sciendo

DOI: 10.2478/sspjce-2024-0019

Investigating Water Balance Configuration in the Urban Areas of Mthatha, South Africa

S. Phelokazi[1], O.T. Amoo[1*], A. Ikudayisi[2] and MDV. Nakin[1]

[1]Centre for Global Change, Walter Sisulu University, Mthatha, South Africa.
[2]Civil Engineering Department, Walter Sisulu University, East London, Eastern Cape, South Africa
*e-mail: oamoo@wsu.ac.za

Abstract

Considering urbanization's effects, quantifying individual components of the hydrological cycle, especially at the catchment scale, has been challenging due to the influence of climate change and human activities. Accordingly, the study assesses the impacts of Land Use and Land Cover Changes (LULCC) on the water quantity degradation. It evaluates the effect of urbanization on water balance configuration between the period 2000-2020. The resultant result of LULC reflected a long-term increase in bare land by 11.72% and a marginal increase in built-up areas (0.52%). In contrast, the annual water balance results show an annual negative water deficit ranging from -19.40 mm to -624.955 mm. The result has demonstrated the use of QSWAT and SWMM in a Quick geographic information systems (QGIS) environment to drive the socio-hydrological framework to model spatially distributed and time-varying hydrologic and meteorologic datasets as an effective scientific visualization technique in water balance evaluation.

Keywords: environmental flows, LULC, water balance, sustainable development, urbanization

1 Introduction

Amongst the most important modifications that affect the urban water balance are the changes in land use and land cover that have increased the impervious cover [1,2]). Hence, most flow pathways in impervious areas contribute to urban water evaluation. These impervious land surfacing have impaired their filter capacity and runoff regulating functions [3]. Land, climatic conditions, and water availability are closely related in catchment water asset management [4]. Thus, the consequence of these impervious surfaces (land sealing) requires an analysis of the relationships between a catchment's socio and hydrological function because it relates to nature's effect with human activities triggering changes in the density and drainage network, soil-borne intensification and soil filtering capacity density in land changes. This development calls for a quantitative assessment of land use conversion under the influence of urbanization in safeguarding water resources.

Although urban growth impacts land use and cover, affecting catchment hydrology, processes like soil water retention and filtration capacity are in decline [5-8]. In addition, the increasing physiographic transition processes of societal and economic activities of built-up areas along the river, and continuous soil-floodplain creation have continuously been encroached by several springs of complex shopping malls, offices, and residential neighborhoods spread in the city's suburb periphery. All these have increased the occupied areas in urban cities, thereby causing more impervious layers with topography seal-off. Moreover, in adverse weather conditions, sewer systems and wastewater treatment plants are further flooded due to the increased capability of collecting large amounts of direct runoff resulting in an increased flood risk. Limited studies have investigated the impacts of inherent land use and land cover changes (LULCC) on urban water balance quantification [9,10]. Moreover, the choice of model and approach adopted has always been placed on the problem specific to the catchment.

Today, various techniques and models are evolving and used in different climatic zones to assess rainfall-runoff for urban water balance. [11] explored how current and future land consumption impacts urban growth and trajectory water balance using simple models based on publicly available data on evapotranspiration, precipitation, and water regulation in replacing the direct runoff and groundwater recharge value. [12] employed environmental tracers to determine the water balance and other hydrological functioning of lakes and reservoirs. Stable isotopes and environmental tracers have been used to quantify lake and wetland pond water loss due to evaporation and infiltration fluxes. [13]. Likewise, an accurate estimation of water budget components and the accompanying physical and chemical changes in a wetland pond, groundwater, and riparian zone has been achieved through the use of stale isotope [14]. Stable water isotopes have proved to be an efficient tool for determining the groundwater dependence of lakes, swamps, glaciers and ice sheets, inland seas, and the atmosphere [15,16]. [17] postulate the use of the hydrological model as a viable method that improves water budget calculation by dividing a watershed into smaller sub-hydrological systems (hydrological response unit), where the loss function is the basis for short-time models for reservoir operation in Nigeria. Other methods include the use of a drainage network and determining the amount of water to be collected from each sub-catchment using geo-informatics [18]. [19] postulates the use of an Ombro-thermic diagram gives a quick graphical component of water balance for a selected thermic place.

Also, the advent of computer modelling has eased time and labour consumption in consideration of other emerging approaches and modern urban models. Past literature work review on water balance shows modeling tools like WMS, STORM, KINEROS [20], SWMM [21,22], AGNPS [23], and HSPF [24] as a suitable option for urban water balance evaluation [25]. Some models are limited only to urban or peri-urban river catchments [26]. However, their choice has always been placed on the catchment characteristics and specific problems. HSPF has proved difficult to set up in gauge and ungauged watersheds [27]. KINEROS, AGNPS, BASINS, and ANSWERS model setup and developments required rigorous calibration with intensive data at different scales [28]. Furthermore, KINEROS, AGNPS, BASINS, and STORM reliability for short periods, especially if days or weeks are being simulated, is not particularly good. Their precision in average values prediction is questionable, unlike over longer periods which tends to be more dependable [29,30]. This is because the land and the rainfall within an area can vary over space and time being simulated. Also, many of these predictive models have been developed based on the in-built parameters' parsimonious simplicity [31].

Hence, QSWAT and SWMM were selected for their robustness, flexibility, data availability, urban focus and accessibility. The components in their quantity analysis can be found in these two models for planning purposes. The QSWAT model has been one of the most sophisticated for simultaneous simulations of hydrology, sediment, and chemical movement prediction. It has enjoyed popular usage for simulating surface runoff into the stream network and defining filtration into the soil-segregated layers with the aquifer profile [32]. The semi-distributed, process-based, continuous-time models could effectively evaluate management strategies on water resources and pollution from sources in large basins. The model integrates specific hydrological soil properties, like porosity and infiltration rates as they affect plant growth and the movement of sediments, nutrients, pesticides, and pathogens. Extracts on how QSWAT simulates surface runoff, Evapotranspiration, percolation, and lateral flow in groundwater recharge estimation were well-detailed and documented in literature work [33-37].

To this end, the study intends to quantitatively assess urban water balance under the influence of urbanization using QSWAT and SWMM to drive an intuitive socio-hydrological approach with certain assumptions. The socio-hydrological approach views water crises from a different perspective not only about human use but also about balancing humans' water and natural water demands from an ecological perspective[38]. The socio-hydrological water balance concept modifies the storage continuity equation[39]. Besides defining the relationship between inflow and outflow variables, it considers water required for ecosystem sustainability. Details for the socio-hydrological water balance framework can be found in [40]. The socio-hydrological water balance framework partitions the evapotranspiration (ET) into societal (consisting of the drainage network and depletive sewer system) and ecological systems (environmental and outflow to the sea) as water that leaves the system. Hence, the groundwater level during the current time step h(t) is derived from equation 1.

$$\Delta H = P(t) + R_{in} - \mathrm{ET_s} - \mathrm{ET_e} - \mathrm{R_{out}} + {}^{\mathrm{dG}}/_{\mathrm{dt}} + \epsilon_t \qquad (1)$$

Where:

$$\mathrm{ET_e} = \mathrm{ET_{ep}} + \mathrm{ET_{eR}} + \mathrm{ET_{eG}} \qquad (2)$$

$$\mathrm{ET_s} = \mathrm{ET_{sP}} + \mathrm{ET_{slR}} + \mathrm{ET_{sH}} + \mathrm{ET_{s,oth}} \qquad (3)$$

$$\text{And } D_R + D_G = ET_{sIR} + ET_{sH} + ET_{s,oth} \qquad (4)$$

Where ΔH is the total water change in the watershed, P = precipitation, ET = evapotranspiration; R = surface runoff, G = surface recharge/discharge and dG/dt = change in soil water storage (net groundwater flux) in the main drain of the manhole. groundwater (DG) represents irrigation water supply to croplands, grasslands, households, and industries. The leftover surface runoff is meant for ecological purposes, (ET_{eR}), and outflows to the sea (R_{out}).

Hence, the paper analyzes how urbanization and land cover changes impact water availability in Mthatha, South Africa, using hydrological models (QSWAT and SWMM) in QGIS environment to drive the socio-hydrological framework.

2. Materials and Methods

The solution for equation (1) is not straightforward because, at any given time, there are two unknowns: the urban storage level at the time (H_t) and the corresponding area change (A). So, the simplest approach to approximate the urban storage level is to use the previous month's ($R_{out}(t)$ and assume the initial storage change H is equal to the mean of the measured runoff. Also, for simplification, we assume that the rightmost term in the equation, $\in_t$, is negligible, and net groundwater flux has been considered as zero with no constructed urban land. The calculation of ET(s,e) depends on the corrected derivation of the soil field capacity derived from the soil texture as given in the QGIS maps. Subsequently, the study area description follows with data collection process, and the methods applied to quantitatively assess urban water balance under the influence of socio-hydrological urbanization are hereby presented.

2.1 Description of the Study Area

The Mthatha River Catchment (MRC) area houses Mthatha, which is the third biggest town in O.R. Tambo District Municipality. The town is a prime illustration of a rapidly urbanizing area in Eastern Cape, South Africa. It is within a 230-kilometer radius of the Transkei region. The city serves as an important economic and social hub for other towns in the area. Figure 1 depicts the study area with the South African Province.

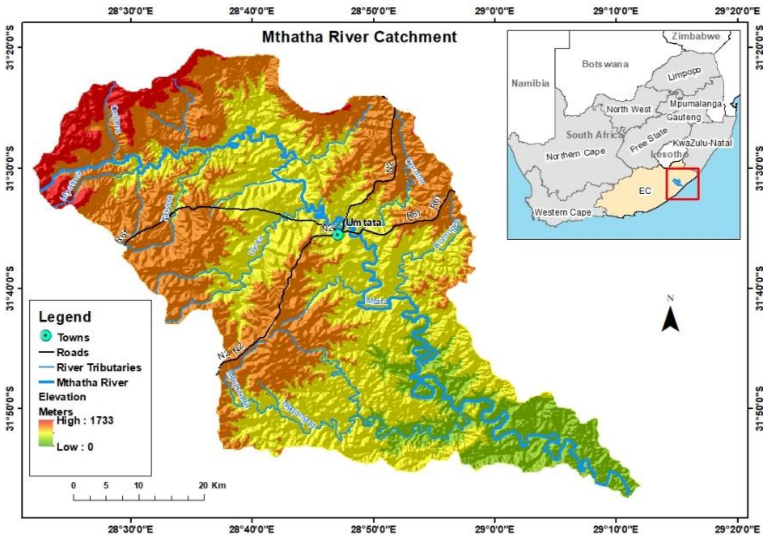

Figure 1: Location map of the Mthatha River catchment

The Mthatha River Catchment has a complex arrangement of commercial and residential settlements, including a range of dwelling types, which can be classified as rural; semi-urban, and urban spatial configurations. The Mthatha River originates in the plateau area of the Eastern Cape Province in South Africa, located about midway between the Drakensberg escarpment and before emptying into the Indian Ocean. The Mthatha River Catchment consists of the main river (Mthatha River) which is approximately 250 km long and 50 km wide and covers an area of about 5520 km^2 with two large tributaries winding their way to the sea north of Coffee Bay [41]. The catchment population densities and its distinct spatial characteristics are evident from the city weather trend pattern from a moderate climate with over 40 inches of precipitation per year on average. Evapotranspiration, on the other hand, is relatively constant around the catchment while there is a wide variety of impacts that human activity (e.g., land development, movement of water and wastewater between watersheds, consumptive uses of water such as irrigation) which could pose challenges on the natural water budget [41].

2.1.1 Biophysical conditions

Figure 2 depicts the MRC soil raster classification and its impacts in determining water balance.

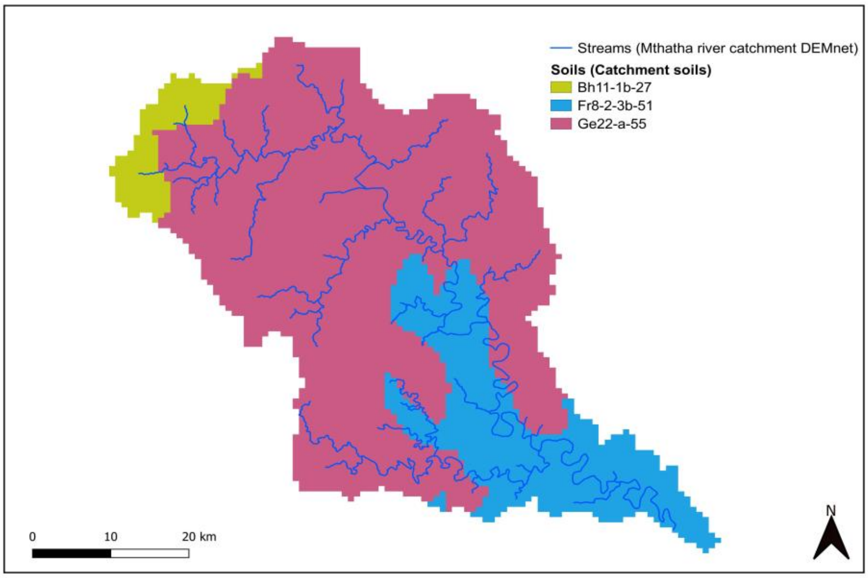

Figure 2: Mthatha River Catchment soil classification

The soil type codes Bh11-1b-27, Fr8-2-3b-51, and Ge22-a-55 stand for the sandy loam, loam, and sandy clayed loam classification labels for the area. Although they seem to have different filtering capacity distributions, a greater extent suggests water holding capacity has dropped in favour of an increasing direct runoff. This particularly holds for loamy soils. In the middle reaches, lies the Mthatha urban settlements with numerous ends of sewer pipe carrying effluents to be discharged into the Mthatha River. Many of the underground drainage system networks carry sewage and direct runoff which flows off the low-lying areas (such as roads, adjacent residential areas, allotments, and green spaces) after heavy rainfalls, and this usually occurs from time to time. The nature of the catchment streamflow network and distribution orders play a key role in transporting the action of water through their drainage discharge. Features such as size, area, shape, slope, and perimeter of the stream network continue to alter the quantification of its water balance.

3. Methodology

3.1 Model Selection and Working Techniques

The study employed an offline coupling of the QSWAT model with the SWMM tool in populating the socio-hydrological approach framework. These models were selected for their robustness flexibility, data availability, urban focus and accessibility. The QSWAT was used to model the streamflow and delineate the catchment into stream network and sub-catchments for water balance evaluation while the SWMM was used to model the drainage network and to determine the amount of water to be collected from each sub-catchment of the Mthatha urban areas. The model was used to simulate the urban flow quantity, the water storage balance in-built was used for the flow from the land surface and the equations of continuity and motion were used for channel flow prediction [42]. The socio-hydrological approach views the urban water balance configuration as a combination of societal urbanization and ecosystem sustainability [43].

3.2 Data Acquisition

Field data such as meteorological, land use change, soil type, societal, economic, and demographic changes for the Mthatha catchment, was collected from past documentation (2000-2020). Hydrological drainage network characteristics such as size, area, shape, slope, and stream network distribution orders that are useful in estimating surface flow discharge and quantifying the runoff were obtained from the catchment delineation in the QSWAT model. Other required data regarding the effects of topography terrain and related features such as soil type, slope, aspect, grain size, groundwater level, and the different degrees of land use/cover change, indices for soil wetness on the hydrologic processes, were evaluated from the compiled soil and land digital elevation model data process in QGIS for the area.

3.3 Data Quality and Validation

Data sources from the Google Earth as base map were refined and processed to the required resolution, by cross-referencing the Google Earth imagery with field surveys while other global source data were compared against local meteorological stations for reliability. We used a 30 m DEM resolution from the SRTM and a 2,000-ha drainage area threshold to define the stream network. At the same time, the rate of changes for different land cover types was generated through Google Earth ground-truth data for historical image classifications (2000, 2005, 2010, 2015, and 2020). Also, because the study lacks detailed sewer infrastructure data, like malfunctioning or pipeline leakages, we assumed constant leakage rates for all pipeline conditions. Moreover, the function of the sewer system (that accelerates the drainage of the land parcels by collecting precipitation and runoff water directly in the river) is estimated according to the land use classes which are included in the QSWAT model via the in-built parameters menu for surface runoff, evapotranspiration, percolation and lateral flow. Also, each land parcel area's soil texture distribution and vegetation in the catchment area were assumed to be uniformly distributed. Table 1 gives an overview of some of the various assumptions made in the QSWAT and SWMM models.

Table 1: Summary of assumptions parameters made in the QSWAT and SWMM

Symbol	Parameter	Description	Domain
CN	SCN	Service Curve Number for land use, soil, vegetation,	(0.3, 0.6)
Sp	Seepage	up_seepage_ flux and down_seepage_flux	(0, 3)
Cw	Cw	Runoff coefficients	(0.3, 0.7)
deep_gw	deep_gw	deep groundwater	(2, 23)
Ns	N-sewerconduit	Manning's n for sewer conduits	(0.002, 0.026)
Dc	Decay-constant	Infiltration coefficient(h-1)	(1, 6)
Min-r	Minrate	Minimum infiltration rate	(18,120)
Max-r	Maxrate	Maximum axfiltration rate	(1,11)
Zi	Zero-impervious	Percent pf impervios area without depression storage (%)	(4, 75)
Dp	Destore-perv	Depression storage for pervious area (mm)	(1,11)
Di	Destore-imperv	Depression storage for impervious area (mm)	(0.1, 0.11)
Np	N-pervious	Manning's n for previous area	(0.01, 0.08)
Ni	N-impervious	Manning's n for impervious area	(0.011, 0.05)

3.4 Data processing, QSWAT model and SWMM drainage network setup

Figure 3 depicts the workflow diagram showing data flow from GIS to SWMM and SWAT for modelling the water resources of the catchment. The data requirements for the SWMM model setup include rainfall data, slope and elevation, land use data, stormwater pipe system, and discharge data while the QSWAT model was set up with processed DEM, soil, and land processed raster data in a QGIS environment. Figure 3 Workflow diagram for water balance estimation from the SWAT and SWMM models

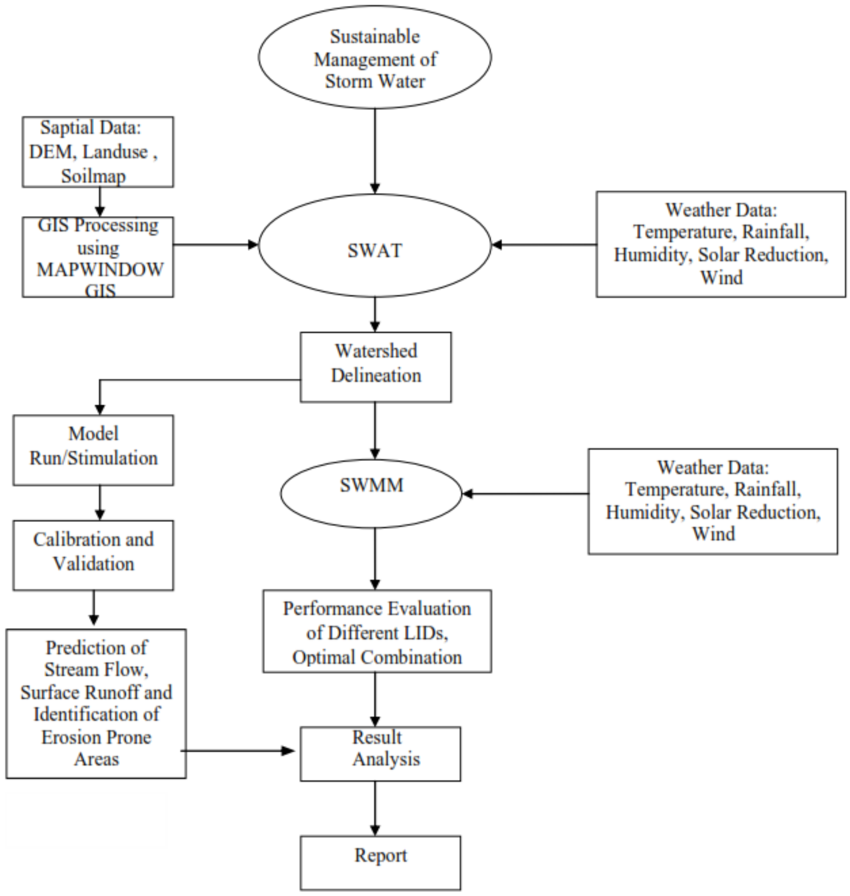

Figure 3: Workflow diagram for water balance estimation from the SWAT and SWMM models

The QGIS hydro statistic tool has been used for Digital Elevation Data (DEM), soil, and land use raster image processed and re-projected to Universal Transverse Mercator Zone 34 South. Before rigorous analysis in QSWAT for the catchment delineated into sub-catchments, consisting of stream network, slope lengths, and other aspect ratio to capture the street drainage network and interconnectivity. Since urbanization meant the growth of new impervious land and built-up areas around the urban periphery, information on soil grain size, and field capacity for each land parcel was assessed through QSWAT land use and soil texture distribution on the catchment area while the regional climate data collected from South Africa Weather Service (SAWs) for the period (2000-2020) for precipitation and evaporation were fed into the used models (QSWAT, SWMM). The temporal changes in the catchment hydrologic water balance were assessed using the modified socio-hydrological urban water balance formula in which water enters the system via precipitation (P), converted into evaporation (E) and runoff (R), and the associated storage (S) or change in storage (ΔS) for the period under investigation (2000-2020). To assess the effect of urbanization, the SWMM model was set up to quantify the urban area runoff, water held up in sewer, re-use, and discharge back to manholes which were computed using spatial analyst tools in a QGIS environment [44] while the socio-hydrological framework approach was used to quantify man use and ecosystem water use in arriving the urban water balance formula.

Due to its simplicity, the open-source EPA-SWMM, developed under the support of the US-EPA, was selected to model the drainage network and to determine the amount of water to be collected from each sub-catchment of the Mthatha urban areas. The model was set up with processed soil, and land raster data, processed in a QGIS environment. The model simulates the drainage system network by (i) rainfall-runoff transformation, (ii) 1D flow routing on a street network, (iii) flow interception at street inlets, and (iv) flow interaction between surface water on the streets and the underground storm-water system.

The hydrologic model (first module) transforms rainfall to runoff using the kinematic wave approximation and simulates the infiltration process with the Green-Ampt method. The street network is based on a finite-volume shock-capturing scheme that solves the fully conservative Saint-Venant equations to model both subcritical and supercritical flows. Flow interaction between surface water on the streets and underground storm-water systems was achieved by interfacing the QGIS model with EPA-SWMM. This interaction allows the flow to enter from streets to the underground storm-water system and vice versa. The proposed model has several potential applications such as the identification of critical zones for flooding (zones with high water depths and flow velocities) in urban development and can be used to take appropriate measures for drainage control (to increase the number and/or size of inlets), to determine the consequences of different degrees of inlet clogging, and to assess flooding hazards through the application of suitable hazard criteria.

4. Results and Discussion

4.1. Model sensitivity, Calibration and Validation Fit

Most model predictions inherit much error and uncertainty by the underlying Empirical Risk Minimization (ERM) principle usage. Hence, before calibration and validation of the QSWAT model, a sensitivity analysis was examined as part of the modelling process to determine which parameters influence the model structure and output most. It is also used to understand the influence of input on model structure and the model outputs. The modelling approach presented several simulations that have been carried out using a range of different input values for the most sensitive model parameters. The calibration and validation technique employed for the models was through comparing the model simulated drainage system network discharge with observed data in rainfall-runoff transformation. Most parameters employed are assumed to be uniformly distributed in the models. We achieved an acceptable fit between predicted and observed flow during calibration and validation for most parameters at the outlet gauge. Suggesting the model was suitable for predicting the discharge flow and reliable over the different hydro-climatic periods. Figures 4 and 5 depict the calibration and validation results for the flow discharge.

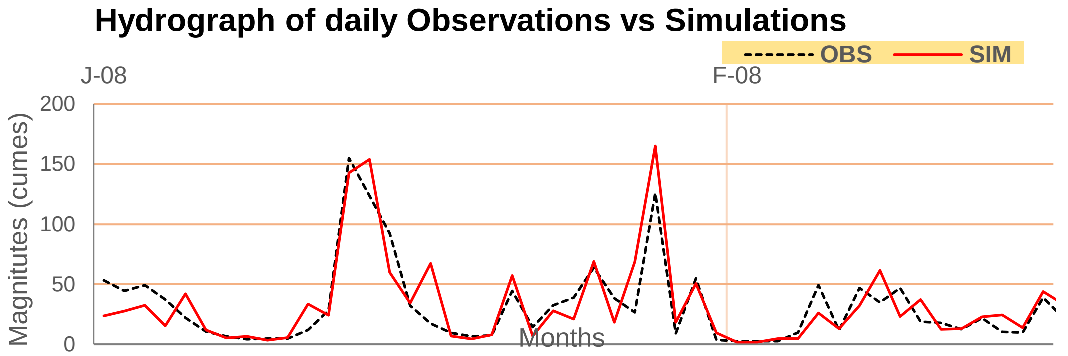

Figure 4: Observed and simulated discharge during the calibration period 2010-2014

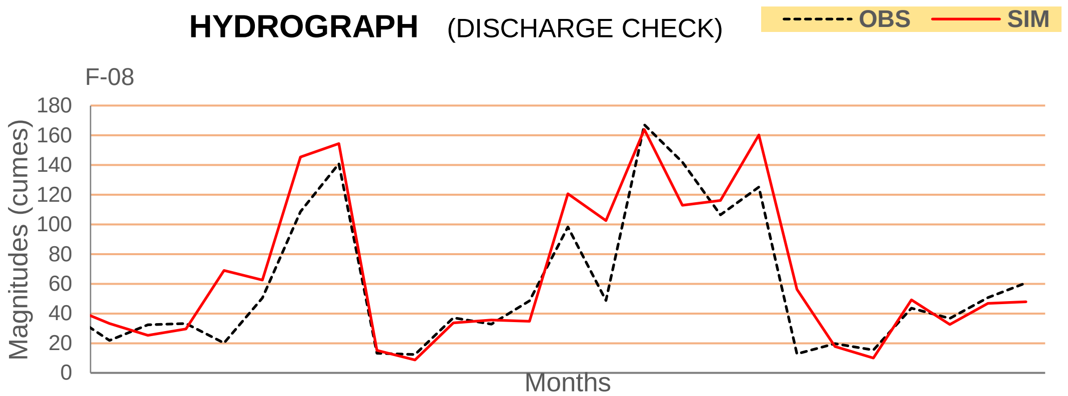

Figure 5: Observed and simulated discharge during the validation period 2015-2020

The most sensitive parameters for the hydrological modelling of MRB watershed are CN2.mgt; ALPHA_BF.gw; GW_DELAY.gw; A__RCHRG_DP. gw. Thus, The CN2.mgt parameter is the most sensitive parameter with best fitting values of less than -0.01 at relative change (r__). [45] also confirmed that these four parameters are the crucial sensitive parameters for water balance and stream flow. Therefore, the goodness-of-fit of the QSWAT model estimates of runoff should be viewed in the context of the goodness-of-fit of the available observed sample data used as inputs. The calibration and validation values for goodness-of-fit (NSE, and R^2), obtained during the calibration and validation period, are all acceptable(values greater than 0.5). For instance, the NSE and R^2 are about 0.84 and 0.79 respectively at validation for daily discharge simulation. Table 2 shows the simulated monthly discharge for MRC for the period.

Table 2: Goodness-of-fit for simulated monthly discharge.

	Calibration (2010-2014)	Validation (2015-2020)
NSE	0.65(g)	0.84(vg)
R^2	0.63	0.79

Where g= good; vg= very good

Both the meteorological data and land use changes have a considerable impact on the water balance of a catchment and sub-catchments. The influence of climatic variables on various parameters such as water yield, surface runoff, and evapotranspiration (ET) transcend land cover as shaped by land use practices which in turn affects the concentration of greenhouse gas emission and transpiration processes. land use change is sensitive to the soil curve number, soil type and distribution. All these parameters are important drivers of the environment and contributors to prevailing weather conditions in an area. A change in land use and land cover invariably affects runoff and available groundwater resources. A decline in groundwater levels may be attributed to increased extraction rates or the intrusion of saltwater in coastal areas. All these interchangeable factors affect and contribute to water scarcity that poses a threat to some part of the country's overall water security. Below are the results of assessing the impacts of Land Use and Land Cover Changes (LULCC) on the water quantity degradation.

4.2 Land use and cover change result

The land use maps were reclassified using detailed land cover types from the prevailing land uses in the area. Much of the land cover was characterized by different grassland and savannah vegetation. As shown in Figure 3, the map codes classified AGRL, PAST, FESC, BARR, URBN, WATR, RNGE, and UCOM to represent Agriculture, Pastures, Forest, Barren, Urban Settlements, Water occupied, Residential, and Urban commercial areas respectively, with varying percentages as the main land use activity in the area. Figure 3 depicts the land use and cover type for the study area.

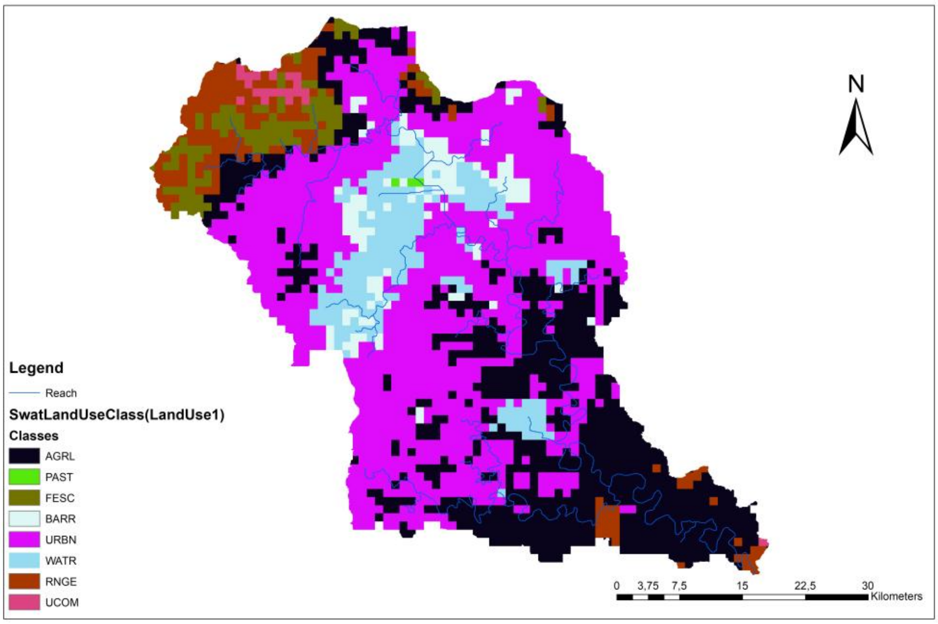

Figure 3: SWAT-based land uses and land cover classification at MRC

4.3 Urban growth and sprawling land consumption result

Table 3 depicts the derived LULC change area composition variation per decade year for the MRC. Urban sprawling land consumption and its effect on water availability within 2000-2020 reflected a long-term increase in bare land by 11.72% with a negative 3.65% in water bodies and a marginal increase in built-up areas (0.52%). The period (2000 – 2010) had the biggest change in bare lands (13.09%) followed by a major decline in agriculture, vegetation, and water bodies. The built-up area covered the smallest area in comparison with/to other land cover types. The results also demonstrated that the area occupied by water decreased from 14152 ha in 2000 to 4758 ha in 2020, representing a -3.65% change in the overall composition of water bodies in response to LULC change. The built-up areas had the least changes overall.

Table 3: Derived LULC change area composition variation per decade year for the MRC

Class name	Area (ha)			% composition			% change		
	2000	2010	2019	2000	2010	2019	2000 - 2010	2010-2019	2000-2019
Agriculture	71 118	38 432	63 181	27,61	14.92	24,53	-12,69	9,61	-3,08
Bare land	128678	162468	158 943	49,98	63,07	61,70	13,09	-1,37	11,72
Built up areas	2 365	2 845	3 701	0,92	1,10	1,44	0,19	0,33	0,52
Vegetation	41 344	26 645	26 918	16,05	10,34	10,45	-5,71	0,11	-5,60
Water bodies	14 152	4 914	4 758	5,49	1,91	1,85	-3,59	-0,06	-3,65
Total area mapped (ha)	257609	257609	257 609	---	---	---	---	---	---

Figure 7 shows the map for the satellite-derived LULC changes for the MRC. There has been a declining trend in water bodies within the catchment since the year 2000, which is also attributed to the observed increase in bare lands.

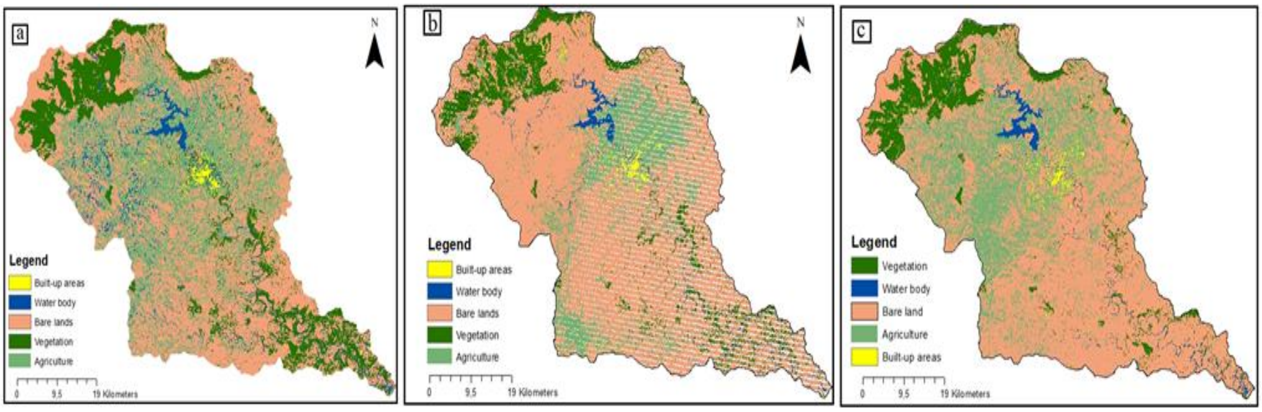

Figure 7: Satellite-derived Land use and Land cover changes for the MRC (2000-2020).

Water bodies were the only land cover type with a persistent decrease throughout the period. Also, land emittance of greenhouse gases leads to global warming and climate change. The world is now warming faster than at any point in recorded history. Warmer temperatures over time are changing weather patterns and disrupting the usual balance of nature.

4.4 Results of Urban Water Balance Components

4.4.1 SWMM simulation results

Figure 8 shows the 3D digital elevation model of the Mthatha case study area. The elevation data is provided in a different file format called *.bed file. The DEM's resolution was set at 4m, which is useful for the pictorial view and demarcation of the sub-catchment area.

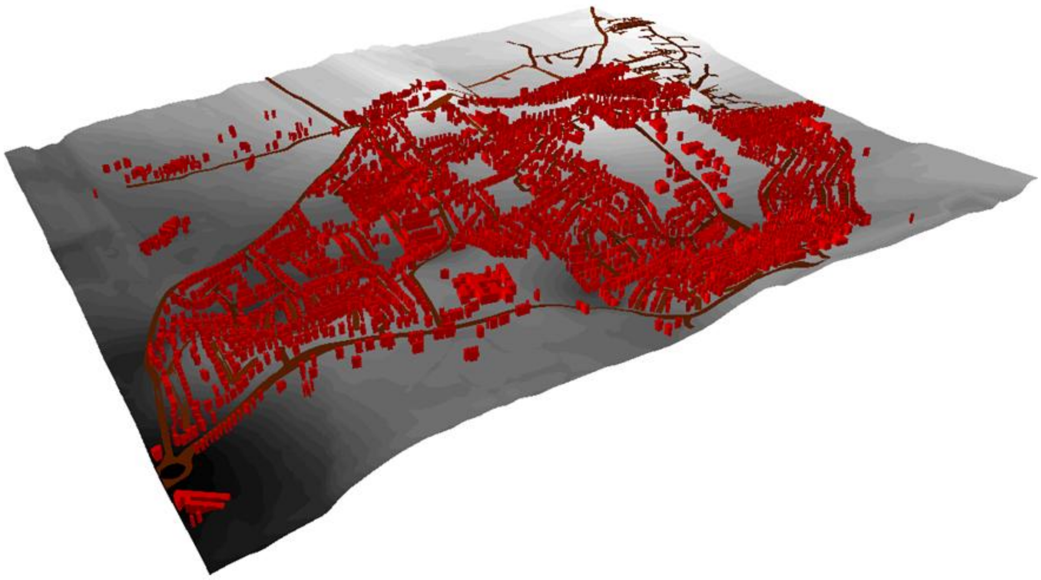

Figure 8: 3D DEM of Mthatha township, attributed with roads and buildings.

4.4.2 SWMM and QSWAT Hydrological Routing

Roughness data was needed for the topographical terrain of the study area in SWMM routing. A uniform value of 0.02 was adopted and Manning's formula was used for the computation of the conveyance friction terms in the shallow water equations. The surcharge flow occurred at separate times depending on the given discharge flow time series from the SWMM simulation. The surcharge flow is contributed by 28 nodes and the total volume from collected street and impervious layer is estimated to be 4,915 m^3. A summary of the model result is presented in Table 4. The run-time of 5hr - simulation is quite an acceptable computational speed especially when considering a quick prediction of urban street flow scenario analysis. The mass balance error of the simulation result is also quite insignificant, and this may be attributed to the finite volume scheme used for the solution of the model equations.
Arising from the street network studies, the interconnecting drains listed in Table 5 were selected based on their capacity to control flow.

Table 4: Summary of the model results for the case study area

Model Results	**Value**
Total simulation time(h)	5
Model run-time (min)	70
Mass balance error (%)	7.6×10^{-9}
Total Inundated area range (Sqm)	65-554

Table 5: Expected Discharge for the Drains

Road / Drain	**Area, Km^2**	**Discharge, Q m^3/s**
1-3dR	0.078	2.651
1-3R	0.037	1.248
1-4R	0.038	1.278
1-5R	0.039	1.339
1-6R	0.039	1.309
1-6aR	0.036	1.218
1-7R	0.038	1.278
1-7aR	0.037	1.248
1-8R	0.032	1.098
1-9R	0.039	1.309
1-10R	0.035	1.188
1-11R	0.036	1.218

Since drains were attached to each side of the roads, the conveyor capacity using the rational formula Qmax = (CIA)/36 - in metric units. Where "A" is the area in hectares; "λ" is the catchment factor governed by the losses and other conditions of the catchment; "I0" is the maximum intensity of rainfall in cm/hr. Catchment factor, C = 2 f P/(tc+1); Where "f" is the speed factor of the depending on its uniformity in a given basin. For basin areas up to 100km2, "f" is taken as 1.0; P is the Permeability factor (coefficient of runoff); "tc" is the time of concentration in hours given by; tc = 0.88 (L^3/F)0.385. Where "L" is the length of the drainage basin in km; F is the fall in elevation in meters in the length "L" of the catchment. The values of the permeability factor, "P", for Steep, bare, rocky, and city pavements (0.9) and for Clayey soil, stiff and bare (0.6) as contained in [46,47]. Figure 9 illustrates the QSWAT rainfall-runoff transformation.

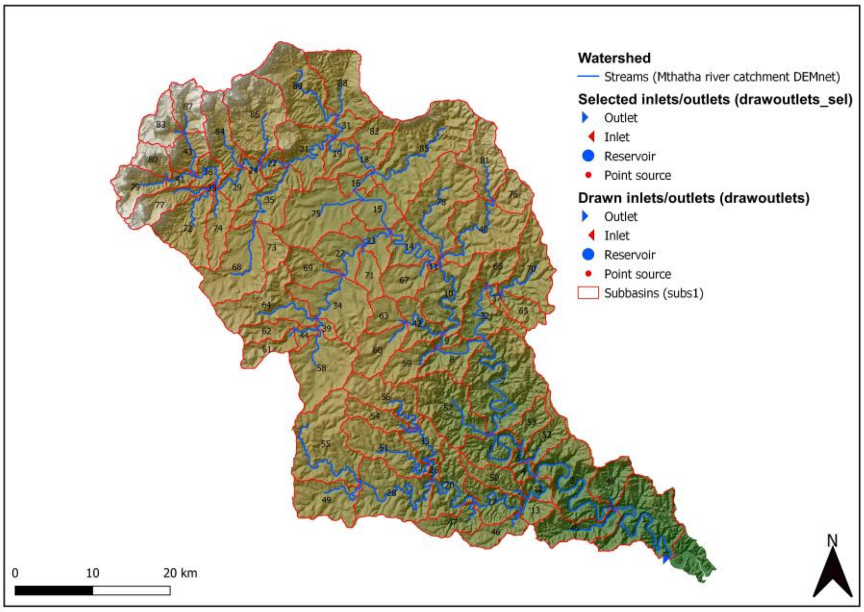

Figure 9: Streamflow network and sub-drainage pattern formation at MRC

Likewise, considering the assumption made on soil grain size and field capacity, these affect the drainage capacities and runoff pathways. The nature of the catchment streamflow network and distribution orders play an important role in the transportation of wastes through their surface flow discharge. The catchment transforms precipitation into runoff patterns, which in consequence affects the surface flow, replenishes the groundwater, and the overall equilibrium of water within the catchment. Also, it’s worth noting the portion of water that flows into/through combined sewers, or even direct water that flows into the channel drainage and those collecting network that flows as runoff through the impervious road layout were all detailed in the SWMM manual [25]. In all, the modified SCS method is used for runoff quantification. This method is based on the area's hydrologic soil group, land use, treatment and hydrologic curve number (CN) condition. Although the method is designed for a single storm event, it can be scaled to find average annual runoff values. Depending on the settlement type (urban versus peri-urban areas), this could influence water balance depending on hydrologic curve number (CN) condition. Figure 9 depicts the streamflow network and sub-drainage pattern of the MRC. Most sub-drainage formation patterns and the catchment drainage network were characterized by radial drainage forms where water flows downward from a hill or mountain to a wheel circular network of parallel channels flowing away from a central high point.

4.4.3 Estimation of Precipitation Component

The average monthly precipitation data for the period under study has been estimated from Precipitation records from 2000-2020 and were used as presented in Figure 10.

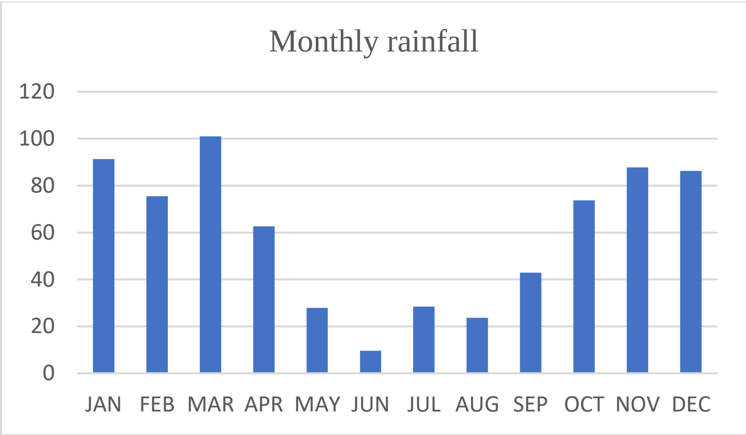

Figure 10: Monthly Rainfall depth in MRC (mm) (2000-2020)

In this study, the mean monthly (11-22 mm) and mean annual precipitation range from 489 to 959 mm of the study area was calculated from data obtained from the South Africa Agriculture Meteorological Agency (ARC), for the Mthatha catchment area.

4.4.4 Estimation of Evapotranspiration (ET) Component

The collected potential evapotranspiration, ET data from ARC is presented in Figure 11. In this study, the mean monthly and mean annual evapotranspiration of the study area was obtained from the South Africa Agriculture Meteorological Agency (ARC), for the Mthatha catchment area. It was noticed no available records were available for the years 2000 and 2001, this was extrapolated from free water surfaces estimated by the Modified Penman method.

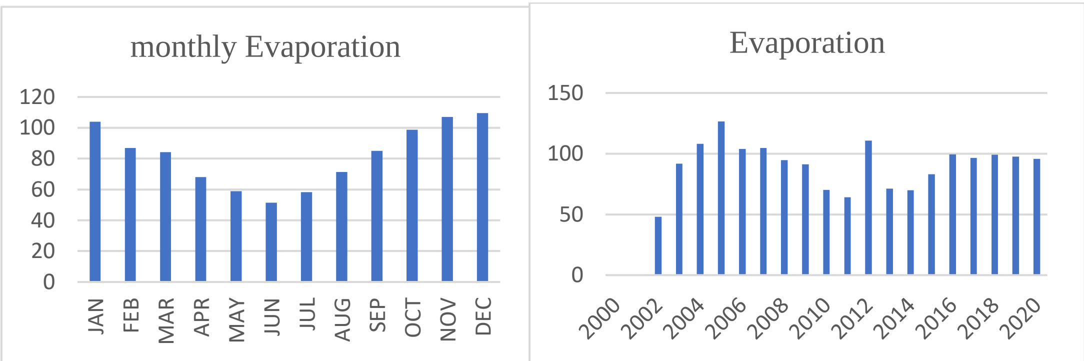

Figure 11: Monthly and yearly Evapotranspiration data from ARC

Even though the evaporation from free water surfaces could be estimated by several methods such as Blaney Criddle, Modified Penman, Thorntwaite, and others. The modified Pennman method provides a reasonable estimate where sophisticated measurement equipment is not available. The mean monthly estimated for the area is 109.426 mm.

4.4.5 Estimation of Catchment Runoff Component

The direct runoff is the result of the immediate response of a catchment to the input rainfall. The catchment runoff was estimated using the rational method by multiplying the volume of rain that falls on that surface by its “runoff coefficient”- (P*Cw). The runoff coefficient ranges from 0.30-0.50 for different land use/land cover with clay and silty loam for both urban and Agricultural areas [48]. Using a coefficient of 0.35, the predicted monthly runoff depth is summarized in Figure 12.

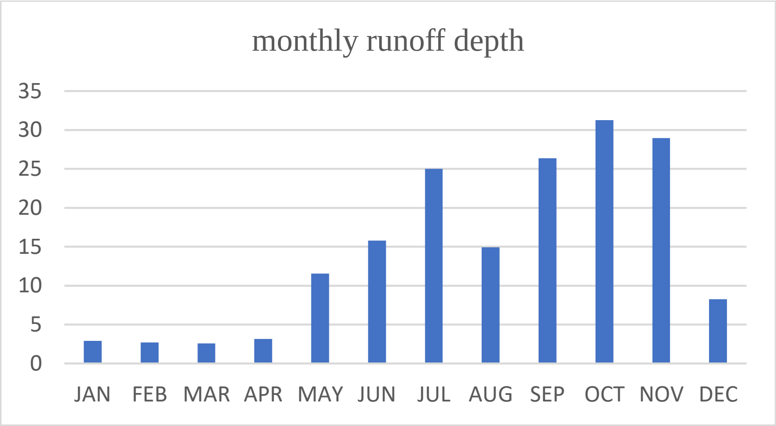

Figure 12: Predicted monthly runoff depth (mm) for MRC (2000 - 2020)

In this study, the mean monthly runoff of the study area was calculated from data obtained from the South Africa Agriculture Meteorological Agency (ARC), for the Mthatha catchment area. The mean monthly runoff ranges from 2.58 to 28.97 mm.

4.4.6 Groundwater Recharge Component

The amount of percolation in the area was to be assumed 20% of sewer collection accrued to percolation due to leakage, malfunction of pipe, and during repair. Thus, 0.20 of 4,915=983 m^3. This is the total permeable leakage and percolation for the area. The average flow per street length equals the total discharge divided by the area (Q=VA). When area occupied =0.038 Km^2. Therefore, the volume of water occupied by each street length was estimated as 37.354 m^3.

4.4.7 Ecosystem and Environment Flow Component

The environmental flow was calculated by subtracting surface water diversion and outflows into the sea from surface runoff or better still, by assuming 20% of the 75% dependable flows in each of the wet months or using 15% of the average monthly flows in different months for the dry months. Thus, using 15% of the average monthly flows in different months for the dry months equals 0.15 of 14.93 = 2.23 mm.

4.5 Urban Monthly Water Balance Configuration Result

The mean monthly hydrologic budget value for 2000 – 2020 using the different computed components from Equation 5 is presented in Figure 13. The change in storage (ΔS) was based on Equation 3: (P - (ET + RO) = ±ΔS), substitution with an appropriate monthly value. Where: P = precipitation, ET = evapotranspiration, R = surface runoff, and ΔS = change in storage.

The analysis shows a surplus in water balance from January to April (a total of 91.86 mm), while the remaining eight months (May till Dec) exhibit a negative balance with a total of 174.248 mm annually. Therefore, there is a need for groundwater inflow of 91.859 mm annually to balance the deficit.

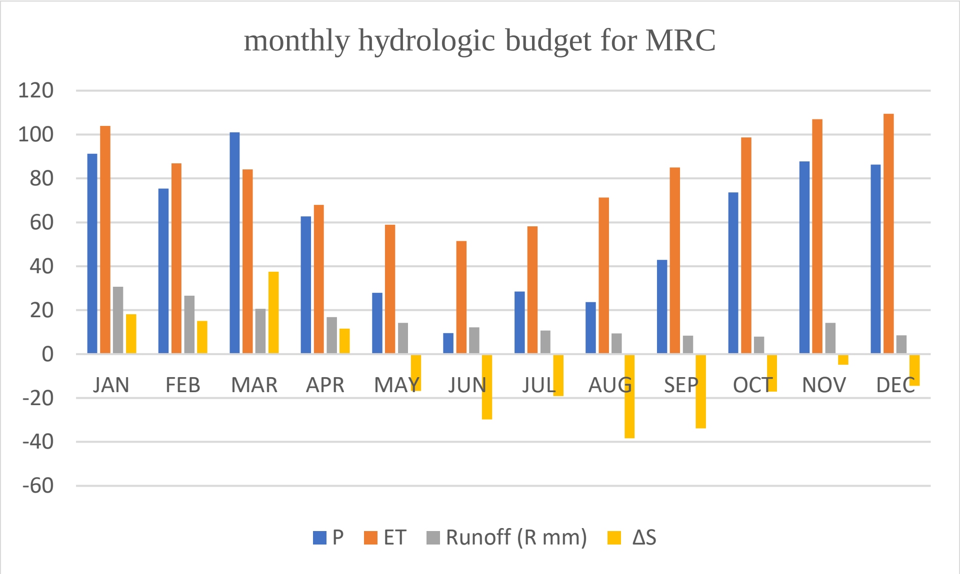

Figure 13:Monthly hydrologic budget for Mthatha River Catchment

4.6 The Mean Annual Hydrologic Budgets

Substituting the appropriate value in Equation 8. The annual average water balance is tabulated in Table 10. Where n = number of years of record = 20 years; P = Mean annual Precipitation = 1225mm; R_{in} = Mean Annual Runoff of MRC at downstream=443mm; $ET_s = 123$ mm; $ET_e = 204$ mm; $R_{out} = 143$ mm; $^{dG}/_{dt} = 534$; The net annual hydrologic budgets indicate a negative budget, the value ranging from -624.955 mm to -19.40 mm. However, this negative budget suggests that for the hydrologic budget to balance, -624.955 mm to -19.40 mm of water must enter the system from some source. The balance has an error margin of 2.22 mm/year. This is small compared to the complexity of the estimation of each of the water budget components.

Figure 15 presents the annual variation of water balance for MRC. However, since the primary input to the watersheds is precipitation, the catchments could be affected by numerous factors including longer dry seasons, topography, soil types, with intense population activities which may have resulted in a negative balance.

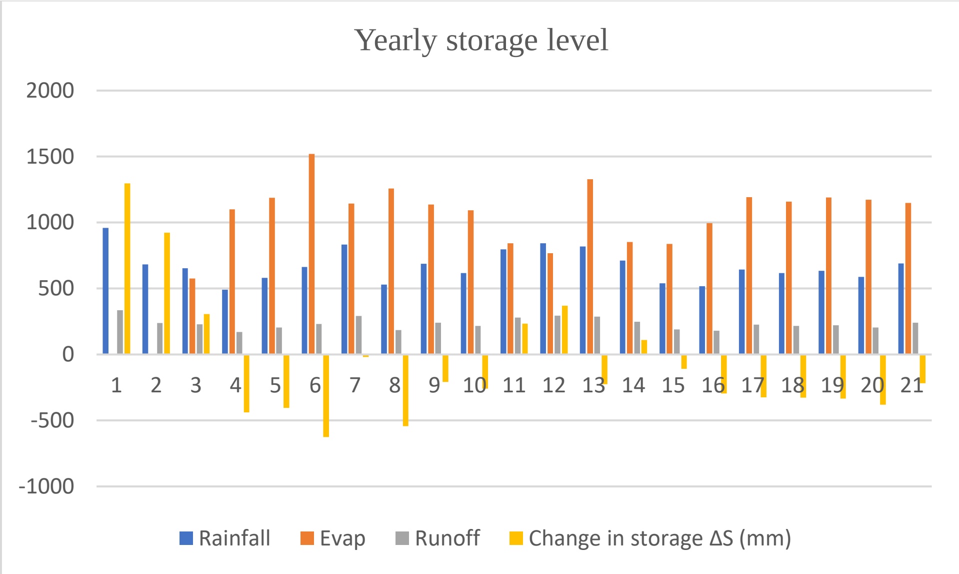

Figure 15: Annual variation of water balance for MRC

The reported negative annual water balances (-624.96 mm) imply insufficient water to meet the population density, forestry, and industrial development needs - such as mining activities, and farming practices, thus hindering industrial growth and many economic activities that may be useful to the city development and urban growth planning. This indicates a total water surplus of 3238.86 mm and a total water deficit of 4707.84 mm annually for the period under investigation. The water balance results reveal time-varying hydrologic-meteorological datasets to evaluate the monthly and annual extrapolation while additional characterization of depletive and consumptive sewer uses would result in wide differences regarding the rate of infiltration and runoff/recharge. Hence, water must enter the system from other sources to maintain hydrological water balance.

4.7 Implication of results

Conversely, the adverse effect of water depletion witnessed in the area has resulted in the extinction of certain species of animals and aquatics preservation in the catchment. Mthatha's socio-economic and ecological conditions had suffered drastically due to the negative annual water. Thus, raises the growing concern that policies for sustainable water use, environmental quality and efficient allocation of the available water resources should be implemented, particularly in the study area. The severe drought and its attendant problems have contributed to the severe consequences on the status of the Mthatha River and its tributaries, biodiversity, landscapes, key habitats, and floodplains. This has caused considerable pressure on the ecosystem, resulting in conflicts over water resource allocation among riparian users.

Most of the converted forests to grazing lands and agricultural lands have resulted in reduced soil infiltration and reduced groundwater recharge in most of MRC's lowlands. The changes in land cover/use have been most rapid on the foot slopes of the mountain where large commercial afforestation has been established. This has adversely affected the downstream and ecological systems leading to conflict over water demand, which calls for careful planning to alleviate the growing water challenges. The diverse uses and demands have resulted in water stress situations particularly in times of drought, which has characterized the South African environment in recent times, The aggregated effect of LULC may have also contributed to the water deficit due to almost impermeable layer and thereby contributed to the continuous flooding volumes.

4.8 Findings Summary

The paper analyzes how urbanization and land cover changes impact water availability in Mthatha, South Africa. Using hydrological models, it finds that increased impervious surfaces and climate variability lead to a consistent water deficit, underscoring the need for sustainable water management in growing urban areas. The study has contributed to and enhanced our understanding of the current land use and land cover as it impacts urban water balance configuration. Accordingly, assesses the impacts of human-ecosystem water relationship over the catchment and before investigating the effect of urbanization on water balance configuration.

From the results, there is a notable change noticed in the shift in land cover between 2010 to 2019, this has a direct bearing on reducing the water bodies area makeup. From 2000 to 2010, there is a negative 3.59% change in water bodies. From 2010, there was a negative 0.06% change in water bodies, while in 2019, there was a negative 3.65% change. Also, in terms of vegetation, there was a negative 5.71% change by 2000, and this was reduced to a positive 0.11 in 2010 before a further reduction of 5.60 in 2019 representing a 76% reduction from the total area mapped (257,609). The correlation coefficient results of negative 3.08 in 2019 suggest built-up area contributes largely to characterize the impervious layer, even though agricultural land use contributes (-12.69) in reduction to (-3.08) in 2019, but the proportion is minimal. This implies that the catchment witnesses geometric man-made land use and land cover for urbanizing areas. Hence, the rate of urbanization is quite different. The water budget developed through this study was based on estimated HRUs within a catchment and then aggregated to the sub-catchment level.

The SCS runoff equation was selected for this study, because it uses daily precipitation data, whereas the Green & Ampt method requires sub-daily precipitation data, which were not available for the study area. Also, the most sensitive parameters for the hydrological modelling of MRC are CN2.mgt; ALPHA_BF.gw; GW_DELAY.gw; A__RCHRG_DP. gw. The CN2.mgt parameter is the most sensitive parameter with best fitting values of less than -0.01 at relative change (r__). The effect of close pavement with runoff, (Table 3) suggests a direct link from substantial conversion in precipitation into runoff patterns, which consequently affect the surface flow, the replenishment of groundwater, and the overall equilibrium of water within the catchment.

Further research on how the different soil types with their soil moisture content help in detecting anomalies in the soil filtration capacity and could be used to respond to both emissivity and resistivity impact on the catchment. The catchment's response to impervious layer implies a reduction of water bodies through evaporation and built-up area, thereby making the area susceptible to losing water content. The study has equally helped to show how human activities impact and could modify the natural flow of water and help to maintain an ecological water balance system. The findings show a simple, but effective water balance component estimation.

The study has maintained that the earth's water is constantly changing form although other components of urban water balance may suggest not. These changes in water form tend to justify more analyses that could require sophisticated models at the sub-catchment scale. The study did not perform any sensitivity analysis on climate parameters, such as varying precipitation and evapotranspiration rates, to observe impacts on water balance as this is beyond the study scope.

Further research concerning urban water balance could focus on varying climatic variables, land use, and soil parameters to observe their impacts on water balance. Also. the effect of sub-division of impervious layers against the assumed broad constructed land surface, air temperature emissivity, and resistivity in land use can be further investigated. The study assumes a mean uniform runoff coefficient based on land use/land cover at the detriment of the area's heterogeneity. Further research on how sensitive this parameter could affect the overall water balance would be beneficial for future studies.

5. Conclusion and Recommendations

Our results contribute to understanding the role of precipitation, infiltration/recharge, runoff, and evapotranspiration in water-related ecosystem services. The study area had witnessed urban water deficits. Hence dependable water uses with land uses recovering in an integrated system that fits with growing urban land development issues was recommended. Also, sustainable integrated management approaches from a catchment perspective in contrast to a fragmented approach that artificially separates land management from water management is suggested as a viable option for policymakers, and the catchment management area board. In short, water management practitioners would find the study useful in formulating laws and practices for controlling or preventing catchment water deficit.

It is crystal clear that of the urbanization impacted soil sealing, hence catchment water balance would benefit by using global big data for improvement in hydraulic conveyance and hydrological model monitoring data, and application of isotopic analysis for groundwater. Likewise, the study of LULC has provided actionable insights for water resources managers to advance environmental conservation initiatives. The study suggests that both the adaptative catchment management and the legislative provincial initiatives approaches are viable ways to ensure water conservation and maintained urban water balance.

Adaptive catchment management is designed to restore or protect water quality conditions in catchments through best management practice (BMP) operation. At the same time, legislative provincial initiatives address the various formulated laws and practices for integrated catchment management. The utilized water balance framework could serve as a suitable decision support system in evaluating available water and provide a comprehensive scientific assessment methodology for the peril of water scarcity experienced in the region. The outputs of this study could also serve as baseline information for water balance management in the MRC.

Acknowledgments

The authors acknowledge and thank the WRC, ARC-ISSC, SAWS, and DWA for providing the data and those who participated in the survey field data. We are also grateful to grant No. C2019/2020-00166 for sponsoring part of this study and the Walter Sisulu University, Mthatha, for providing the enabling environment. We also thank the financial support from the Department of Science, Technology and Innovation and the National Research Foundation through the Centre for Global Change. We are indeed grateful for the constructive comments and suggestions from the two anonymous reviewers which have improved the presentation of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Astuti, I. S., Sahoo, K., Milewski, A., & Mishra, D. R. (2019). Impact of land use land cover (LULC) change on surface runoff in an increasingly urbanized tropical watershed. *Water Resources Management*, *33*(12), 4087-4103.

[2] McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal*, *61*(13), pp.2295-2311.

[3] Haase, D., 2009. Effects of urbanization on the water balance–A long-term trajectory. *Environmental Impact Assessment Review*, *29*(4), pp.211-219.

[4] Aspinall, R. and Pearson, D., 2000. Integrated geographical assessment of environmental condition in water catchments: Linking landscape ecology, environmental modelling and GIS. *Journal of Environmental Management*, *59*(4), pp.299-319.

[5] Melloul, A.J. and Collin, M.L., 2003. Harmonizing water management and social needs: a necessary condition for sustainable development. The case of Israel's coastal aquifer. *Journal of Environmental Management*, *67*(4), pp.385-394.

[6] Akram, M. and Hamid, A., 2013. A comprehensive review on water balance. *Biomedicine & Preventive Nutrition*, *3*(2), pp.193-195.

[7] Huang, X., Wang, H. and Xiao, F., 2022. Simulating urban growth affected by national and regional land use policies: Case study from Wuhan, China. *Land Use Policy*, *112*, p.105850.

[8] Fletcher, T.D., Andrieu, H. and Hamel, P., 2013. Understanding, management, and modeling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in water resources*, *51*, pp.261-279.

[9] Kleemann, J., Inkoom, J.N., Thiel, M., Shankar, S., Lautenbach, S. and Fürst, C., 2017. Peri-urban land use pattern and its relation to land use planning in Ghana, West Africa. *Landscape and urban planning*, *165*, pp.280-294.

[10] Enoguanbhor, E.C., Gollnow, F., Walker, B.B., Nielsen, J.O. and Lakes, T., 2022. Simulating urban land expansion in the context of land use planning in the Abuja City-Region, Nigeria. *GeoJournal*, pp.1-19.

[11] Haase D., 2003. Holocene floodplains and their distribution in urban areas – functionality indicators for their retention potentials. Landsc Urban Plan ; 66: 5-18.

[12] Herczeg, A.L. and Leaney, F.W., 2011. Environmental tracers in arid-zone hydrology. *Hydrogeology Journal*, *19*(1), p.17.

[13] Bam, E.K. and Ireson, A.M., 2019. Quantifying the wetland water balance: a new isotope-based approach that includes precipitation and infiltration. *Journal of Hydrology*, *570*, pp.185-200.

[14] Birkel, C., Duvert, C., Correa, A., Munksgaard, N.C., Maher, D.T. and Hutley, L.B., 2020. Tracer-aided modeling in the low-relief, wet-dry tropics suggests water ages and DOC export are driven by seasonal wetlands and deep groundwater. *Water Resources Research*, *56*(4), p.e2019WR026175.

[15] Mook, W. and Rozanski, K., 2000. Environmental isotopes in the hydrological cycle. *IAEA Publish*, *39*(1), p.2.

[16] Tondu, J.M.E., Turner, K.W., Wolfe, B.B., Hall, R.I., Edwards, T.W.D. and McDonald, I., 2013. Using water isotope tracers to develop the hydrological component of a long-term aquatic ecosystem monitoring program for a northern lake-rich landscape. *Arctic, antarctic, and alpine research*, *45*(4), pp.594-614.

[17] Mohammed, A.A., Sule, B.F., Salami, A.W., Adeogun, A.G., Ayanshola, A.M. and Oladeji, A.S., 2022. Prediction and Simulation of Kainji Hydropower Reservoir Operation in Nigeria. *Nigerian Journal of Engineering*, *29*(1), pp.29-29.

[18] Jain, G.V., Agrawal, R., Bhanderi, R.J., Jayaprasad, P., Patel, J.N., Agnihotri, P.G. and Samtani, B.M., 2016. Estimation of sub-catchment area parameters for Storm Water Management Model (SWMM) using geo-informatics. *Geocarto International*, *31*(4), pp.462-476.

[19] Amoo, T.O., 2018. Integrated hydrological modelling for sustainable water allocation planning: Mkomazi Basin, South Africa case study (Doctoral dissertation).

[20] Borah, D. K., Ahmadisharaf, E., Padmanabhan, G., Imen, S., & Mohamoud, Y. M. (2019). Watershed models for development and implementation of total maximum daily loads. *Journal of Hydrologic Engineering*, *24*(1), 03118001.

[21] Ballinas-González, H.; Alcocer-Yamanaka, V.; Canto-Rios, J.; Simuta-Champo, R. **2020.** Sensitivity Analysis of the Rainfall–Runoff Modeling Parameters in Data-Scarce Urban Catchment. *Hydrology*, *7*, 73.

[22] Hussain, S.N.; Zwain, H.M.; Nile, B.K. 2021. Modeling the effects of land-use and climate change on the performance of stormwater sewer system using SWMM simulation: Case study. *J. Water Clim. Chang. 13*, 125–138.

[23] Duarte, A. C., Ferreira, C., & Vitali, G. (2022). Use of simulation models to aid soil and water conservation actions for sustainable agro-forested systems. In *Natural resources conservation and advances for sustainability* (pp. 389-412). Elsevier.

[24] Lin, Z. (2011). Estimating Water Budgets and Vertical Leakages for Karst Lakes in North-Central Florida (United States) Via Hydrological Modeling 1. *JAWRA Journal of the American Water Resources Association*, *47*(2), 287-302.

[25] Arjenaki, M.O., Sanayei, H.R.Z., Heidarzadeh, H. and Mahabadi, N.A., 2021. Modeling and investigating the effect of the LID methods on collection network of urban runoff using the SWMM model (case study: Shahrekord City). *Modeling Earth Systems and Environment*, *7*(1), pp.1-16.

[26] Branger, F., Kermadi, S., Jacqueminet, C., Michel, K., Labbas, M., Krause, P., ... & Braud, I. (2013). Assessment of the influence of land use data on the water balance components of a peri-urban catchment using a distributed modelling approach. *Journal of Hydrology*, *505*, 312-325.

[27] Clark, G.E., Ahn, K.H. and Palmer, R.N., 2017. Assessing a regression-based regionalization approach to ungauged sites with various hydrologic models in a forested catchment in the northeastern United States. *Journal of Hydrologic Engineering*, *22*(12), p.05017027.

[28] Duarte, A. C., Ferreira, C., & Vitali, G. (2022). Use of simulation models to aid soil and water conservation actions for sustainable agro-forested systems. In *Natural resources conservation and advances for sustainability* (pp. 389-412). Elsevier.

[29] Daniel, E. B., Camp, J. V., LeBoeuf, E. J., Penrod, J. R., Dobbins, J. P., & Abkowitz, M. D. (2011). Watershed modeling and its applications: A state-of-the-art review. *The Open Hydrology Journal*, *5*(1).Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., & Koivusalo, H. (2014). Spatial resolution considerations for urban hydrological modelling. *Journal of hydrology*, *512*, 482-497.

[30] Pandi, D., Kothandaraman, S., & Kuppusamy, M. (2021). Hydrological models: a review. *International Journal of Hydrology Science and Technology*, *12*(3), 223-242.

[31] Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., & Koivusalo, H. (2014). Spatial resolution considerations for urban hydrological modelling. *Journal of hydrology*, *512*, 482-497.

[32] Akoko, G., Le, T.H., Gomi, T. and Kato, T., 2021. A review of SWAT model application in Africa. *Water*, *13*(9), p.1313.

[33] Fu, B., Merritt, W. S., Croke, B. F., Weber, T. R., & Jakeman, A. J. (2019). A review of catchment-scale water quality and erosion models and a synthesis of future prospects. *Environmental modelling & software*, *114*, 75-97.

[34] Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A. and Van Liew, M. W. 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, 55 (4): 1491-1508.

[35] Tetsoane, S. T., Woyessa, Y. E., & Welderufael, W. A. (2013). Evaluation of the SWAT model in simulating catchment hydrology: case study of the Modder River Basin. *Interim: Interdisciplinary Journal*, *12*(3), 73-85.

[36] Lee, S., Yeo, I.Y., Lang, M.W., Sadeghi, A.M., McCarty, G.W., Moglen, G.E. and Evenson, G.R., 2018. Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules. *Journal of Environmental Management*, *223*, pp.37-48.

[37] Tufa, F.G. and Sime, C.H., 2021. Stream flow modeling using SWAT model and the model performance evaluation in Toba sub-watershed, Ethiopia. *Modeling Earth Systems and Environment*, *7*, pp.2653-2665.

[38] Blair, P., & Buytaert, W. (2016). Socio-hydrological modelling: a review asking "why, what and how?". *Hydrology and Earth System Sciences*, *20*(1), 443-478.

[39] Zhou, S., Huang, Y., Wei, Y. and Wang, G., 2015. Socio-hydrological water balance for water allocation between human and environmental purposes in catchments. *Hydrology and Earth System Sciences*, *19*(8), pp.3715-3726.

[40] Sivapalan, M., Savenije, H.H. and Blöschl, G., 2012. Socio-hydrology: A new science of people and water. *Hydrol. Process*, *26*(8), pp.1270-1276.

[41] Vika, V., Ndhleve, S., Mbandzi, N., & Nakin, M. D. V. (2023). Assessment of Physico-Chemical and Microbiological Parameters of Mthatha River in Eastern Cape, South Africa. Environmental Forensics, 1-14.

[42] Rattanaviwatpong, P., 2001. Comparison of Water Quality Models-HSPF, SWMM, and WASP and TMDL applications. *University of Washington, Department of Chemical Engineering*.

[43] Kumar, P., Avtar, R., Dasgupta, R., Johnson, B. A., Mukherjee, A., Ahsan, M. N., ... & Mishra, B. K. (2020). Socio-hydrology: A key approach for adaptation to water scarcity and achieving human well-being in large riverine islands. *Progress in Disaster Science*, *8*, 100134.

[44] Sivapalan, M., 2015. Debates—Perspectives on socio-hydrology: Changing water systems and the "tyranny of small problems"—Socio-hydrology. *Water Resources Research*, *51*(6), pp.4795-4805.

[45] Neitsch, S. L., Arnold, J. G., Kiniry, J. R. and Williams, J. R. 2011. *Soil and water assessment tool theoretical documentation version 2009*. Texas Water Resources Institute.

[46] Horne, D., 1997. FHWA study of South African pavement and other highway technologies and practices. Federal Highway Administration.

[47] Hainin, M.R., Cooley Jr, L.A. and Prowell, B.D., 2003. An investigation of factors influencing permeability of Superpave mixes. *International Journal of Pavements*, *2*(2), pp.41-52.

[48] Wolski, P., Conradie, S., Jack, C. and Tadross, M., 2021. Spatio-temporal patterns of rainfall trends and the 2015–2017 drought over the winter rainfall region of South Africa. *International Journal of Climatology*, *41*, pp.E1303-E1319.