Modelling Groundwater Recharge in a Semi-arid River Basin: A Retrospective Assessment

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***Abstract*— Groundwater constitutes an essential resource that augments surface water resources in meeting the water supply needs of man and the ecosystem. Most importantly in arid and semi-arid environments where rainfall patterns are erratic, groundwater resources are often the preferred source of water. This causes enormous pressure on the resource leading to diminishing groundwater resources. Land use changes also impact on groundwater resources through alterations in the hydrologic regime. It is imperative therefore to evaluate groundwater recharge dynamics under changing land uses to provide for a better resource planning and allocation. We present in this study, an investigation into groundwater recharge dynamics of the Olifants Basin, a water stressed basin in Southern Africa over the past decade with considerations to land use changes. Three land use change scenarios were developed to simulate the groundwater recharge of the basin within the Soil and Water Assessment Tool (SWAT) environment. The SWAT model was calibrated (1988-2001) and validated (2002-2013) with good model performance statistics; NSE, R^2, PBIAS, RSR of 0.88, 0.89, -11.49%, 0.34 and 0.67, 0.78, -20.69%, 0.57 respectively for calibration and validation stages. Results indicate groundwater recharge declined by 30.3% (10.37 mm) and 37.2% (12.71 mm) during the periods 2000 -2007 and 2007-2013 respectively. The decline in groundwater recharge was linked to the changes in urban (9.2%), agriculture (6.1%), rangelands (-16.8%) during the period 2000-2007 and urban (1.3%), agricultural (14%), rangelands (-14.8%) during 2007-2013. The SWAT model reveals it capabilities as a decision support tool (DST) in groundwater recharge assessment.**

***Keywords*— Groundwater recharge, land use, Olifants Basin, SWAT.**

I. INTRODUCTION

In arid and semi-arid regions of the world, groundwater serves as an essential alternative to surface water resources for water supply purposes. It plays a significant role in meeting the water demands of man and the ecosystem and is perceived as the panacea to the looming water scarcity scare [1]. This is reflective on its dependency for the supply of 43% of irrigation water, 36 % of potable water and 24% of industrial water globally [2]. At the current rate of abstraction, the sustainability of groundwater resources is questioned on the basis of its overexploitation [3] which is further worsened by land use/land cover (LULC) dynamics [4] coupled with the on-going climate change phenomenon. Land use /land cover changes (LULCCs) have widely been acknowledged to alter the hydrologic regime with consequent repercussions on the quantity of overland flow and indirectly affecting the quantum of groundwater recharge [5] – [8]. LULCCs are reported to have far reaching implications on the hydrologic cycle compared to the effects of climate change [9]. Increasing population is identified as a major driver to LULCCs causing a shift in natural vegetation towards more productive uses of land. This has triggered the conversion of the natural cover to arable lands with the focus of expanding the frontiers of dryland and irrigated agriculture in order to meet the ever increasing food demand [10], [11]. The conversion of natural vegetation to agriculture results in the modification of key vegetation parameters that influences recharge [12] and this has the tendency to irreversibly alter aquifer characteristics with replicative effects on groundwater availability [4].

Although there exist substantial evidence of LULCC impacts on the hydrologic cycle, most of these studies have focused on the atmospheric component of the hydrologic cycle leaving much to be desired on subsurface components of the hydrologic cycle and more in particular on groundwater resources [12]. In purview of this limitation, the impacts of LULCCs on groundwater resources need to be investigated with particular emphasis on groundwater recharge. Groundwater recharge defined as the portion of rainfall that reaches the saturated zone, either by direct contact in the riparian zone or by downward percolation through the unsaturated zone [13] is a vital part of the groundwater system that needs to be monitored to provide information of recharge dynamics with oriented focus on long term sustainability strategies for the management of groundwater resources.

The foregone discussions are not farfetched in the case of South Africa. In South Africa, the reliance on groundwater for agricultural, industrial and household water supply cannot be overemphasized [14], [15]. Perhaps, in many rural parts of South Africa groundwater remains the only reliable source of water supply [16]. This is particularly the case due to the semi-arid nature of the country predisposing it to erratic rainfall patterns with high inter-annual variations which tend to affect surface water availability. This has caused over dependency on groundwater resources resulting in their

Manuscript received **Sept. 9, 2015**. (Write the date on which you submitted your paper for review.) This work was supported by Tshwane University of Technology, Pretoria, South Africa.

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overexploitation. In the midst of this quagmire of overexploitation is also the incidence of LULCCs further altering the hydrologic regime and subsequently the recharge process [17]. Awakening to the call for sustainable management of water resources is the need for sustainable strategies to be devised not only for surface water resources but also for the inimitable groundwater resources. A critical approach in ensuring groundwater sustainability in the midst of changing land uses is to understand how LULCCs impact on groundwater recharge in order to provide the requisite knowledge to inform policy direction.

In this paper, we investigate the impacts of LULCC patterns on groundwater recharge through a modelling approach with a semi-distributed hydrologic model. The objective of the study was to investigate the feasibility of using a physically based distributed model to predict the changes that occur in groundwater recharge as a result of LULCCs and to quantify these changes. The approach is a simplistic way of cost effectively assessing groundwater recharge using readily available sources of information.

II. Materials And Methods

A. Description of Study Area and Extent

The Olifants River Basin is located in the northeastern part of South Africa with a total drainage surface area of 74,000 km^2 (Fig.1). With a main stem of 770 km, the Olifants River originates from Trichardt to the east of Johannesburg in the province of Gauteng and then flows in northeasterly direction through the provinces of Mpumalanga and Limpopo crossing the Mozambique border where it finally empties into the Massingir dam. Geographically, the basin lies on longitudes 28.3º E - 31.9º E and latitudes 22.6º S - 26.5º S. For the purposes of this study, the Olifants Basin is herein referred to as the area extending from the upper Olifants to the location of gauge B7H015 (Fig. 1). The selection of the study area extent was solely informed by data availability on existing gauge stations that were required to calibrate and validate the model.

The Olifants River is drained by some major tributaries; on the right bank are Klein Olifant, Steelpoort and Blyde rivers with Wilge, Moses, Elands, Ga-Selati and Letaba on the left bank. Generally, the elevation of the basin ranges from 0 - 2328 meters above mean sea level (masl). Rainfall is erratic occurring during the months of October to April with appreciable spatio-temporal variability [18], [19]. The mean annual precipitation (MAP) is documented by [18] to be 664 mm with peaks in January. Temperatures range from 18 °C - 34 °C in summer and 5°C - 26°C in winter. The basin is characterized by five major soil types namely; cambic arenosols, chromic luvisols, chromic vertisols, orthic acrisols and rhodic ferralsols [20]. The population of the basin is estimated to be slightly over 5 million with a greater proportion being rural populace [21], [22].

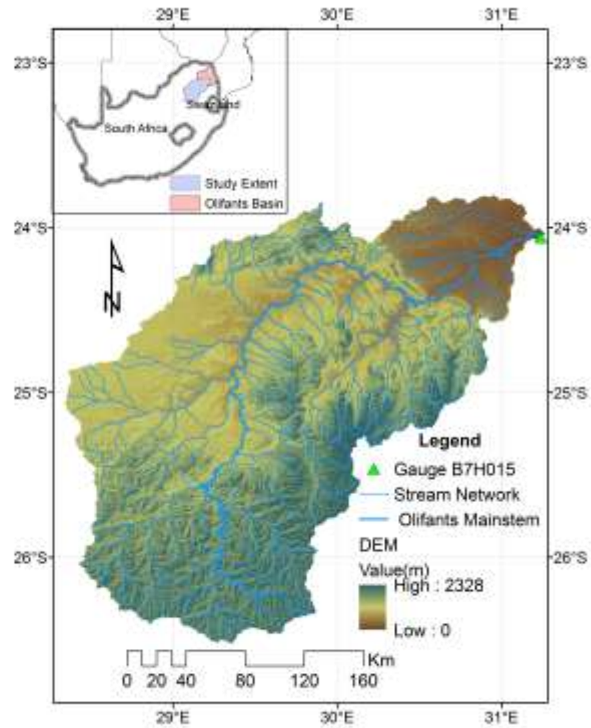

Fig. 1. Location and extent of study area showing gauge station.

B. Hydrological Setting and Groundwater Occurrence

The basin is characterized by four types of aquifers namely; weathered rock aquifer, fractured (structural) aquifer, dolomitic (karst) and the alluvial aquifers. Groundwater in the basin is mostly exploited from the dolomitic and weathered aquifer systems [15], [16]. The weathered aquifer has depth ranges of 5-12 m [23]. Groundwater yields from the weathered aquifer are low with approximately 1 litres/second. Groundwater in fractured aquifers normally occurs in crevices. Fractured aquifers are encountered some few meters from the earth surface to a depth of about 30 m [23]. At depths below 30 m, the crevices tend to close up due to the exertion of weight from the overlying formations. Yields in fractured aquifers are highly variable with high initial yields but tend to decline as a result of continuous abstraction.

Dolomitic aquifers in the Olifants Basin are mainly located in the western foothills of Drakensberg Mountains, Delmas and Marble Hall with yields ranging between 5 – 40 liters/second [16]. Dolomitic aquifers have the highest yields. Similar to dolomitic aquifers, alluvial aquifers have high yields and are located along watercourses with historic floodplains [16]. However for management purposes the Olifants Basin has been classified into three aquifer regions [24] to include major, minor and poor regions (Fig. 2). The major aquifer regions are associated with high yielding aquifer systems with good water quality whiles the minor aquifer regions are noted for moderately yielding aquifer systems. The poor regions have aquifers with low to negligible yielding aquifers.

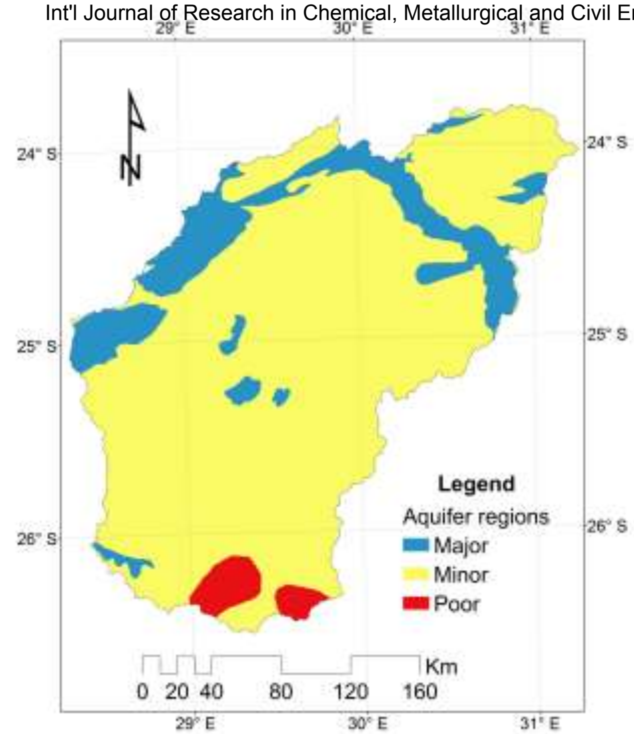

Fig. 2. Aquifer regions in the Olifants Basin.

III. MODELLING APPROACH

A. *Model Selection*

The assessment of LULCC impacts on groundwater recharge was carried out within the Soil and Water Assessment Tool (SWAT) environment. SWAT was developed jointly by United States Department of Agriculture–Agricultural Research Services (USDA–ARS) and Agricultural Experiment Station in Temple, Texas as a continuous, long-term, physically based distributed model suitable for the simulation of land use impacts on water, agricultural pollutants and sediment in large complex watersheds [25], [26]. Due to the model's versatility, it has been employed by many in diverse areas of land and water resources studies [27] – [30]. A comparison of SWAT with other hydrologic models revealed a higher success rate in SWAT [31] – [33]. The basic operational unit of the model is the hydrologic response unit (HRUs) which consist of an area of homogenous land use, management and soil characteristics. The HRUs are nested within sub-basins and hence simulations are aggregated at the HRUs and then unto the sub-basins. The model simulates the major components of the hydrologic cycle (surface runoff, evapotranspiration, percolation, lateral flow, return flow, transmission losses and ponds) base on the water balance equation represented in [26] as;

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

Where; SW_t is final soil water content (mm), SW_o is initial soil water content in day i (mm), t is time in days, R_{day} is amount of precipitation in day i (mm), Q_{surf} is amount of surface runoff in day i (mm), E_a is amount of evapotranspiration in day i (mm), W_{seep} is amount of water entering the vadose zone from the soil profile in day i (mm) and Q_{gw} is amount of return flow in day i (mm).

B. *Surface Runoff and Evapotranspiration Estimation*

Surface runoff $\left(Q_{surf}\right)$ which refers to overland flow of excess water after infiltration and depression storages are fulfilled was estimated using a modification of the SCS-CN method [34]. The SCS-CN method is a function of antecedent moisture conditions, infiltration, soil type, land cover and other basin characteristics such as topography. The SCS-CN method as used in this study is defined as [34];

$$Q_{surf} = \left\{ \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)}, R_{day} > 0.2S \right. \qquad (2)$$

Where; Q_{surf} is rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm).

The retention parameter S is influenced by the changes that occur in land uses, soil water content and slopes and as result varies spatially across a watershed. The retention parameter was estimated as;

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (3)$$

Where; S is retention parameter (mm) and CN is the curve number. CN is a function of soil permeability, antecedent soil conditions and land use. CN can be read from tables available in the literature by combining soil type and land use of a particular watershed.

Evapotranspiration which refers to water losses through evaporation and transpiration were accounted for using the Penman-Monteith method given as;

$$ET = \frac{0.408\Delta(R_n - G_o) + \gamma \frac{900}{T + 273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (4)$$

Where; ET is the reference evapotranspiration (mm d^{-1}), Δ is the slope of the saturation vapour pressure temperature curve (kPa $^{o}C^{-1}$), R_n is the net radiation (MJ m^{-2} d^{-1}), G_o is the soil heat flux density (MJ m^{-2} d^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), γ is the psychrometric constant (kPa $^{o}C^{-1}$), $e_s - e_a$ is saturation vapour pressure deficit (kPa), u_2 is wind speed (ms^{-1}), mean daily temperature (°C).

C. *Groundwater Recharge Estimation*

Groundwater resources are replenished through the downward movement of water by percolation and further through the vadose zone to recharge aquifers. The amount of recharge that occurs is dependent on the hydraulic properties of existing geologic formations in the vadose zone and the water table [35]. In estimating the recharge, the exponential decay function proposed by [36] was used. The exponential function is formulated as;

$$W_{rchrg,i} = \left\{ W_{seep} \cdot \left(1 - \exp\left[\frac{-1}{\delta_{gw}} \right] \right) + W_{rchrg,i-1} \cdot \exp\left[\frac{-1}{\delta_{gw}} \right] \right\} \quad (5$$

Where; $W_{rchrg,i}$ is the amount of recharge entering the aquifers on day i (mm), δ_{gw} is the delay time or drainage time of the overlying geologic formations (days), W_{seep} is the total amount of water exiting the bottom of the soil profile on day i (mm) and $W_{rchrg,i-1}$ is the amount of recharge entering the aquifers on day i-1(mm).

D. Input Datasets and Sources

Required data for the model setup were digital elevation model (DEM), digital soil, data digital land use maps and climatic datasets (Fig. 3). The DEM was acquired from the global land cover facility database (GLCF) and is of spatial resolution 90 m x 90 m (3 arc sec). The DEM was used for basin discretization and extraction of geomorphologic characteristics such as width, depth, length of streams and slopes. Slopes discretization for the study area followed FAO classification scheme [37] to include; level to gently undulating (< 8%), rolling to hilly (8 - 30%) and steeply dissected to mountainous (>30%). Soil data and information on related soil properties were obtained from FAO soil map [20]. This data was augmented with information from field sampled soils. The extracted FAO soil data for the study area shows that the Olifants Basin is underlain by five major soil types namely; chromic luvisols (Lc) (38.81%), cambic arenosols (Qc) (33.03%), chromic vertisols (Vc) (21.21%), orthic acrisols (Ao) (5.77%) and rhodic ferralsols (Fr) (1.18%).

LULC data for three epochs (2000, 2007 and 2013) was obtained through a supervised land use classification of Landsat 7 ETM+ images. The images are of spatial resolution 30 m and were acquired for Path/Row; 168/077, 169/077, 169/078, 170/077 and 170/078. The images were classified into five-level 1 classes based on the land cover and land use classification system developed by [38] for the interpretation of remote sensor data at various scales and resolutions. Climatic data consisted of daily rainfall, maximum and minimum temperatures and wind speed at thirteen weather stations acquired from the South African Weather Service (SAWS) for 1980 – 2013. The climatic dataset was augmented with data from the climate forecast system reanalysis (CFSR) database.

E. Calibration and Validation Analysis

The model was calibrated (01/01/1988 - 01/12/2001) and validated (01/01/2002 - 01/12/2013) using monthly stream flow data from gauge station B7H015. The first 8 years prior to 1988 were used as warm up period to mitigate unknown initial conditions. Sensitive parameters to streamflow with their fitted values were adopted from [39]. The model performance was evaluated using four objective functions commonly used in the assessment of model performance [40] – [42].

- Coefficient of determination (R^2): R^2 is calculated as follows;

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - S_i)(S_i - \bar{S})}{\left(\sum_{i=1}^{n} (O_i - \bar{O})^2 \right)^{0.5} \left(\sum_{i=1}^{n} (S_i - \bar{S})^2 \right)^{0.5}} \right]^2 \quad (6)$$

- Nash-Sutcliffe (NSE): NSE is formulated as;

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \quad (7)$$

- RMSE - observations standard deviation ratio (RSR): RSR is calculated as;

$$RSR = \frac{RMSE}{STD_{obs}} = \frac{\sqrt{\sum_{i=1}^{n} (O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2}} \quad (8)$$

- Percent Bias (PBIAS): PBIAS is calculated as shown;

$$PBIAS = \frac{\sum_{i=1}^{n} (O_i - S_i)}{\sum_{i=1}^{n} O_i} \times 100\% \quad (9)$$

where; O_i is observed variable, S_i is simulated variable, $\bar{O}$ is mean of observed variable, $\bar{S}$ is mean of simulated variable, n is number of observations under consideration, $RMSE$ is root mean square error, STD_{obs} is standard deviation of observed variable.

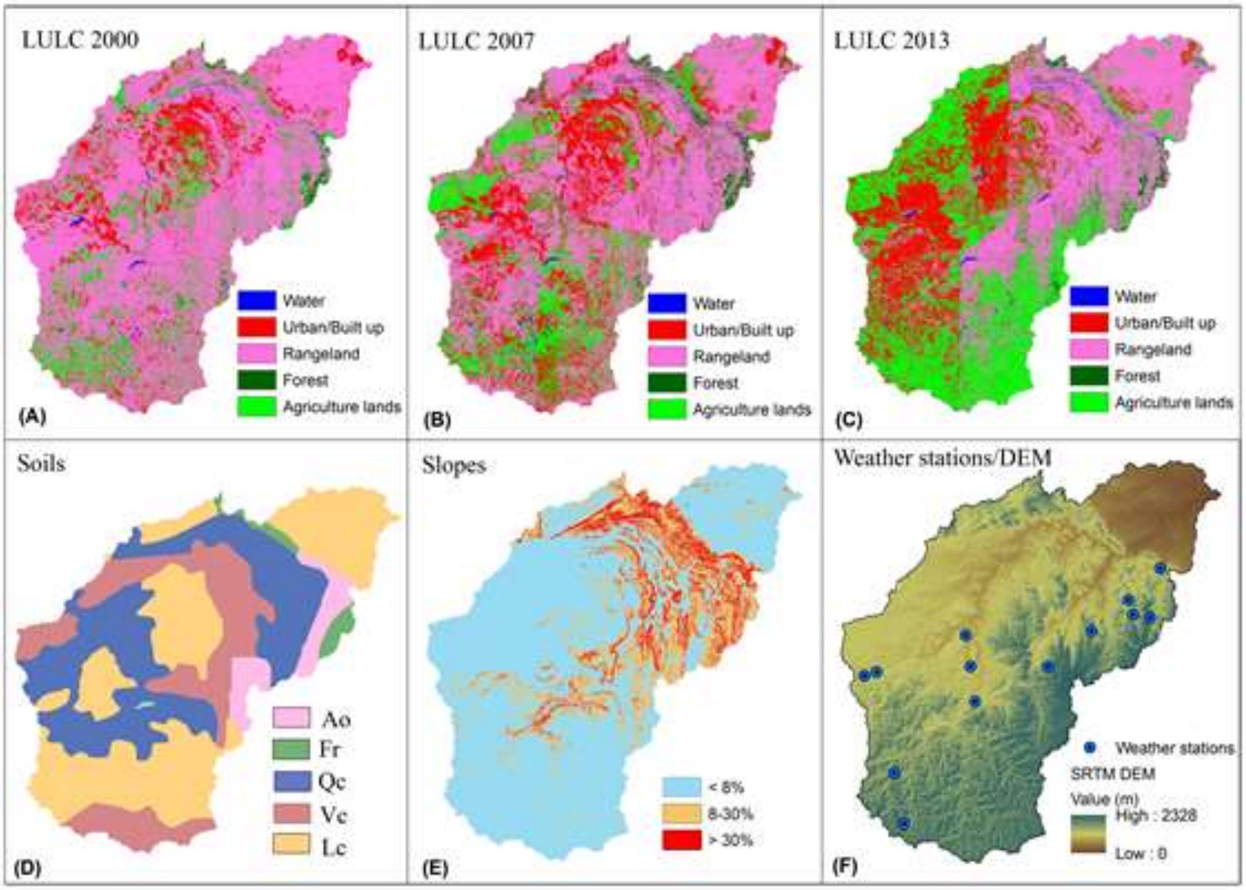

Fig. 3. Spatial model input parameters.

A. *Model Application and Statistical Analysis*

To assess the impacts of LULCCs on groundwater recharge of the Olifants Basin, the “fix-changing” method was used [6], [30], [43] - [45]. With this method, the calibrated model was run for each of the land use maps (2000, 2007 and 2013) whiles keeping constant the DEM, climatological parameters and soil data. Simulated results were further used to evaluate the impact of LULCCs on groundwater recharge. All statistical analyses were carried out in SPSS 20.0 and MS Excel 2010.

IV. Results And Discussion

A. *Land Use Change Detection*

Changes observed in LULC are shown in Fig. 4 for the period 2000 – 2013. All land use classes had undergone some degree of change. However, most significant changes were observed in three land use classes namely; urban areas, agricultural lands and rangelands. Urban and agricultural lands continually increased for all the years under review. Urban area extent of 13.2% in 2000 increased to 22.4% in 2007. Urban areas gradually increased again from 22.4% in 2007 to 23.7% in 2013. Similarly, from 2000 to 2007, agricultural areas increased from 15.2% to 21.3%. Further expansion in agriculture lands were observed, increasing from 21.3% in 2007 to 35.3% in 2013. Unlike agriculture and urban areas, rangeland continually decreased from 69.2% to 52.4% between the periods 2000 to 2007.

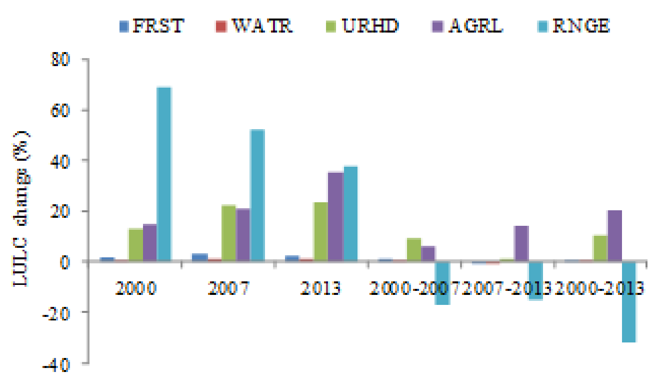

Fig. 4. Land use and land cover change for 2000 – 2013.

By the end of 2013, rangeland had decreased from 52.4% in 2007 to 37.6% making it the land use type to have received most significant reduction for the period under review. The annual rate of change for forest, urban, agriculture and rangeland for 2000 – 2007 were 10.1%, 9.9%, 5.8% and -3.5% respectively.

Similarly during 2007 – 2013, the annual rates of change were -2.8%, 0.9%, 10.9% and 4.7% for forest, urban, agriculture and rangelands respectively.

B. Calibration and Validation of Model

The simulated and observed streamflow for the calibration period (01/01/1988 - 01/12/2001) and the validation period (01/01/2002 - 01/12/2013) are compared in Fig. 5. The simulated streamflow matched well the observed data. The performance statistics are shown in Table I. Evidently from Table I, NSE and R^2 values for both calibration and validation period are greater than 0.6 and the PBIAS values are in the range of ±10% indicating a good model performance [41]. Although the model performance was satisfactory, system overestimations were witnessed as shown by the negative PBIAS values. Observed streamflow was overestimated by 11.49 % and 20.69% for calibration and validation periods respectively.

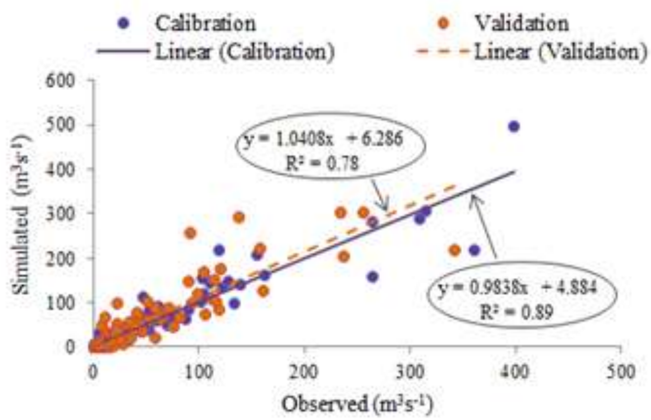

Fig. 5. Monthly simulated and observed discharge for calibration and validation periods

TABLE I: MODEL PERFORMANCE EVALUATION STATISTICS

Model Stage	Objective function			
	NSE	R^2	PBIAS (%)	RSR
Calibration(1988 - 2001)	0.88	0.89	-11.49	0.34
Validation (2002 - 2013)	0.67	0.78	-20.69	0.57

C. Impact of LULCC on Groundwater Recharge

A trend of continuous groundwater decline was noticed for 2000 – 2013 (Fig. 6). From 2000 to 2007, the annual groundwater recharge decreased by 10.37 mm (30.3%) and the reduction was associated with LULCCs in urban (9.2%), agriculture (6.1%) and rangelands (-16.8%) for the same period. A further decline in groundwater recharge of 12.71 mm (37.2%) was observed in 2013 with concomitant changes in urban (1.3%), agriculture (14%) and rangelands (-14.8%). Similar decline in groundwater recharge have been reported by other studies [7], [30], [46]. The declining trend seen in the average groundwater recharge is attributed to increases in impervious areas due to urban and agriculture expansion which causes less soil infiltration. Groundwater resources within the basin are sourced for several activities including household water use, industrial uses, animal husbandry and irrigation [14], [15]. The decreasing trend in groundwater recharge can also be interpreted to mean the rate of abstraction exceeds that of recharge. The reduction in groundwater recharge as depicted by the model results is consistent with the findings of [3] where they asserted that groundwater is a preferred source of water over surface water due to the high inter-annual variations in precipitation which tend to affect surface water availability. This is particularly the case in semi-arid environments in Africa and so is the case of the Olifants Basin [47]. A further investigation revealed that groundwater recharge constituted 3 – 5% (ratios of 0.03 - 0.05) of basin-wide mean annual precipitation (Table II). This range has in the past been established by [48] to be 3 – 6%.

TABLE II: POTENTIAL RATIOS OF BASIN HYDROLOGY SIMULATED ON THREE LULC SCENARIOS BASED ON HYDROLOGICAL YEAR (OCTOBER – SEPTEMBER).

LULC Scenario	Water Balance Ratios*					
	B/TF	SR/TF	SF/P	PC/P	DR/P	ET/P
2000	0.26	0.74	0.07	0.1	0.05	0.78
2007	0.25	0.75	0.09	0.05	0.04	0.82
2013	0.24	0.76	0.09	0.08	0.03	0.80

*SF/P; Streamflow/Precipitation, PC/P; Perculation/Precipitation, DR/P; Deep Recharge/Precipitation, ET/P; Evapotranspiration/Precipitation, B/TF; Baseflow/Total flow, SR/TF; Surface runoff/Total flow.

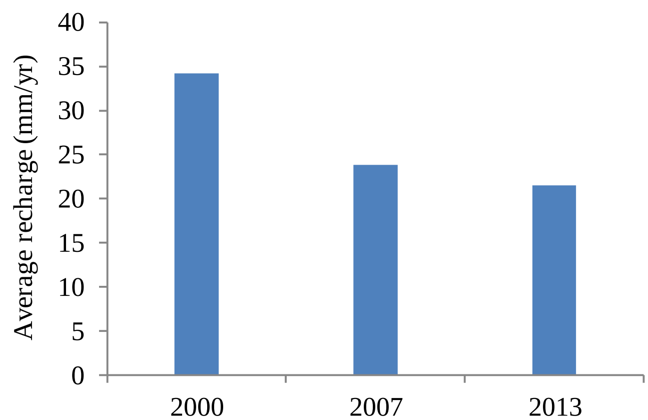

Fig. 6. Declining groundwater recharge for 2000 – 2013.

V. Conclusion

The effects of LULCCs on groundwater recharge were investigated in this study using a physically based distributed hydrologic model. Results indicate that groundwater resources in the Olifants Basin are declining as a result of the continuous decline in recharge and also due to overexploitation issues. The declines in recharge were associated with the changes in major land uses within the Olifants Basin. The feasibility of using the SWAT distributed model with readily available data has proven worthwhile in the investigation of groundwater resources in terms of its recharge rate. It is recommended that further groundwater investigations should couple hydrologic models with field monitored groundwater data to optimize the application of such models.

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