Calibration, validation and application of the SWAT model to determine the hydrological benefit of wetland rehabilitation in KwaZulu-Natal, South Africa

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In South Africa, with highly variable and intense land-use practices, coupled with limited soil fertility and water resources, there has been a long history of encroachment of arable lands (sugarcane and timber plantations) into surrounding wetlands. Although wetland delineation within the timber and sugar sectors is well-defined in policy, and existing and proposed legislation, there are significant areas of non-compliance. The spatially-explicit Soil Water Assessment Tool (SWAT) was adopted to investigate the interactions of climate, land-use and soil on the water-use of natural and encroached wetlands. This paper documents the calibration, validation and application of the SWAT model on Quaternary Catchment (QC) U20G, which is a 498 km² catchment that forms part of the uMngeni River basin. The SWAT-CUP parameter sensitivity and optimization model was tested with daily observed streamflow data for this catchment. Parameters were modified using the sequential uncertainty fitting (SUFI-2) analysis routine to calibrate the model. The simulated flow had a close fit to the observed flow with a regression coefficient (r^2) of 0.87 and a Nash-Sutcliffe (NS) coefficient of 0.8. Through the buffer scenario analysis, the model showed that if the wetland and a 20-m buffer were to be returned to a natural state, there could be a 16% increase in the annual streamflow contribution, with an upper limit of a 60% increase in some hydrologic response units (HRUs). Thus there would be a hydrological gain if wetlands and sensitive buffer areas were to be cleared of commercial timber species and sugarcane.

INTRODUCTION

Commercial forestry has been shown to increase the 'green water' (water lost by total evaporation) and decrease the 'blue water' (water in rivers and dams) across South Africa (Jewitt, 2006; Everson et al., 2008; Gush, 2011). The National Water Act (Act No. 36 of 1998) declares commercial forestry to be a streamflow reduction activity (SFRA), whilst sugarcane, although not legislated as an SFRA, has shown to be a high water user (Bezuidenhout et al., 2006; Jarmain et al., 2014). All timber and most sugarcane in South Africa is rainfed or non-irrigated (Olivier and Singels, 2015), with soil water availability being the key limiting factor in their production. Historically, wetland areas, particularly in KwaZulu-Natal, have proved to be attractive for timber and sugarcane farmers, leading to the complete degradation of these wetland systems and, inter alia, an increased evaporation loss as a consequence of these 'thirsty' crops.

Although wetland delineation, within the timber and sugarcane sectors, has become well-defined in policy and existing (and proposed) legislation, and despite considerable pull-back in many timber estates, there are significant areas of non-compliance (Edwards and Roberts, 2006). The full implications of complete wetland delineation for production, regional economics, hydrological security and biodiversity have not been quantified and are poorly understood. Current drivers of policy and legislation are based on assumed, but untested, hydrological and biodiversity benefits. This study aims to calibrate the model selected to quantify the potential hydrological benefits of achieving complete delineation and buffering of wetlands within a significant forestry and sugarcane area of KwaZulu-Natal.

Hydrological modelling is an appropriate approach to investigate the complex interactions of climate, land-use and soil on the water-use of agricultural systems, in particular where spatial heterogeneity exists. KwaZulu-Natal has a spatially variable climate and complex land-use patterns, resulting in many of the commonly used models being unsuitable for spatial scenario testing. The objective of this study is to develop a methodology to apply a hydrological model to forestry and sugarcane delineation and buffering scenarios that could guide legislation, policy and management decisions. The Soil and Water Assessment Tool (SWAT) has emerged as one of the most widely used water quality, watershed and river basin–scale models, applied for a diverse range of hydrologic and/or environmental problems (Gassman et al., 2007; Gassman et al., 2014). The recent development of SWAT+ has allowed for the implementation of landscape units, improving flow and pollutant routing across the landscape (Bieger et al., 2017).

South Africa has been sub-divided into primary, secondary, tertiary and quaternary catchments (QCs). These interlinked and hydrologically cascading quaternary catchments vary in size from 48 to 18 100 km² (Schulze and Horan, 2007). In this research, the calibrated baseline state, with the current patterns of land-use for QC U20G, was compared to two scenarios: (i) where all encroached wetlands

were delineated and restored to a natural state, and (ii) an additional 20 m buffer surrounding the wetland was restored to natural vegetation. The model, using newly derived calibrated input values, was simulated for a time period beyond the calibration period. In addition, a highly afforested catchment with higher rainfall was simulated and compared with observed flow data. This catchment (QC U40A) was selected as it is one of a few QCs with good quality observed flow and no upstream catchments. For the calibration period, the model provided a close fit to the observed data, allowing for the model to be validated.

The SWAT model

In South Africa, models such as the Agricultural Catchments Research Unit (ACRU), Système Hydrologique Européen (SHE) model group and WAVES have been extensively applied (Lewarne, 2009). However, given the spatially complex nature of the data, the recent development of the ArcSWAT GIS interface, and recent studies adopting this model, SWAT (ArcSWAT ver. 2012.10_5.21) was selected as the most appropriate model. SWAT is a conceptual continuous time model developed in the early 1990s to assist in water resource management, to assess the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins (Arnold and Fohrer, 2005). Recently SWAT has been applied in tropical and sub-tropical regions of Africa (Easton et al., 2010; Schuol et al., 2008; Everson et al., 2018; Akoko et al., 2021), Asia (Thampi et al., 2010; Wagner et al., 2011), and Latin America (Strauch et al., 2013). It is physically based, uses readily available inputs and is computationally efficient to operate on large catchments over extended time periods (Everson et al., 2007). The required data inputs for SWAT to drive flows and direct sub-basin routing include; soil distributions, land-use patterns, management plans, elevation and daily/monthly climate (Arnold and Fohrer, 2005). SWAT integrates these parameters into hydrologic response units (HRUs), effectively replacing the underlying spatial data; these units are grouped according to topography, soils (type/structure/depth/chemical properties), land use and slope. The SWAT model uses the water balance equation (Eq. 1) in its simulation of the hydrological cycle (Neitsch et al., 2011).

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad (1)$$

where SW_t is the final soil water content (mm); SW_0 the initial soil water content on day i (mm); R_{day} the precipitation on day i (mm); Q_{surf} the surface runoff on day i (mm); E_a the total evaporation on day i (mm); W_{seep} the water entering the vadose zone on day i (mm) and Q_{gw} the return flow on day i (mm). The wetland module in SWAT is simple, where wetland area is allocated per sub-basin. The simulation uses unidirectional seepage from the wetland to groundwater, surface runoff and lateral subsurface generated from surrounding uplands and the wetland water surface area, with the discharge of water from the wetland to the river (Raham et al., 2016).

The study area

Quaternary Catchment U20G drains into the Mkhabela River, a key tributary in the uMngeni River that is managed by a state-owned entity, Umgeni Water (Fig. 1). U20G is heavily transformed, primarily by commercial forestry and agriculture, with some built-up areas such as the town of Wartburg. Rainfall in the region occurs mostly in summer (December to February), with a mean annual precipitation of 863 mm, ranging from 650 mm towards the lowland southern areas to 1 060 mm in the upland northern areas. The reference potential evaporation (ET_o) is approximately 1 675 mm (A-pan equivalent, after Schulze, 2011) and the mean annual evaporation is between 1 200 and 1 300 mm, which exceeds the annual rainfall, suggesting the catchment is water

limited. Summers are warm to hot and winters are cool. The mean annual temperature ranges between 20.1°C in summer and 11.7°C in winter. This 498 km² catchment ranges from 1 120 m asl to 293 m asl at the catchment outlet. The underlying geology of the site is Natal Group Shale that leads to the formation of deep, well-drained soils such as the Avalon, Westleigh and Hutton forms.

The catchment area is dominated by commercial forestry (hybrids of *Eucalyptus grandis*, *Pinus patula* / *P. elliotii*, *Acacia mearnsii*) and sugarcane (*Saccharum officinarum*). The areas covered by these crops are extensive (Table 1) and there are numerous scientific findings indicating their high water use in contrast to the natural vegetation that they replaced (Olbrich et al., 1996; Everson et al., 2007; Dye et al., 2008; Gush and Dye, 2009; Gush and Dye, 2015). Many of these planted lands have historically, and in some instances currently, encroached into wetland areas or their buffers, sometimes in their entirety. This is largely due to the attractive arable conditions associated with wetlands: high fertility, easy access to groundwater, and amenable topography. Indeed, government policies and subsidies in past decades encouraged the conversion of wetlands to arable lands, particularly sugarcane and timber. The few remnant natural areas are a combination of KwaZulu-Natal Sandstone Sourveld, KwaZulu-Natal Hinterland Thornveld and Ngongoni Veld of Valley Thicket Biome and Natal Central Bushveld of the sub-escarpment savanna bioregion (Mucina and Rutherford, 2006).

METHODS

Elevation and topography

The output of SWAT is largely dependent on the resolution of the input data, in particular the digital elevation model (DEM). Much of the model development time was spent translating data into suitable input data. Figure 2 shows the elevation model, soils layer and land-use layer with the five climate stations indicated in red. These layers were used to derive a total of 3 745 hydrological response units (HRUs). This allowed for the spatial complexity of the model outputs to be maintained.

The 30 m Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM was used to delineate the watershed (improved using verified point and contour data to correct inaccuracies associated with tall vegetation, and interpolated into a higher resolution DEM). Soils and hydropedological units were defined according to research published by Neitsch et al. (2011) and through personal communication (Van Tol and Lorentz, 2019). Daily data from five spatially variable weather stations were obtained and modified to drive the model.

Daily observed flow from the stream gauges at the two inlets (U2H014 below Albert Falls Dam and U2H012 on the Mpolweni River) and a sub-catchment outlet (U2H059 upstream of Nagle Dam) were used in the model. This allowed for the contributing catchment above U20G (U20A, U20B, U20C, U20D, U20E and U20F, totalling 2 605 km²), where less information was available, to be excluded within the model using accurate observations.

Land use and vegetation

A combination of provincial and industry-based GIS layers were integrated to create a new land-use layer. User-defined vegetation growth input parameters were constructed for the study area based on site observations, scientific publications, available databases (EKZNW, 2014) and expert opinion. The accuracy of the timber and sugarcane boundaries of the provincial landcover layer (EKZNW, 2014) was improved by cutting in the relatively accurate commercial forestry and sugarcane layers obtained from the various industry GIS databases. The accuracy of the wetland delineations was improved by cutting in a detailed wetland layer digitised from aerial imagery (Lechmere-Oertel, 2017), including a 20 m buffer around the delineated wetland edge.
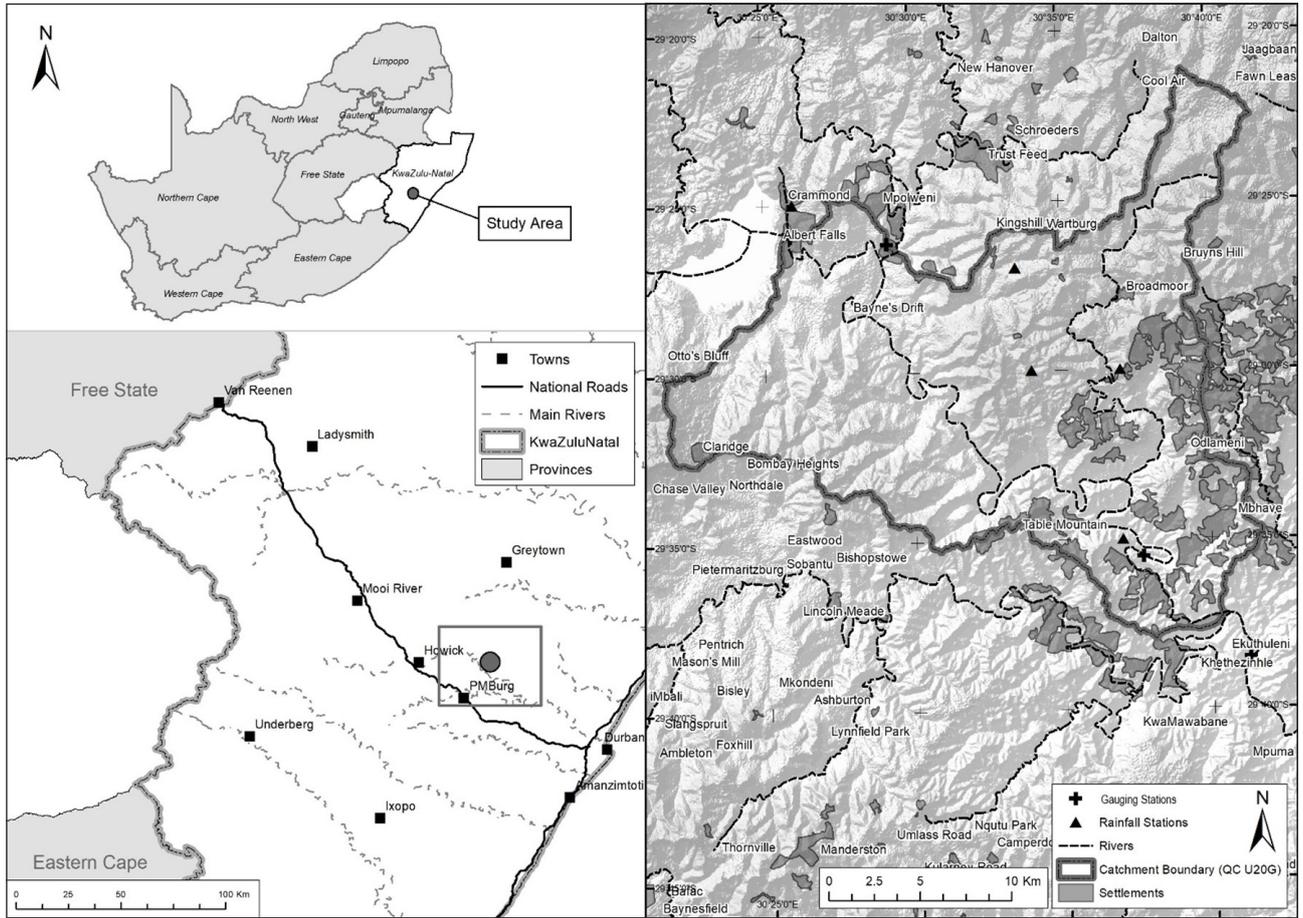
Figure 1. Location of Quaternary Catchment U20G
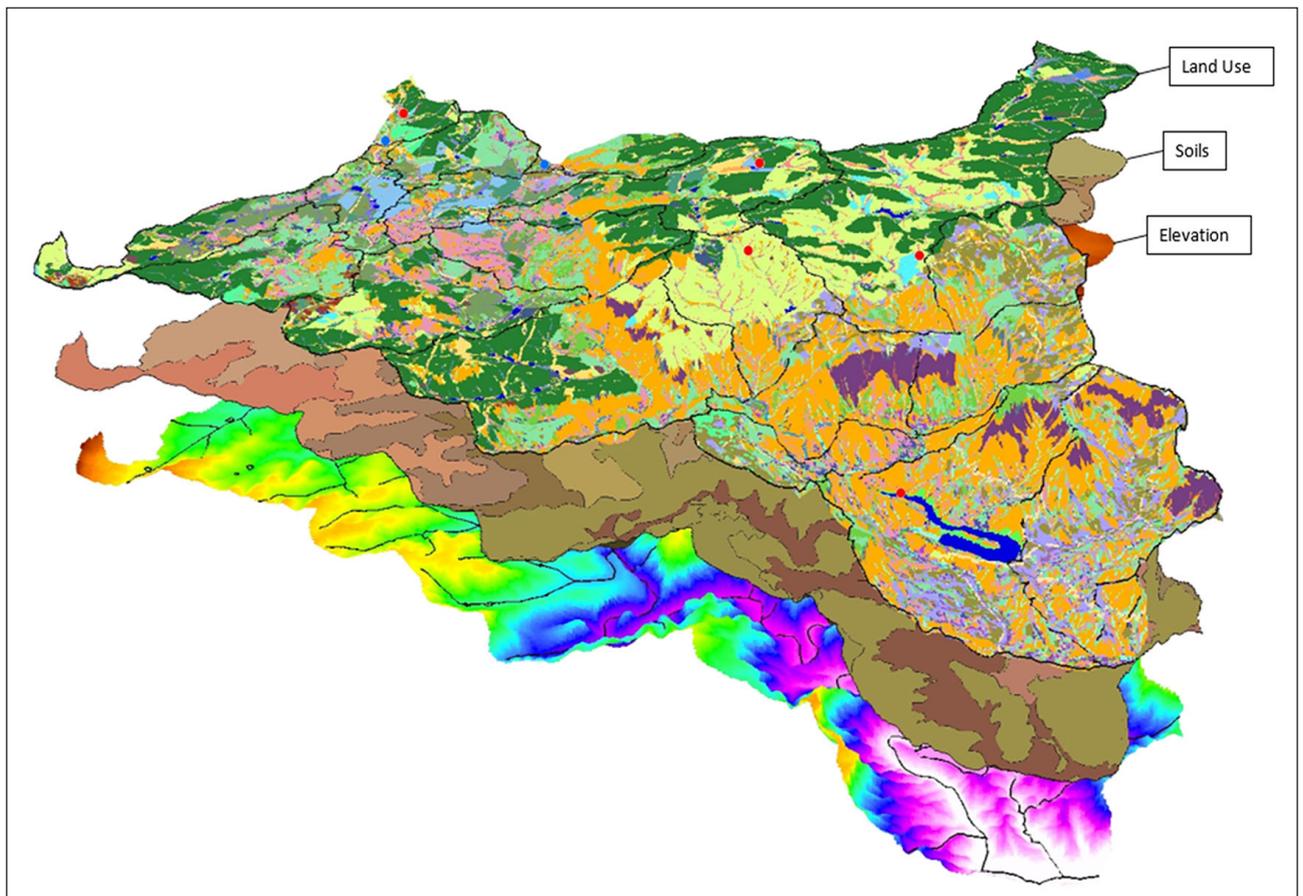
Figure 2. Key spatial input data for the derivation of HRUs for Quaternary Catchment U20G

The wetland and 20 m buffer layers retained the detail of the underlying landcover classes, essentially creating a series of new classes, such as 'natural wetland, 'timber in wetland', and 'sugarcane in buffer'. The original wetland areas were still simulated with wetland characteristics but with a modified land use. Any areas that would not realistically change (e.g. built up areas and roads) were left unchanged within the wetland and buffer areas. The SWAT Land-use Definition Tool (ArcSWAT interface) was used to clip the land-use layer to the catchment boundary and to reclassify the land-use layer to match the attributes contained in the SWAT database. The resulting landcover layer indicates the significance of timber and sugarcane in U20G, and shows the degree to which they encroach into wetlands and their 20 m buffer (Table 1).

Specific SWAT input parameters were obtained for the key vegetation types in this area (Scott-Shaw, 2018, Table 2). The *Eucalyptus*, wattle and sugarcane parameters were modified to match species and hybrids grown in KwaZulu-Natal. New parameters for 'Wattle in Wetlands', 'Eucalyptus in Wetlands' and

'Sugarcane in Wetlands' were generated. From a land management perspective, it is important to determine which areas should be recognised as priority areas for management changes (i.e. changes in future planting areas). These are areas that provide the greatest hydrological benefit due to their current level of encroachment and location in the catchment. To identify these areas, three scenarios were applied:

1. Current/baseline state defined by the latest landcover intersected with detailed timber, sugar and wetlands outlines (including probable wetlands encroached by commercial forestry and sugarcane).
2. Baseline landcover with all encroached or invaded wetlands rehabilitated to a natural state (either hygrophilous/sedge dominated or riparian forest without management).
3. Baseline landcover with all encroached or invaded wetlands rehabilitated to a natural state and a 20 m buffer applied to the wetland edge. The buffer was delineated as a natural grassland (excluding natural forest areas).

Table 1. Areas of commercial forestry and sugarcane summarised for U20G and its contributing quaternary catchments, including the area planted into wetlands and their 20 m buffers

Quaternary catchment (QC)	River system	Commercial forestry (ha)	Sugarcane (ha)	Commercial forestry within wetlands (ha)	Sugarcane within wetlands (ha)
U20G	uMngeni and Mkhabela	3 305	11 794	497	438
U20A, U20B, U20C, U20D, U20E, U20F	Upper uMngeni	80 280	31 550	7 490	360

Table 2. Summary of modified land-use parameters used for the SWAT model

Parameter description	Crop code	Units	Modified land-use									
			Indigenous riparian forest		Sugarcane (*S. officinarum*)		Pine (*Pinus elliottii*)		Gum (*Eucalyptus grandis*)		Wattle (*Acacia mearnsii*)	
			Initial	Parameterized	Initial	Parameterized	Initial	Parameterized	Initial	Parameterized	Initial	Parameterized
Radiation-use efficiency	BIO_E	MJ·m^{-2}	15	15	25	27	15	15	15	15	15	15
Maximum potential LAI	BLAI	m^2·m^{-2}	4.5	4.5	6	6	5	5	5	4.2	5	4.5
Fraction of growing season leaf decline	DLAI	m^2·m^{-2}	0.6	0.4	0.75	0.9	0.6	0.99	0.6	0.99	0.6	0.99
Maximum canopy height	CHTMX	m	20	20	3	3	24	24	26	26	22	22
Maximum root depth	RDMX	m	3.5	3.5	2	3	3.5	3.5	3.5	3.5	3.5	3.5
Optimal temperature for plant growth	T_OPT	C	25	25	25	25	30	30	30	30	30	30
Minimum temperature for plant growth	T_BASE	C	5	5	11	11	0	0	0	0	0	0
Lower harvest index	WSYF	kg·ha^{-1}	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Maximum stomatal conductance	GSI	m·s^{-1}	0.0004	0.0004	0.005	0.006	0.01	0.012	0.012	0.015	0.002	0.013
Vpd on stomatal conductance curve	VPDFR	kPa	1	1	4	4	1	1.6	1	1.6	1	1.6
Fraction of maximum stomatal conductance	FRGMAX	Frac	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Decline in radiation-use efficiency	WAVP	g·MJ^{-1}·kPa^{-1}	8	8.5	10	10	8	8.5	8	8.5	8	8.5
Elevated CO_2 efficiency	CO2HI	uL CO_2·L^{-1}	660	660	660	660	660	660	660	660	660	660
Plant uptake compensation factor	EPCO	N/A	1	0.2	1	0.8	1	0.2	1	0.2	1	0.2
Soil evaporation compensation factor	ESCO	N/A	0.01	0.9	0.01	0.05	0.01	0.9	0.01	0.9	0.01	0.9
Minimum LAI during dormancy	ALAI_MIN	m^2·m^{-2}	1.4	1.4	0	0	2.8	2.8	2.6	2.6	2.8	2.8
Years until full development	MAT_YRS	Years	30	30	0	0	30	30	30	30	30	30
Management schedule	OpSchedule	N/A	FRSD	FRSD	SUGC	SUGC	FRSE	FRSE	FRSE	FRSE	FRSE	FRSE
Initial SCS runoff curve number (ii)	CN2	N/A	80	50	75	40	60	38	60	35	60	38
Groundwater 'revap' coefficient	GWREVAP	N/A	0.2	0.05	0.2	0.2	0.8	0.05	0.8	0.02	0.8	0.05

Note: Detailed information on hybrids was not available and, as such, these input parameters represent the typical physical attributes for each commercial species. More information on the operation schedule can be found under the 'management' section.

Soil physical and chemical properties

No SWAT soil database currently exists in South Africa. As such, soils information was taken from existing sites within the catchment boundary (described by Le Roux et al., 2015 – Hydrology of South African Soils and Hillslopes) and extrapolated, where possible, using terrain models. Some soil attribute data were obtained from ongoing research projects in the region. The structure, depth, number of layers and texture were used to construct a detailed soil layer with up to five variable soil horizons. Where available, the South African Soil Classification system (Soil Classification Working Group, 1991) and the soil hydrologic group (NRCS, 1996) were used to determine the soil form and family and to estimate the key physical and chemical soil properties for the typical soil forms required by SWAT (Table 3). Additional soils data were used to create a more comprehensive soil database, and are not included in Table 3. The use of the Soil-Landscape Estimation and Evaluation Program (SLEEP) was considered but not utilised, as a suitable soil layer was manually derived.

Climate

SWAT weather data definitions were modified to include data from five climate stations in U20G, all of which had daily rainfall records. However, only two had daily temperature, relative humidity, solar radiation and wind speed records. The climate period (from July 1971 to December 2018) accounted for wet, dry and average climate years. The averaged monthly data can be seen in Fig. 3.

Table 3. Physical and chemical soil properties for typical soils in U20G (Van Tol, 2014) adapted for the parameters required by SWAT

| Soil parameters	Avalon (Av)		Westleigh (We)		Cartref (Cf)		Hutton (Hu)	
	A1	B1	A1	B1	A1	B1	A1	B1
Organic matter (OM) (%)	1.20	0.67	1.55	0.86	1.03	0.52	1.2	0.86
Bulk density (BD) (g/cc)	1.65	1.65	1.64	1.65	1.52	1.66	1.4	1.5
Base saturation (BSAT) (%)	62	83	37	50	68	61	36	24
pH (PH)	4.5	5.83	5.0	5.2	5.3	5.6	4.4	5.1
Clay content (CL) (%)	11	18.67	21	23	9.7	17	42.1	54
Silt content (SLT) (%)	22.7	24.29	28.7	30.2	30.1	32.9	27.7	21.1
Nutrient parameters (kg·ha⁻¹)	A1	B1	A1	B1	A1	B1	A1	B1
Stable N (STN)	1 100.3	653.08	1 437.8	492.5	1 191.1	559.1	3 826.9	582
Active N (ACN)	529.4	234.60	650.1	329.9	461.1	160.5	703.1	239.9
Stable P (STP)	717.8	180.37	175.78	170.44	201.7	190.42	256.84	165.49
Active P (ACP)	179.45	45.09	43.95	42.61	50.4	47.6	64.21	41.37
Organic humus P (OHP)	1 042.3	1 040.67	905.2	1041.3	1 571.9	1 740.8	822.9	1 076.1
Ammonium-N (AMMN)	3.3	3.3	2.9	3.3	3.34	3.3	2.6	3.4
Nitrate-N (NITN)	16.5	16.43	14.3	16.45	24.8	27.5	13	17
Labile P (LABP)	35.18	15.50	10.21	9.79	16	12.3	8.38	10.66
Residual biomass (PLBMAS)	9 595	9 595	9 595	9 595	9 595	9 595	9 595	9 595
Fresh organic N (PLRSN)	37	37	37	37	37	37	37	37
Fresh organic P (PLRSP)	10	10	10	10	10	10	10	10
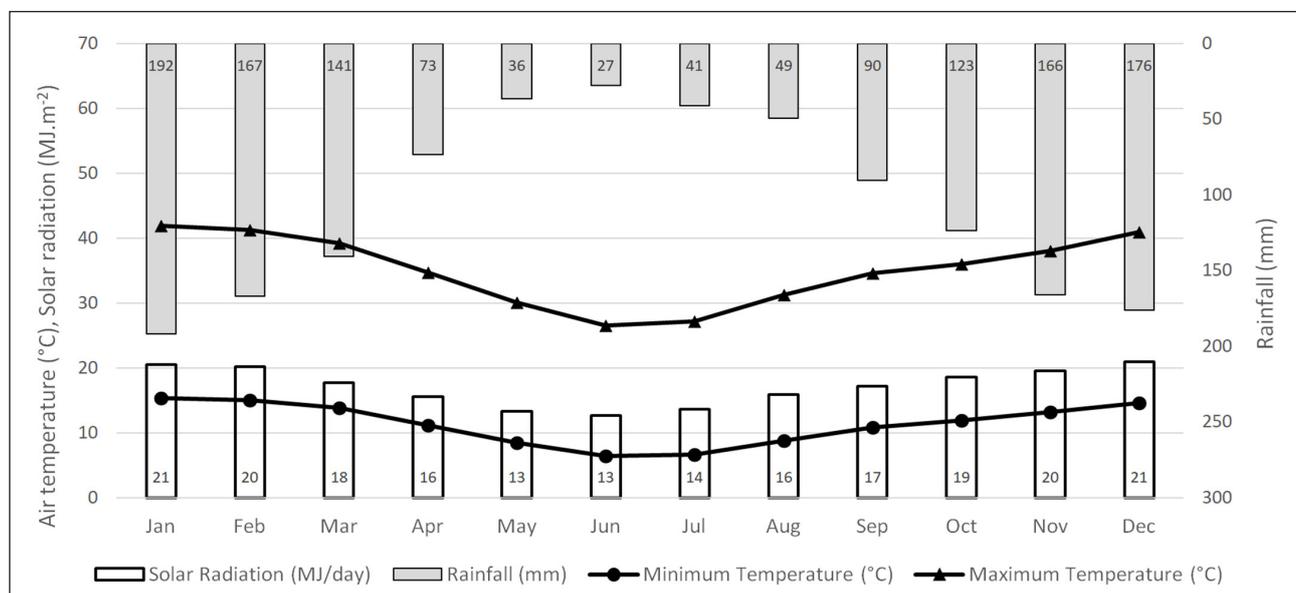
Figure 3. Long-term (47 years) averaged monthly rainfall, temperature and solar radiation near Nagel Dam

Management

Within a land-use type, management is crucial for hydrological simulations as it has a significant impact on the hydrological partitions of the lands. SWAT allows for the adoption of management operations through potential heat units (PHU) or through fixed dates of specific operations. The management operations were modified in SWAT at an HRU level to specify the initial growing state and periods during harvest, fallow lands and planting. Local management practices were accounted for where information could be obtained. Depending on the vegetation type, a management period was applied allowing for the complete removal of the vegetation at specified intervals. A 10-year rotation was applied for *Eucalyptus* and *Acacia* species, while a 15-year rotation was applied for pulp *Pinus* species. The planting operation was distributed according to satellite observations following periods where significant areas were clearfelled. However, fixed 'kill' and 'plant' dates do not adequately represent evergreen species as the LAI decline is linear towards zero, rather than sigmoidal towards the LAI_{MIN} (Strauch and Volk, 2013). Although considered in this study, a process-based soil moisture approach (modified plant growth module – Strauch and Volk, 2013) was not used but is recommended for future studies.

Within the management routine of the model, for rainfed sugarcane in KwaZulu-Natal, the land use was ratooned up to a maximum of 6 times, taking approximately 10 to 12 years. During the replanting period, tillage was initiated in the form of a deep disk and rip. Further information can be obtained from Abdalla et al. (2019).

Model calibration and validation

It is commonly accepted that deterministic calibration approaches are outdated and fundamentally flawed (Abbaspour et al., 2015). On the contrary, stochastic calibration approaches recognize the errors and uncertainties in our models and attempt to capture, to some degree, the lack of understanding of the processes in natural systems (Abbaspour et al., 2015). However, as SWAT input parameters are process-based, they must be held within a realistic uncertainty range during the calibration process (Arnold et al., 2015). Automatic calibration may lead to substantial errors if limitations exist in measured data, there is a lack of knowledge on physical processes and operational procedures, and there is uncertainty on mathematical equations and model sensitivity (Moriasi et al., 2007). Thus stricter performance ratings should

be adopted during model calibration than during validation, with the inclusion of uncertainty analysis (Moriasi et al., 2007).

In sequential uncertainty fitting (SUFI-2), uncertainty in parameters, expressed as ranges (uniform distributions), accounts for all sources of uncertainty, such as in driving input variables (e.g., rainfall), conceptual model, parameters, and measured data (Abbaspour et al., 2015). SWAT-CUP was run using observed streamflow data extracted for the outlet of the catchment using verified data obtained from the Department of Water and Sanitation. A total of 300 simulations were performed with the relative parameters activated. Model sensitivity is defined as the change in model output per unit change in parameter input (Tesfahunegn et al., 2012). After pre-processing of the required input for the SWAT model, monthly flow simulations were performed for 46 years of recording periods (1972 to 2018). Three years were used as a 'warm-up' period, following which the simulation was used for a sensitivity analysis of hydrologic parameters and calibration of the model. The sensitivity analysis was performed using the standalone SWAT-CUP sensitivity analysis tool that uses the Latin hypercube one-factor-at-a-time sampling (LH-OAT).

A validation period for a higher rainfall catchment with intensive commercial forestry was selected. The model (using parameterized inputs) was used to simulate QC U40A (Mistley catchment) over a 31-year period (1985 to 2018). This catchment was selected as it is relatively close to QC U20G, has good quality observed streamflow data and is an isolated catchment, limiting the uncertainty present where upstream catchments exist.

RESULTS AND DISCUSSION

Sensitivity analysis

Results from the sensitivity analysis using SWAT-CUP allowed for the mean relative sensitivity of each input parameter to be determined and ranked (Table 4). The ranking was determined from the resultant *P*-value (significance of the sensitivity where the parameter becomes significant if the *P*-values are close to zero). The SCS runoff curve number (CN2) and maximum canopy storage (CANMX) were the most sensitive parameters. The authors took consideration where fitted values were produced which were outside of realistic known bounds to ensure that unrealistic input values were not used. The fitted value indicates the best value of the objective function for the simulation with the best fit. A minimum and maximum value range was used when parameterizing the model, where relevant.

Table 4. Sensitivity analysis of the SWAT input

Parameter	Description	Result		
		Method	Rank	Fitted value/range
CN2.mgt	SCS runoff curve number	Relative (r_)	1	0.172–0.51
CANMX.hru	Maximum canopy storage (mm)	Absolute (a_)	2	12.5
GW_DELAY.gw	Groundwater delay (days)	Replace (v_)	3	0–412
RCHRG_DP.gw	Deep aquifer percolation fraction	Replace (v_)	4	0.38
SOL_AWC.sol	Available water capacity of the soil layer (mm H$_2$O/mm soil)	Relative (r_)	5	0.38
ALPHA_BF.gw	Baseflow alpha factor (days)	Replace (v_)	6	0.39–1.1
GW_REVAP.gw	Groundwater 'revap' coefficient	Relative (r_)	7	0.67
EPCO.bsn	Plant uptake compensation factor	Replace (v_)	8	0.2
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	Absolute (a_)	9	0.83
ESCO.bsn	Soil evaporation compensation factor	Replace (v_)	10	0.9
REVAPMN.gw	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)	Absolute (a_)	11	40.7

Model calibration

Although the pre-calibration results provided a reasonable fit with the observed data, the model generally over-simulated streamflow. Possible causes include: inaccurate spatially distributed climate data, under-estimation of abstraction for irrigation or, more likely, incorrect input parameters (particularly for lesser studied land types). The post-calibration simulated monthly flow had a close fit to the observed flow (Fig. 4) with a regression coefficient (r^2) of 0.87 and a Nash-Sutcliffe (NS) coefficient of 0.8. The model uncertainty was predicted using the computed percent prediction uncertainty (95 PPU) and dotty plots for each parameter (plots of parameter values or relative changes versus objective function).

Model validation

Observed streamflow was obtained from U4H002 at the Mistley station, representing QC U40A. The model simulated monthly volumes well with a r^2 of 0.67, Nash-Sutcliffe of 0.8 and a root mean square error (RMSE) of 0.70 (Fig. 5). The p-factor (percentage of observations covered by the 95 PPU) was 67% and the r-factor (average thickness of the 95PPU band divided by the standard deviation of the measured data) was 0.59, indicating an acceptable goodness of fit.

Low flows were well simulated in this catchment. However, some peak events were over-simulated. Through further investigation, it is likely that the large wetland situated above the outlet of the catchment attenuates these peak flows in reality and is not accommodated for in this model simulation. Although wetlands were included as a land use, the detailed functioning of this wetland was not included, which would release water when the volume exceeds the storage of the wetland. Thus, if the wetland were not at full capacity, flows would be attenuated, much like it would in a pond or reservoir. However, it does illustrate that the output volumes from the model are realistic and could be applied to similar catchments within KwaZulu-Natal. The inclusion of significant wetland areas is recommended for future modelling studies.
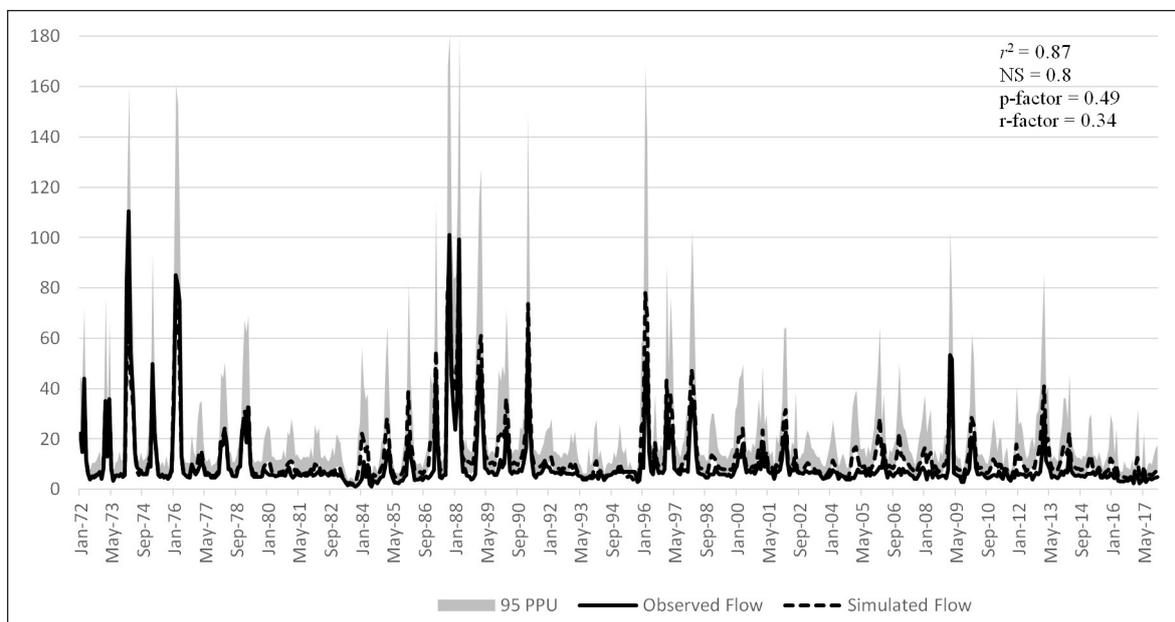

Figure 4. Comparison between observed and post-calibration simulated streamflow for QC U20G from January 1972 to November 2017
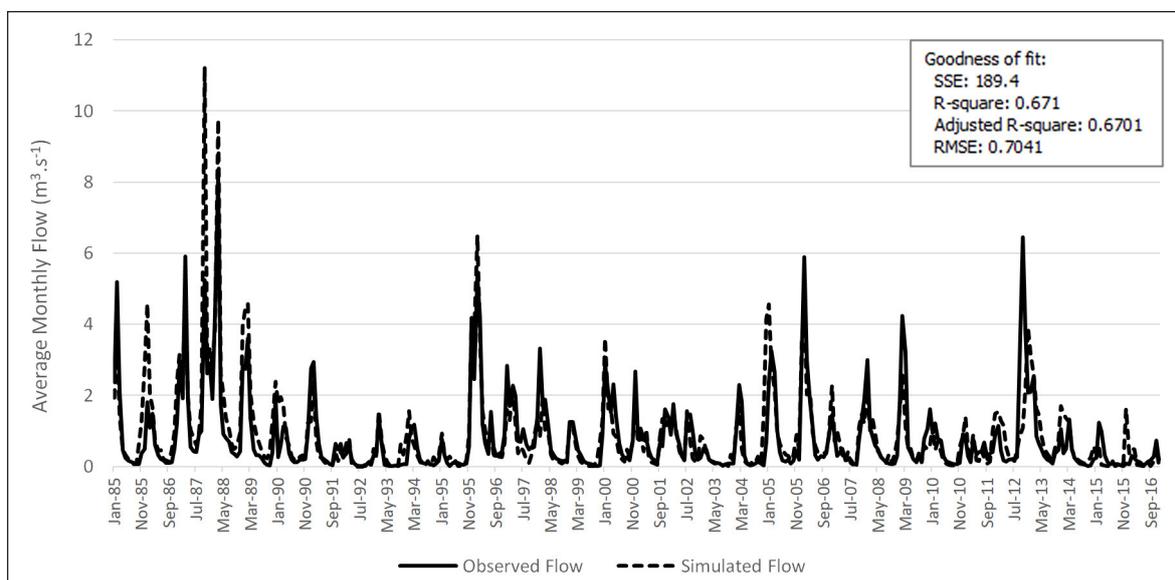

Figure 5. Comparison between observed and parameterized streamflow at the outlet of QC U40A

Model application

The calibrated model was simulated for a larger catchment area comprising of seven QCs. The results show that if wetlands and a 20 m buffer were to be returned to a natural state, as much as a 16% increase in streamflow could be gained (with an upper limit of 60% streamflow contribution per HRU). This is a significant increase and highlights key priority areas that not only are heavily encroached by commercial forestry or sugarcane, but are important water generating areas.

The water yield output is defined as the total amount of water leaving the HRU and contributing to the main channel for the given time step. The model clearly shows that water yield is not uniform across the study area (Fig. 6) but is rather correlated to bio-climatic variations. Of widest applicability is the relationship between land-use and water yield, with greatest yields over areas of natural grassland. The impact of land-use can be clearly seen throughout the upper uMngeni (particularly in QC U20F) where the plantation and sugarcane areas have a low water yield compared to the surrounding natural land.

Evapotranspiration (ET) is an important component as it comprises almost half of the water balance in most catchments in the area and is the primary determinant of streamflow reduction. ET, throughout the study area, is highly variable and dependent on the landcover input (Fig. 6). Water bodies, wetlands, plantations and sugarcane use the highest amount of water. The ET is further increased in wetlands and riparian areas where encroachment by timber and sugarcane has occurred. In addition to ET, commercial forestry and sugarcane can significantly impact upon the groundwater component. This is accounted for in SWAT through the 'revap' coefficient, where water may move from the shallow aquifer into the overlying unsaturated zone, allowing deep-rooted plants to be able to take up water directly (Neitsch et al., 2011). Areas of low recharge can correspond to soils with higher clay contents and vegetation with a high biomass and deep rooting systems. Areas of higher rainfall have a greater recharge to the shallow and deep aquifers whereas areas of low rainfall, coupled with geology and soils that do not promote infiltration, have a low recharge (Fig. 6).

The results highlight the spatial variability in response to clearing scenarios, at scales ranging from farm units to quaternary catchments, when compared to a historic baseline time period. Clearly there are priority areas where the costs of removing timber and/or sugarcane and rehabilitating the natural vegetation are more likely to have a greater return on investment. The importance of these spatial outputs is the relative difference between scenarios which could indicate key areas for clearing at a very fine scale. There is also potential for climate scenarios to be considered, ranging from simple temperature and rainfall corrections to more complex climate models and vegetation parameter modifications.

Priority areas were identified by converting the water yield output from each scenario to a high-resolution raster grid (5 x 5 m) calculating the difference in water yield between the different scenarios. The distribution of priority areas (where the % increase between scenarios is > 50%) is spatially highly uneven, suggesting that there are distinct areas where it would be beneficial to enact the scenarios (Fig. 7).
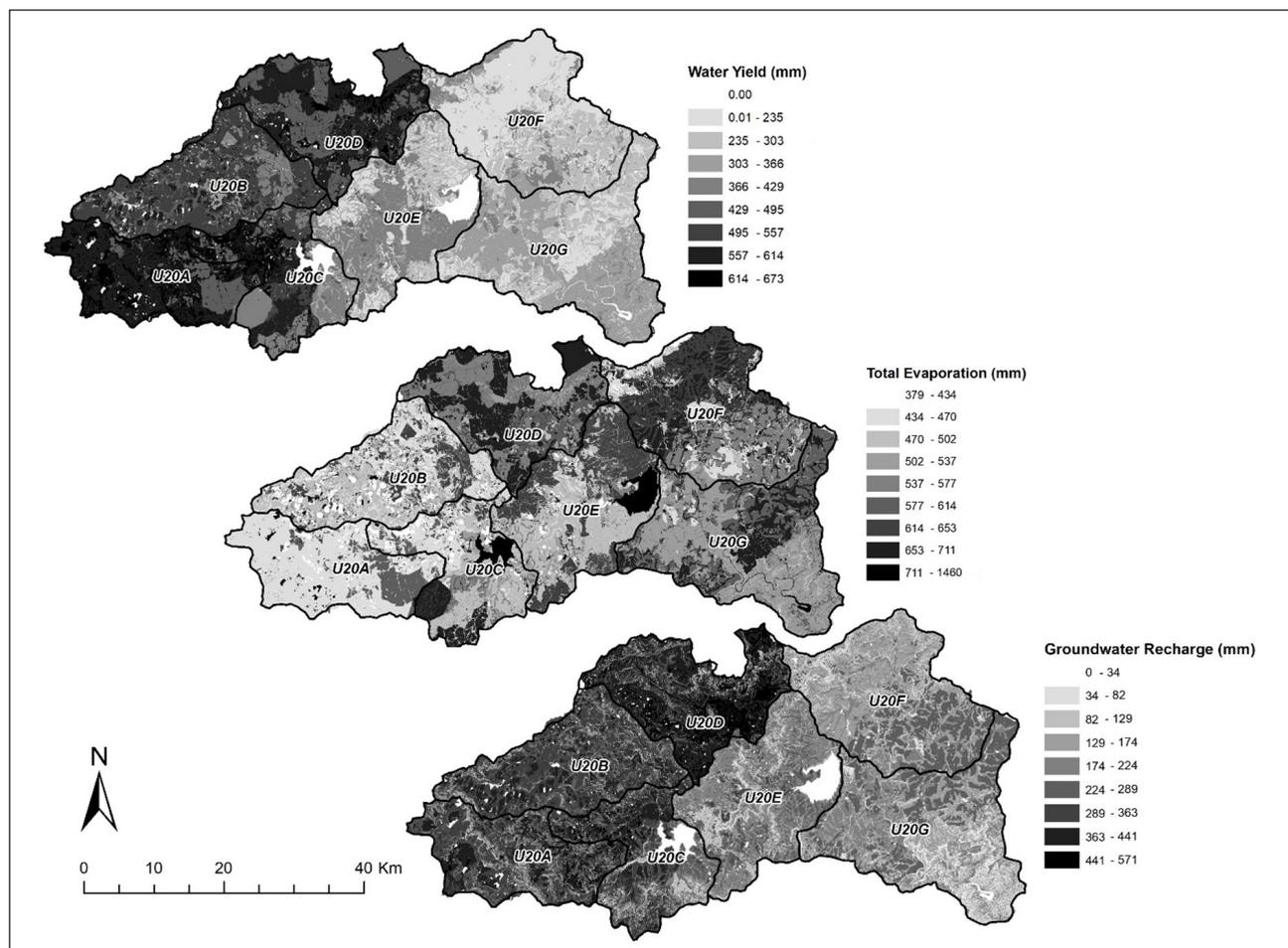

Figure 6. Average annual water yield, total evaporation (ET) and groundwater recharge distribution throughout the greater study area for the baseline state
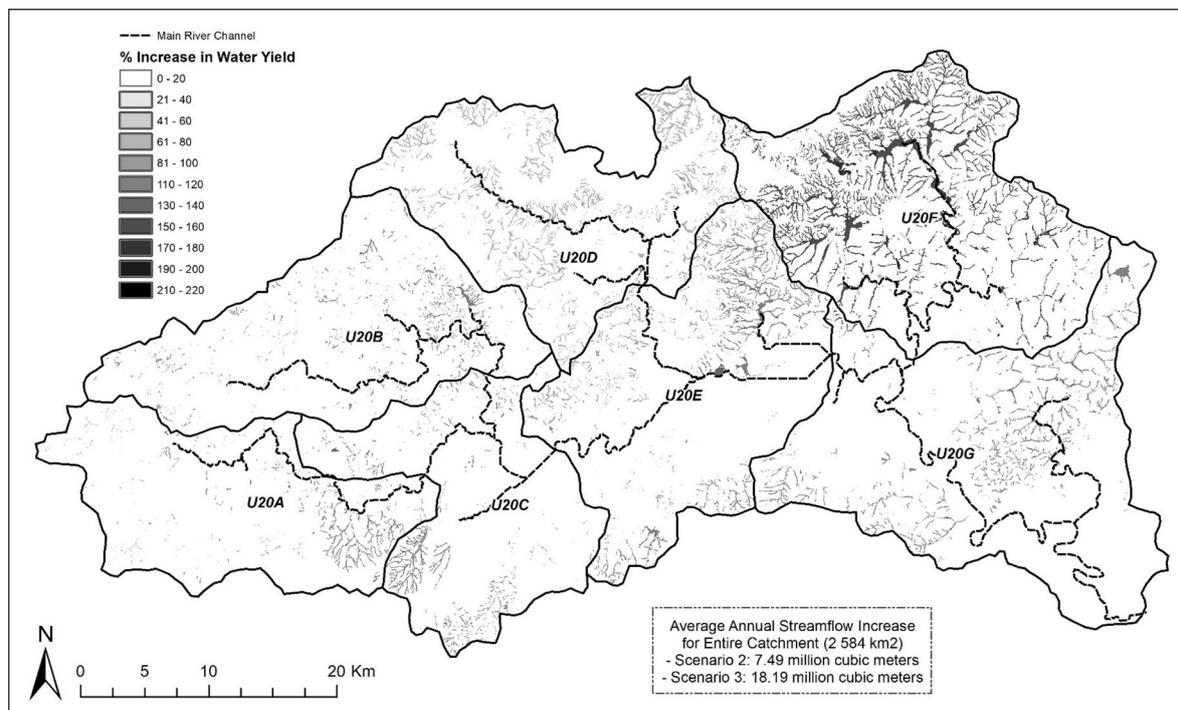
Figure 7. Priority areas indicated by the percentage increase between the baseline and cleared state for the upper uMngeni (U20A, U20B, U20C, U20D, U20E, U20F and U20G)

CONCLUSION

The overall objective of the study was to calibrate the SWAT model for a well-researched and data-rich catchment in KwaZulu-Natal, with the aim of comparing hydrological gains due to the removal of exotic commercial species from wetlands and surrounding buffer areas. Previous modelling studies in this area have not captured the spatial complexity that exists in these catchments, where there are significant hydrological differences throughout each catchment. In addition, studies have not considered the existing high water-use of wetland and riparian systems. This study has modelled, calibrated and validated a highly complex catchment system using the SWAT model. The SWAT-CUP parameter sensitivity and optimization model (Abbaspour, 2015) was tested with monthly observed streamflow data. Parameters were modified using the SUFI-2 analysis routine to calibrate the model. This study has allowed for the calibration and validation of the SWAT model and the subsequent application of the model to a broader study area comprising of 17 QCs. The model calibration showed that with slight adjustment to sensitive input parameters, while keeping within realistic bounds, a strong correlation could be obtained between simulated and observed streamflow. The simulation was within the upper- and lower percent prediction uncertainty bounds. However, 49% of the observations were within the uncertainty band (p-factor of 0.49) and the r-factor (average thickness of the uncertainty band divided by standard deviation of observed data) was 0.36. This suggests that the model uncertainty is within an acceptable range, although there is potential for improvement by increasing the number of iterations and including additional observations of additional parameters. Thus one potential direction for future research is to extend the scale (catchment level), undertake similar modelling exercises for neighbouring and/or paired catchments and increase diversity of land-use types and management practices, to increase the regional-specific variables and diversity. This will provide us with greater confidence in model output at the regional scale and begin to allow comparison between biophysical characteristics and land-use practices between catchments and crops.

The spatial distribution of total evaporation (ET), water yield and groundwater recharge provide a valuable output for scenario testing. This study went beyond determining an area-weighted increase due to clearing, as it allowed for a soil-, slope- and climate-specific simulation for each land unit. The changes in hydrological partitions were output based on landcover, climate, soils and the proximity of the landcover to wetlands. This allowed for a highly detailed output of the spatial distribution of the hydrological partitions.

The results show that the SWAT model is a suitable model to be used for a range of land uses and soil types in KwaZulu-Natal. The calibration, which allowed for 200 behavioural simulations, resulted in the percentage of data bracketed by the 95% prediction uncertainty (95PPU) being 0.49 (p-factor of 0.49 and r-factor of 0.36). The regression coefficient (r^2) was 0.87 with a Nash-Sutcliffe (NS) coefficient of 0.8, indicating a good fit and confidence in the input parameters used. The model, using newly derived calibrated input values, was run for a time period beyond the calibration period. In addition, a nearby catchment was simulated and compared with observed flow data. Much like the calibration period, the model provided a close fit to the observed data, allowing for the model to be validated. The model, through a scenario comparison, allowed for the compilation of annual water balances, time-series data and spatially explicit data that were linked back to the derived GIS data to provide a useful spatial priority-benefit product. Some of the cleared hydrological response units had an increase of streamflow contribution exceeding 60%. Within the greater catchment area (including upstream cleared catchments), an average annual increase of 18.2 million cubic meters was observed under the cleared scenario. This was as a result of 152 km² of commercial forestry and 26.8 km² of sugarcane being cleared from the wetland and the surrounding 20 m buffer.

The management component in SWAT is detailed and suitable for catchments in KwaZulu-Natal that are afforested and cultivated with sugarcane. If this model were to be calibrated for additional spatially variable catchment areas, the model could be adopted for

a broad range of applications in South Africa. However, a major limitation is the lack of SWAT-ready input data, such as soils, land use and climate. Although climate change projections have not been considered in this study, the methods displayed, and the subsequent results, provide a suitable platform for the application and testing of likely climatic extremes.

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