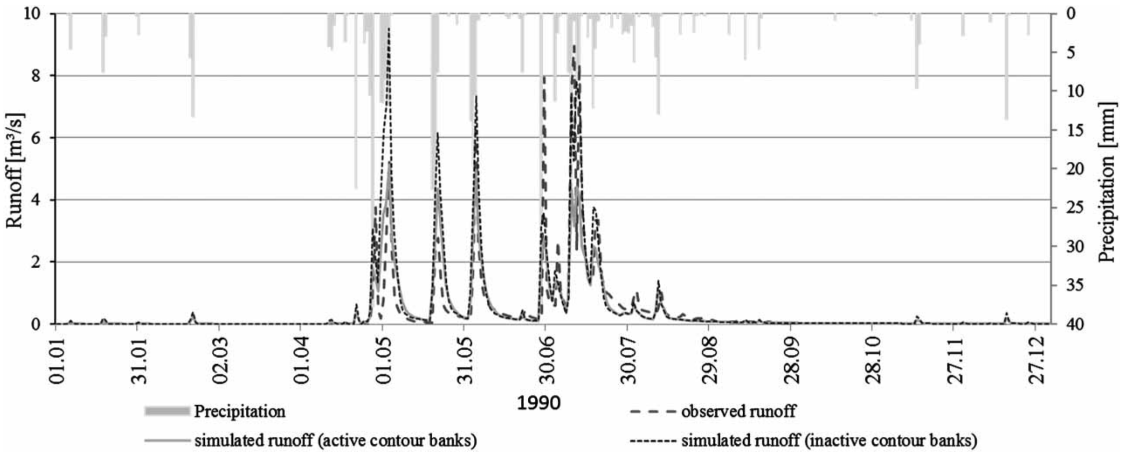

Figure 8 | Rainfall, and observed and simulated daily runoff with active and inactive contour bank module of the Sandspruit basin for the year 1990.

a slight decrease in the contribution of groundwater runoff components (RG1 and RG2) is observed in favour of the overland and subsurface flow components, when comparing the values of the model with the active contour bank module and that with the inactive contour bank module (see Table 2).

The predicted catchment sediment yield is significantly increased by applying the model with the inactive contour bank module. The simulated sediment yield at the gauging station is 22 tonnes in total, a total increase of over 19 tonnes. Overall, for an area of 66.63 km^2 (10.67 km^2 with the active contour bank module) of the Sandspruit catchment, soil loss amounting to 33.98 tonnes (5.89 tonnes with the active contour bank module) is predicted. Figure 9 is an overview of the spatial (top) and statistical distribution (bottom) of areas with sediment yield according to the model version applied for the year 1990. It becomes clear and visible, that the contour bank module and the subsequent shortening of slope length have a significant impact on erosion prediction. Indeed, it is visible from the histograms in Figure 9 (bottom) that the total number of HRUs with simulated sediment yield, as well as the sum of simulated sediment yield, decreases through application of the J2000 model with the implemented contour bank module. These decreases are caused by shorter slopes and less simulated, erosive surface runoff (RD1) into adjacent HRUs. Similarly, by applying the J2000 model without the contour bank module, a significantly higher sediment yield is simulated on a greater number of HRUs.

Table 2 | Fraction of runoff components modelled in dependence of the used model version for the year 1990

	Fraction of runoff components [%]			
Model version	**RD1**	**RD2**	**RG1**	**RG2**
With contour bank module	6.57	68.58	13.40	11.45
Without contour bank module	9.9	71.67	9.65	8.77
Percentage change	+3.3	+3.1	−3.75	−2.68

CONCLUSIONS

This research demonstrated that the effect of contour banks on runoff generation and erosion dynamics needs to be considered in semi-arid areas characterised by contour bank farming. Thus, the implementation of a contour bank module is a requirement for distributed hydrological and erosion modelling approaches.

The model results from the hydrological modelling under consideration of contour bank farming showed that the measured catchment runoff at the basin outlet could be predicted quite well. This is confirmed by the objective functions used for model evaluation. Besides this, the implementation of the contour bank module into the J2000 model framework leads to a more realistic representation of hydrologic relevant processes and their spatial distribution within the catchment. Accordingly, it could be

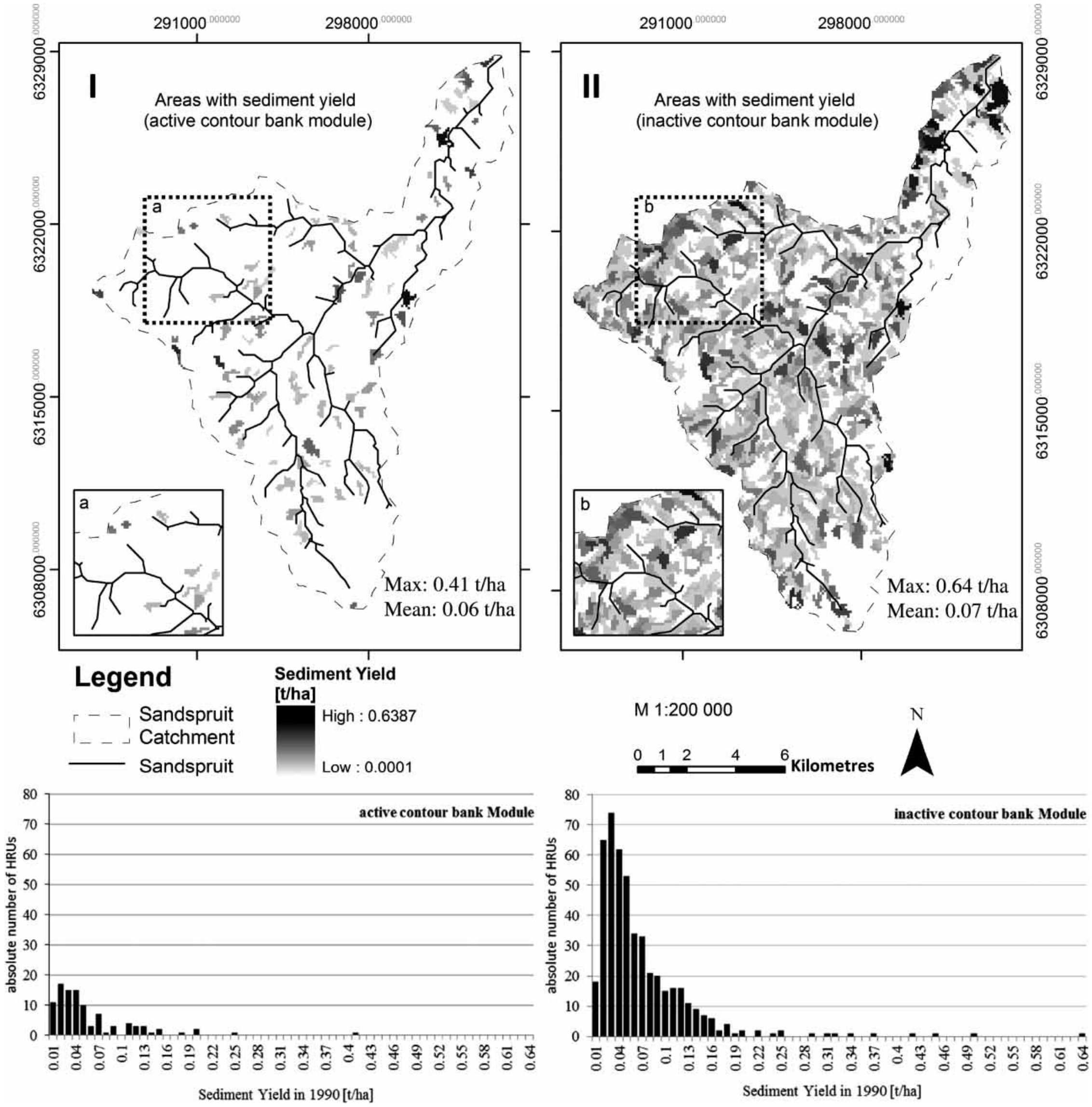

Figure 9 | Modelled sediment yield using the (I) active contour bank module and (II) no contour bank module. Top: spatial distribution of areas with simulated sediment yield. Bottom: statistical distribution of HRUs with simulated sediment yield.

shown, that the integration of the contour bank module led to a significant reduction in surface runoff along steep slopes, and consequently implies a significant reduction of soil loss from the affected areas, particularly during high precipitation events. For previous model versions without the active contour bank recognition, no surface runoff was simulated during high rainfall events for the contour bank areas. For the comparison of different approaches of topological linkage under contour bank areas, there was an equalisation of the approaches. The reason can be found in the underlying concept of the contour bank module, and in particular in the rerouting of water to the river system through the contour channels and the water transfer to downhill localised neighbouring entities. The runoff from an entity under contour banking depended on the total number of contour channels per entity. The higher the amount of water that can be stored behind contour banks per entity, the smaller the impact of topological linkage between the modelling entities. The impact of topological linkage became clearer, when comparing the approaches using a model version with an inactive contour bank module and analysing the spatial distribution of sediment yield prediction. It could be shown that the one-dimensional routing model simulated (spatially distributed) more erosion on less model entities. The reason is that the approach leads to swift runoff by just following the flow path over the point of highest flow accumulation. Therefore, the advantage of using a multi-dimensional approach for flow routing can be seen in a more accurate and realistic representation of the natural distribution of erosion dynamics or any other material fluxes within a catchment.

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REFERENCES

Abbott, M. B., Bathurst, J. C., Cunge, J. A., ÓConnell, P. E. & Rasmussen, J. 1986 An introduction to the European Hydrological System – Systeme Hydrologique Europeen, "SHE", 1: History and Philosophy of a physically-based distributed modeling system. *Journal of Hydrology* **87**, 45–59.

Arnold, J. G. & Fohrer, N. 2005 SWAT2000: current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes* **19**, 563–572.

Arnold, J., Srinivasan, R., Muttiah, R. & Williams, J. 1998 Large area hydrologic modelling and assessment. Part I, Model development. *Journal of the American Water Resources Association* **34** (1), 73–89.

Baccari, N., Boussema, M. R., Lamachère, J-M. & Nasri, S. 2008 Efficiency of contour benches, filling-in and silting-up of a hillside reservoir in a semi-arid climate in Tunisia. *Comptes Rendus Geoscience* **340** (1), 38–48.

Beven, K. 2008 *Rainfall Runoff Modelling*, 2nd edn, The Primer. John Wiley & Sons Ltd, New York.

Biondi, D., Freni, G., Iacobellis, V., Mascaro, G. & Montanari, A. 2012 Validation of hydrological models: Conceptual basis, methodological approaches and a proposal for a code of practice. *Physics and Chemistry of the Earth* **42**, 70–76.

Böhner, J., Köthe, R., Conrad, O., Gross, J., Ringeler, A. & Selige, T. 2002 Soil regionalisation by means of terrain analysis and process parameterisation. In: *Soil Classification 2001* (E. Micheli, F. Nachtergaele & L. Montanarella, eds). European Soil Bureau, Research Report No. 7, EUR 20398 EN, Luxembourg, pp. 213–222.

Bugan, R. D. H., Javanovic, N. Z. & De Clercq, W. P. 2012 The water balance of a seasonal stream in the semi-arid Western Cape (South Africa). *Water SA* **38** (2), 201–212.

Bugan, R. D. H., Jovanovic, N. Z., De Clercq, W. P., Helmschrot, J., Flügel, W. & Leavesley, G. H. 2009 A comparative analysis of the PRMS and J2000 hydrological models applied to the Sandspruit Catchment (Western Cape, South Africa). In: *Management of Natural Resources, Sustainable Development and Ecological Hazards*, 2nd edn (C. A. Brebbia, N. Z. Jovanovic & E. Tiezzi, eds). WIT Press, Southampton, pp. 391–402.

Callow, J. N. & Smettem, K. R. J. 2009 The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes. *Environmental. Modelling & Software* **24**, 959–968.

CSIR and ARC 2005 *National Land Cover. Raster Data Set*. Council for Scientific and Industrial Research & Agricultural Research Council, Pretoria, South Africa.

DERM 2004 *Soil conservation measures–Design manual for Queensland*. Chapter 9: Contour Bank Specifications. Department of Environment and Resource Management, http://www.derm.qld.gov.au/land/management/erosion/index.html#design_manual.

Dickinson, R. E. 1984 Modelling evapotranspiration for three-dimensional global climate models. In: *Climate Processes and Climate Sensitivity* (J. E. Hansen & T. Takahasi, eds). Geophysical Monograph Series 29, Washington, DC, pp. 58–72.

DWAF 2007 Berg River Baseline Monitoring Programme. Final Report, Volume 1. Introduction to the Berg River Catchment; Groundwater and Hydrology. DWAF Report No. P WMA 19/G10/00/1707. Department of Water Affairs and Forestry, South Africa.

Fey, M. V. 2010 Soils of South Africa. Their Distribution, Properties, Classification, Genesis, Use and Environmental Significance. Cambridge University Press, Cambridge.

Fischer, C., Kralisch, S., Krause, P., Fink, M. & Flügel, W. A. 2009 Calibration of hydrological model parameters with the JAMS framework. In: *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation* (R. S. Anderssen, R. D. Braddock & L. T. H. Newham, eds). Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, July 2009, Cairns, Australia, pp. 866–872.

Flügel, W. A. 1995 River salinization due to dryland agriculture in the Western Cape Province, Republic of South Africa. *Environment International* **21** (5), 679–686.

Flügel, W. A. 1996 Hydrological Response Units (HRUs) as modeling entities for hydrological river basin simulation and their methodological potential for modeling complex environmental process systems. *Results from the Sieg catchment. Die Erde* **127**, 43–62.

Freebairn, D. 2004 Erosion Control. Some observations on the role of soil conservation structures and conservation. *Journal of the Australian Association of Natural Resource Management* **7** (1), 8–13.

Friedrich, K. 1996 Digitale Reliefgliederungsverfahren zur Ableitung bodenkundlich relevanter Flächeneinheiten. Frankfurter Geowissenschaftliche Arbeiten D 21, Frankfurt am Main.

Friedrich, K. 1998 Multivariate distance methods for geomorphographic relief classification. In: *Land Information Systems. Developments for Planning the Sustainable use of Land Resources* (H. J. Heineke, W. Eckelmann, A. J. Thomasson, R. J. A. Jones, L. Montanarella & B. Buckley, eds). European Soil Bureau - Research Report No. 4, EUR 17729 EN, Office for official publication of the European Communities, Ispra, pp. 259–266.

Google Inc. 2011 Google Earth (Version 6.1.0.5001) [Software]. Available from http://www.google.de/intl/de/earth/index.html.

Görgens, A. H. M. & de Clerq, W. P. 2006 Summary of Water Quality Information System and Soil Quality Studies: Research on Berg River Water Management. WRC Report: TT252/06.

Hughes, D. A. 2004 Three decades of hydrological modeling research in South Africa. *South African Journal of Science* **100**, 638–642.

Hughes, D. A. 2008 Modelling semi-arid and arid hydrology and water resources: The southern African experience. In: *Hydrological Modeling in Arid and Semi-Arid Areas* (H. S. Weather, S. Sorooshian & K. D. Sharma, eds). Cambridge University Press, New York, USA, pp. 29–40.

ILMSWIKI 2012 Hydrological Model J2000. Available from http://ilms.uni-jena.de/ilmswiki/index.php/Hydrological_Model_J2000 (accessed 07.09.2013).

Janssen, P. H. M. & Heuberger, P. S. C. 1995 Calibration of process-oriented models. *Ecological Modelling* **83**, 55–66.

Jetten, V., de Roo, A. & Favis-Mortlock, D. 1999 Evaluation of field-scale and catchment-scale soil erosion models. *Catena* **37**, 521–541.

Kingumbi, A., Besbes, M., Bourges, J. & Garetta, P. 2004 Evaluation des transferts entre barrage et aquifères par la méthode de bilan d'une retenue en zone semi-aride. Cas d'El Haouareb en Tunisie centrale. *Revue des sciences de ĺeau* **17** (2), 213–225.

Kipka, H., Fink, M., Wetzel, M., Varga, D., Kralisch, S., Krause, P. & Flügel, W. A. 2010 *Entwicklung und Anwendung von Modellerweiterungen für das hydrologische Modell J2000S/JAMS (Jena Adaptable Modelling System) zur Erosions und Phosphorkreislauf -Modellierung*. Marktredwitzer Bodenschutztage, Tagungsband 6, Marktredwitz, pp. 167–169.

Kolberg, S. 1997 Catchment relief characteristics for hydrological purposes. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography* **51** (1), 15–22.

Krause, P. 2001 Das Hydrologische Modellsystem J2000. Beschreibung und Anwendung in großen Flussgebieten. Schriften des Forschungszentrum Jülich, Reihe Umwelt, Band 29. Jülich.

Krause, P. 2002 Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model. *Physics and Chemistry of the Earth* **27**, 663–673.

Krause, P., Bäse, F., Bende-Michl, U., Fink, M., Flügel, W. A. & Pfennig, B. 2006 Multiscale investigations in a mesoscale catchment – hydrological modelling in the Gera catchment. *Advances in Geosciences* **9**, 53–61.

Krause, P., Boyle, D. & Bäse, F. 2005 Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences* **5**, 89–97.

Kruger, A. C., Goliger, A. M., Retief, J. V. & Sekele, S. 2010 Strong wind climatic zones in South Africa. *Wind Structures* **13**, 1–19.

Lacombe, G., Cappelaere, B. & Leduc, C. 2008 Hydrological impact of water and soil conservation works in the Merguellil catchment of central Tunisia. *Journal of Hydrology* **359** (3–4), 210–224.

Lambrechts, J. J. N. 2007 Proposed Construction of a New Cement Factory and Extension to the Existing Mining Operation in Riebeek West, Western Cape. Agricultural Assessment. Department of Soil Science, University of Stellenbosch.

Leduc, C., Ben Ammar, S., Favreau, G., Béji, R., Virrion, R., Lacombe, G., Tarhouni, J., Aouadi, C., Zenati Chelli, B., Jebnoun, N., Oï, M., Michelot, J. L. & Zouari, K. 2007 Impacts of hydrological changes in the Mediterranean zone: Environmental modifications and rural development in the Merguellil catchment (central Tunisia). *Hydrological Science Journal* **52** (6), 1162–1178.

Legates, D. R. & McCabe Jr., G. J. 1999 Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research* **35**, 233–241.

Lesschen, J. P., Schoorl, J. M. & Cammeraat, L. H. 2009 Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. *Geomorphology* **109**, 174–183.

Mathee, J. A. La G. 1984 Beskerming van Bewerkte Landerye. In: *National Soil Conservation Manual. Chapter 8* (Directorate of Agricultural Engineering and Water Supply, eds). Govt Printer, Pretoria, South Africa.

McCune, B. & Keon, D. 2002 Equations for potential annual direct incident radiation and heat load. Short Note. *Journal of Vegetation Science* **13**, 603–606.

Meadows, M. E. 2003 Soil erosion in the Swartland, Western Cape Province, South Africa: Implications of past and present policy and practice. *Environmental Science & Policy* **6**, 17–28.

Meadows, M. E. & Hoffman, M. T. 2002 The nature, extent and causes of land degradation in South Africa: Legacy of the past, lessons for the future? *Area* **34** (4), 428–437.

Metzler, D. 2002 Hinweise zur Anwendung des Programms ivhg. Technical Report. Dirk Metzler, Oberursel.

Midgley, D. C., Pitman, W. V. & Middleton, B. J. 1994 Surface Water Resources of South Africa 1990WRC Report No. 298/1.1/94–298/6.1/94. Volumes 1–6, Water Research Commission, Pretoria.

Moberly, P. K. & Meyer, J. H. 1984 Soils: a management factor in sugarcane production in the South African sugar industry. In Proceedings of the South African Sugar Technologists' Association, June 1984, South Africa, pp. 192–197.

Möller, M., Volk, M., Friedrich, K. & Lymburner, L. 2008 Placing soil-genesis and transport processes into a landscape context: A multiscale terrain-analysis approach. *Journal of Plant Nutrition and Soil Science* **171**, 419–430.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Binger, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural And Biological Engineers* **50**, 885–900.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptual models part I – A discussion of principles. *Journal of Hydrology*. **10**, 282–292.

Nasri, S. 2007 Caractéristiques et impacts hydrologiques de banquettes en cascade sur un versant semi-aride en Tunisie central. *Hydrological Science Journal* **52** (2), 1134–1145.

Nasri, S., Albergel, J., Cudennec, C. & Berndtsson, R. 2004a Hydrological processes in macrocatchment water harvesting in the arid region of Tunisia: The traditional system of tabias. *Hydrogeological Sciences – Journal-des Sciences Hydrologiques* **49** (2), 261–272.

Nasri, S., Lamachère, J-M. & Albergel, J. 2004b Impact des banquettes sur le ruissellement d'un petit bassin versant. *Revue des Sciences de l'eau* **17** (2), 265–289.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. 2001 *Soil and Water Assessment Tool*. Theoretical Documentation. Version 2000, Temple.

ÓCallaghan, J. F. & Mark, D. M. 1994 The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing* **28**, 323–344.

Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R. H., Gabriels, D. & Cornelis, W. M. 2009 Modelling water-harvesting systems in the arid south of Tunisia using SWAT. *Hydrology and Earth System Sciences* **13**, 2003–2021.

Pfennig, B., Kipka, H., Wolf, M., Fink, M., Krause, P. & Flügel, W. A. 2009 Development of an extended routing scheme in reference to consideration of multi-dimensional flow relations between hydrological model entities. In: *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation* (R. S. Anderssen, R. D. Braddock & L. T. H. Newham, eds). Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, July 2009, pp. 1972–1978.

Pfennig, B. & Wolf, M. 2007 Extraction of process-based topographic model units using SRTM elevation data for Prediction in Ungauged Basins (PUB) in different landscapes. In: *MODSIM 2007 International Congress on Modelling and Simulation* (L. Oxley & D. Kulasiri, eds). Modelling and Simulation Society of Australia and New Zealand, December 2007, Christchurch, New Zealand, pp. 685–691.

Pfennig, B., Wolf, M., Helmschrot, J., Fink, M., Krause, P. & Flügel, W. A. 2010 Berücksichtigung von "contour farming" in der hydrologischen Modellierung am Beispiel des Sandspruit River (Südafrika). – aktueller Stand der Arbeiten. In Jahrestagung der Afrikagruppe deutscher Geowissenschaftler (AdG), 25.–26. Juni 2010, Frankfurt am Main. Abstract and Oral Presentation.

RPS 2010 The Benefits of Soil Conservation Works in the Moonie (Back Ck) and Upper Boogera Clusters of the Talwood Planning Group. Final Report. Report for the Queensland Murray Darling Committee. RPS Group, Toowoomba.

Staatsouteursreg 1981 *1:50 000 Scale Topographic Map, 3318BB Porterville from South Africa*. Chief Director of Surveys and Mapping, Republic of South Africa.

Staudenrausch, H. 2001 Untersuchungen zur hydrologischen Topologie von Landschaftsobjekten für die distributive Flussgebietsmodellierung. Dissertationsschrift. Friedrich-Schiller-Universität Jena, Jena.

USGS (United States Geological Survey) 2003 *Shuttle Radar Topography Mission (SRTM). Fact Sheet 071-03*. US Geological Survey, Reston, 2 pp.

Visser, D. J. L. 1989 *Explanation: 1:1 000 000 Geological Map* – The Geology of the Republic of South Africa, Transkei, Bophuthatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland. Geological Survey, Pretoria, 491 pp.

Wagener, T., McIntyre, N., Lees, J., Wheater, H. S. & Gupta, H. V. 2003 Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis. *Hydrological Processes* **17**, 455–476.

Wakindiki, I. I. C., Mochoge, B. O. & Semoka, J. M. R. 2007 Assessment of indigenous soil and water conservation technology for smallholder farms in semi-arid areas in Africa and close spaced trash lines effect of erosion and crop yield. In: *Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and Opportunities* (A. Bationo, B. Waswa, J. Kihara & J. Kimetu, eds). Springer, Dordrecht, pp. 805–814.

Wheater, H. S. 2008 Modelling hydrological processes in arid and semi-arid areas: An introduction to the workshop. In: *Hydrological Modeling in Arid and Semi-Arid Areas* (H. S. Weather, S. Sorooshian & K. D. Sharma, eds). Cambridge University Press, New York, pp. 1–20.

Williams, J. R. 1975 Sediment Routing for agricultural watersheds. Water Resources Bulletin. *Journal of the American Water Resources Association* **11** (5), 965–974.

Willmott, C. J. 1981 On the validation of models. *Phys. Geogr.* **2**, 184–194.

Wischmeier, W. H. & Smith, D. D. 1965 *Predicting Rainfall-Erosion Losses from Cropland East of the Rocky Mountains*. Agriculture Handbook, No. 282, Washington, DC.

Wolf, M., Pfennig, B., Krause, P. & Flügel, W. A. 2009 Delineation of topographic process entities using SRTM for hydrological modeling. In: *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation* (R. S. Anderssen, R. D. Braddock & L. T. H. Newham, eds). Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, July 2009, Cairns, Australia, pp. 2021–2027.

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