

Developing a foundational hydrological model for the Limpopo River basin using the Soil and Water Assessment Tool Plus (SWAT+)

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INFORMATION

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Work package	System Monitoring
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ABSTRACT

This study aimed to create a foundational hydrological model for the transboundary Limpopo River Basin (LRB) in Southern Africa using the Soil and Water Assessment Tool Plus (SWAT+) model. The model is a crucial part of a larger project to develop a digital twin of the river basin. The SWAT+ model simulated streamflow and other important hydrological processes in the LRB, using various data sources such as global gridded rainfall and other weather parameters, soils, landcover datasets, and in-situ discharge measurements from seven locations in South Africa for calibration and validation. The automatic calibration routine IPEAT+, freely available as part of the SWAT+ framework, was used for model calibration. The model was run for 23 years, from 2001 to 2023, with the calibration and validation periods varying for each gauge location. The calibration of the LRB SWAT+ model primarily consists of the discharge data from South Africa with Botswana, Zimbabwe, and Mozambique still awaited from the stakeholders. The results showed that the foundational LRB SWAT+ model achieved a good performance in simulating streamflow in the South Africa part of the LRB, with Nash Sutcliffe efficiency values ranging from 0.42 to 0.69. Further calibration in other sub-basins and the incorporation of additional reservoir data are expected to improve the overall performance of the LRB SWAT+ model.

The partially calibrated and validated foundational SWAT+ model for the LRB (mainly in the South Africa part of LRB) will be the initial core of a river basin digital twin that is under development. It will integrate seasonal rainfall forecasts to simulate seasonal water availability. The fully calibrated foundational SWAT+ LRB model is expected to be available by the end of this year. It will serve as the basis for several planned applications as part of the LRB DT. The first application will focus on deriving flow patterns in the LRB catchment under unaltered natural conditions. The next application will concentrate on integrating ECMWF seasonal rainfall forecasts to predict water availability at 310 sub-basins and key channel reaches critical for environmental flows in the LRB. An updated version of the SWAT+ LRB foundational model is currently in progress. It aims to enhance the representation of reservoirs and their operations within the SWAT+ model and provide additional calibration sites within different sub-basins. This model will act as a baseline to create multiple planned applications co-developed with stakeholders.



Citation

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BACKGROUND

The Limpopo River Basin (LRB) in Southern Africa is a transboundary river basin shared by four riparian countries (Botswana, Zimbabwe, South Africa and Mozambique). The LRB faces numerous water management challenges, from population growth, competing water uses, historic droughts in the upstream countries, and flooding downstream during heavy rainfall (FAO 2004). Climate change impacts are felt through warmer and wetter winters and hotter and drier summers (Tshiala, 2011, Rankoana, 2020). To address these challenges, it's important to reliably assess and communicate changes in water availability to relevant stakeholders which will help in designing and implementing coping and adaptation strategies. We need reliable hydrological tools that cover the entire LRB to assess water availability and other changes as this will provide critical insights into the hydrological processes. A publicly available hydrological modeling tool is essential for the LRB as this will facilitate informed decision-making and support cooperative, integrated water resource management across the four riparian countries in the LRB.

In the LRB, Pitman is the most widely applied hydrological model in southern Africa (Hughes, 2013). It is a monthly time step hydrological model that operates at the spatial scale of sub-basin with each sub-basin having its own climate inputs and parameter sets. Pitman model was used as the basis for the 2013 LRB Monograph Study by the Limpopo Watercourse Commission (LIMCOM) to develop alternative development scenarios and an Integrated Water Resources Management Strategy and Plan (Sitoe and Qwist-Hoffman, 2013). Initial SWAT model applications in the LRB were primarily from the research domain. The SWAT model (SWAT 2012) was used to assess the availability of water resources in the LRB (Mosase et al., 2019). This baseline model was further extended to couple MODFLOW for modelling potential groundwater recharge zones. A national input database was developed to run the SWAT model for South Africa which includes a portion of the LRB (Le Roux, 2020). In addition to the basin scale studies covering the entire LRB, multiple hydrological models were developed for different sub-basins within the LRB. In addition to the basin specific models for LRB, continental scale models like Famine Early Warning Systems Network Land Data Assimilation System provides hydrological variables for the LRB (McNally et al., 2017). Trambauer et al., 2014 used a finer resolution of the global scale hydrological model PCR-GLOBWB to identify and simulate historical drought events in the LRB. A semi-distributed Global Hydrological Model was coupled with the Water Simulation Module of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to assess climate change impacts on water availability in the LRB (Zhu and Ringler, 2012). Most of these existing LRB models are neither accessible nor publicly available to enable adoption and continuous updating.

Borrowing the concepts from the Artificial Intelligence community, a foundational hydrological model for a river basin is defined as a calibrated and validated physical-based model for a specific basin river basin using a widely well-established modelling framework to serve as the basis for developing diverse water resources modelling applications. A foundational hydrological model for the LRB will enable the development of applications for specific water management issues, including water availability predictions, flood and drought occurrences, environmental flow requirements, and management of withdrawals among others. This specific model for the basin will provide the necessary setup to simulate hydrological processes driven by climate forcings, based on given land use, topography, and soil conditions. A foundational LRB model is crucial for predicting the impacts of various factors on water availability in a dynamic manner. Making such a foundational LRB model publicly available could allow for continuous updates, serving as a knowledge repository for a wide range of stakeholders to access and adapt it for different potential applications.

This study aimed to use SWAT+ to build a foundational hydrological model of LRB at daily time intervals to serve as a basis for potential applications in the Digital Twin (DT) and beyond. A foundational hydrological model for the LRB using the SWAT+ modeling tool was developed to fill the crucial gap of a publicly available tool for water resources assessment. This model will serve as a basis for multiple applications as part of the river-basin digital twin. We chose SWAT+ as the tool to develop the LRB foundational model due to its open-source nature, extensive applications across different hydro-climatological conditions, the existing applications in LRB, and stakeholders' familiarity with the model. The previous version of the Pitman model used in the LRB monograph study is also currently being updated as part of the Global Environment Facility-funded Integrated Transboundary River Basin Management for the sustainable development of the LRB.

PURPOSE AND SCOPE

The main objective of this study was to develop a calibrated and validated SWAT+ model for the transboundary LRB to simulate streamflow and key hydrological process to serve as a foundational model for a variety of potential applications to be developed as a part of the DT and beyond. The LRB SWAT+ model will be made available publicly for applications by the riparian country stakeholders beyond the planned activities in the DT. This will be achieved through

- Developing the SWAT+ model to simulate various hydrologic variables at a daily time step for the transboundary LRB in the Southern Africa region.
- Carrying out multi-step calibration and validation of the model outputs using observed streamflow, and remote sensing-based evapotranspiration.

STUDY AREA

The LRB (Figure 1) is a transboundary river located in Southern Africa with its catchment divided between four riparian countries consisting of South Africa (45 %), Botswana (19 %), Zimbabwe (15 %) and Mozambique (21 %). Flowing 1750 km, the LRB total catchment area is 416,296 km² with an annual average discharge of 170 m³/s at its basin outlet (GWP, 2011). The river originates from South Africa at an elevation of 2331 m and drains into the Indian ocean in Mozambique after creating a vast floodplain area. It supports 21 million people in the region. Overall, the LRB is affected by physical and economic water scarcity. The LRB hosts large urban areas and key industrial clusters in Southern Africa. Competing water demands from different sectors over finite allocated water resources make it difficult for the riparian countries to manage the shared water resources. Furthermore, climate change has and will continue to make the water availability highly variable, aggravating the situation in the water stressed basin.

The LRB is predominantly semi-arid but temperate in the South African highveld part and warm temperate in the Mozambique plains. Hot weather dominates the semi-arid region with less than 400 mm of annual average rainfall which increases to 1000 mm in the downstream coastal plains. There exists an east-west and north-south gradient in terms of rainfall variability within the LRB. Rainfall is seasonally concentrated between October and April (95 % of the annual average), with significant inter-annual variability leading to droughts and floods (FAO, 2004).

The Limpopo region receives most of its annual rainfall between October and April, with a concentration in the months of December, January, and February. This pattern is heavily influenced by the Inter-Tropical Convergence Zone and is subject to significant year-to-year variations, leading to periods of drought and flooding (Wetterhall et al., 2014). The region's precipitation is also impacted by the El Nino Southern Oscillation (ENSO), resulting in warmer and drier conditions during strong ENSO events. In the LRB, summers are hot, and winters are mild, with average maximum temperatures ranging from 30-34 °C in the summer and 22-26 °C in winter. Minimum daily temperatures range from 18-22 °C in summer to 5-10 °C in winter, with temperature variations influenced by elevation and proximity to the ocean.

Three landcover classes dominate the LRB: cultivated agriculture, savanna, and grassland (Figures 2 and 3). These three classes account for 98 % of the basin area. Agriculture is the most dominant land cover in the LRB, occupying 53 % and

signifying its impact on the overall water resources availability within the basin. A significant part of the agricultural area within the basin is in the South African part of the LRB. Savana and grasslands occupy 25 and 20 %, respectively.

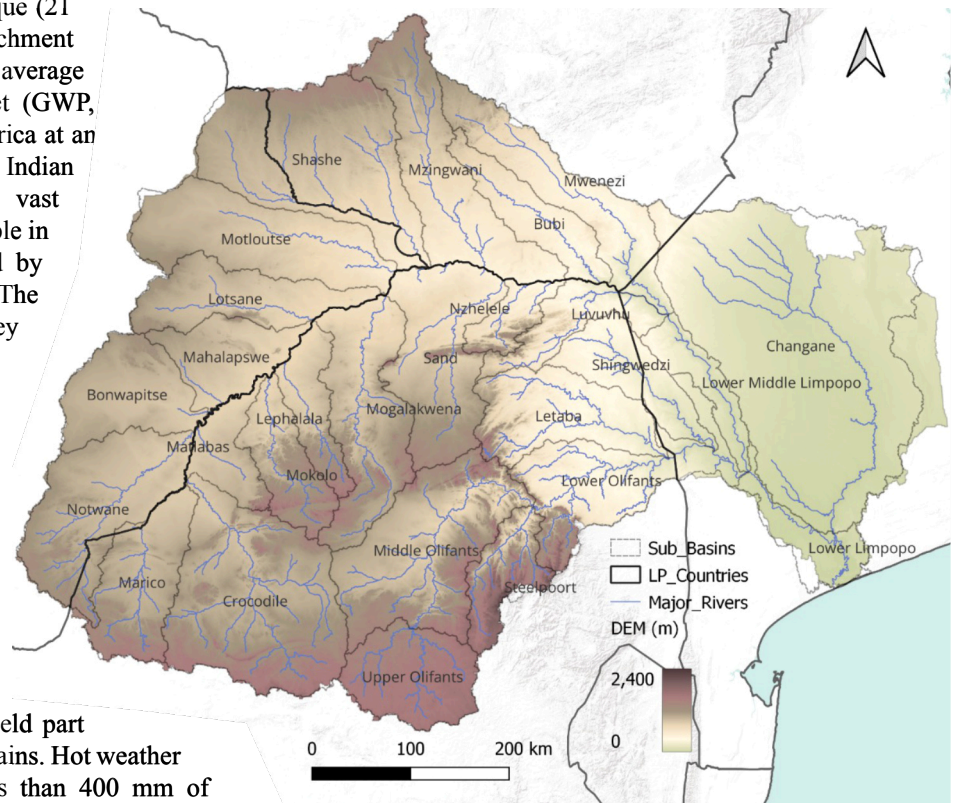


Figure 1. LRB showing elevation above sea level, the river basins and national boundaries (IWMI)

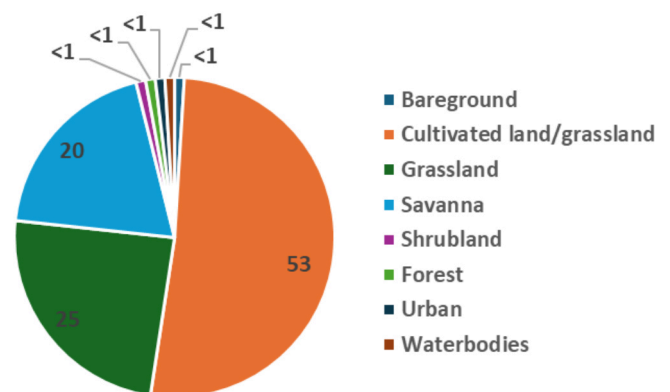


Figure 2. Land cover distribution in the LRB

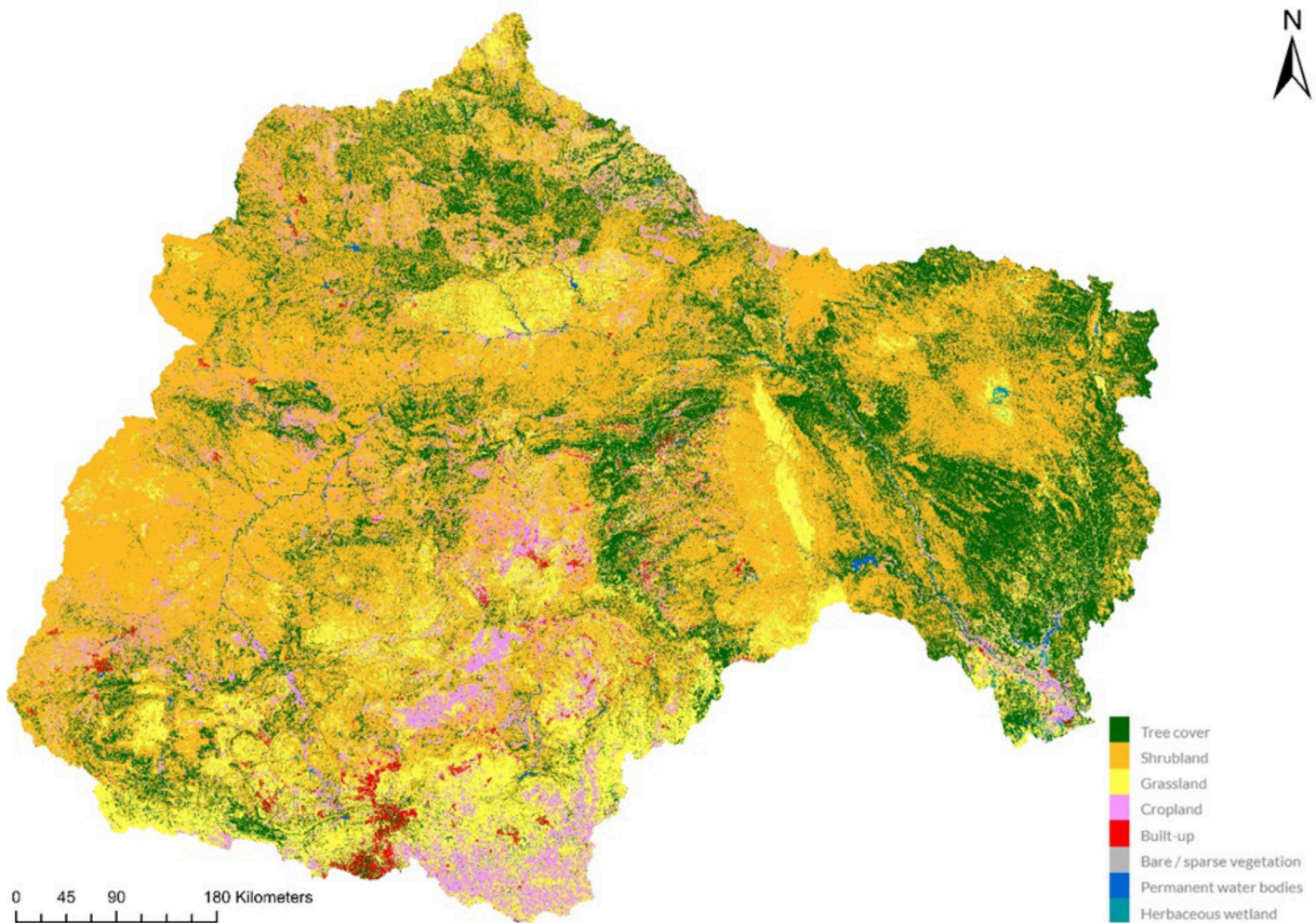


Figure 3. Landcover map of the LRB from ESA 10 m global landcover map for 2021 (ESA, 2021)

Large urban centres such as Gaborone, Pretoria, Johannesburg and Bulawayo are the major domestic water users in the basin (USAID et al., 2016). Irrigated agriculture is the largest overall user of water, accounting for approximately 50% of the total water demand. With a total irrigation potential 295,400 ha, the LRB has already realized 243,381 ha of irrigated area most of which is in the South African part of the catchment (LIMCOM, 2023). It also has a gross potential water requirement of 3453 million m³/year LIMCOM, 2023). The LRB is also key for the region’s energy security with an installed hydroelectric power capacity of 7072 MW (South Africa - 3596MW, Mozambique – 2216 MW, Zimbabwe – 1091 MW, and Botswana – 72 MW). In addition to irrigation and hydropower generation, the mining sector uses a significant amount of water in the basin and is predicted to grow by 30 % by the year 2025 (FAO, 2021).

METHODS

SWAT+ catchment Model

The SWAT program is a comprehensive, semi-distributed, continuous-time, processed-based model (Figure 4) (Arnold et al., 2012). The SWAT+ is a recently advanced and restructured version of the original SWAT model, designed to offer greater flexibility in representing and connecting spatial units within the model for simulating complex hydrological processes (Bieger et al., 2017). SWAT+ allows for the explicit calculation of various water balance components at the subbasin level. The model simulates surface runoff, sediment yield, evapotranspiration, and nutrient and soil-water interactions through water balance, routed through the channels. It has been widely used worldwide in different catchments across diverse hydro-climatological landscapes to assess the impacts of landuse, climate change, and various management decisions. In SWAT, a river basin is separated into several subbasins, further segmented into Hydrologic Response Units (HRUs) containing unique landuse, elevation, soil, and management.

Further, discharge can be aggregated at sub-basin levels or channel reach levels. It also provides advanced features for incorporating water availability in reservoirs and management scheduling. The SWAT+ model can be set up using QGIS as the front end to delineate sub-basins and HRUs based on the inputs from DEM, land use, and soil. .

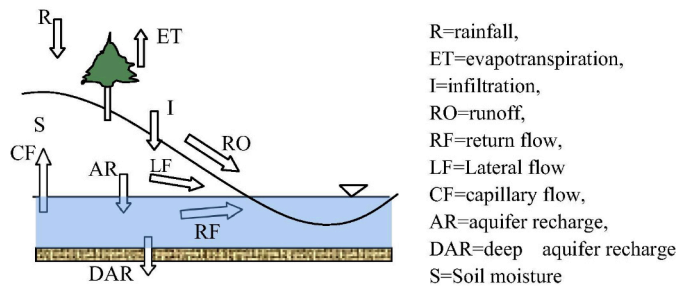


Figure 4. SWAT conceptual model (Abbaspour et al., 2015)

Data and default model setup for LRB

Global datasets were primarily used to setup the foundational LRB SWAT+ model, the plan being to upgrade with in-country data across all four riparian countries once this is available (Table 1). The NASADEM Digital Elevation Model (DEM) was downloaded from an Open Topography website using the QGIS plugin with LRB as the boundary at 30 m resolution. The European Space Agency (ESA) 10 m land cover map was used along with ISRIC world for soil information. Rainfall data from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) at 10 km resolution was used as the primary meteorological input. Other meteorological parameters were downloaded from the ERA5Land dataset, which is available at 9 km resolution. The QSWAT tool available as a part of the larger SWAT+ tool was primarily used to setup the LRB foundational hydrological model. The 30 m NASADEM DEM was used as the source to delineate stream networks and sub-basins in the LRB. The delineated sub-basins were checked for consistency with the larger sub-basin map available from the previous LIMIS database. In total, the entire LRB area of ~400,00 km² was divided into 310 sub-basins which were further subdivided into multiple HRUs based on unique slope, soil, and landuse, characteristics. The locations of 28 reservoirs, 20 environmental flow sites and 21 river flow measuring sites were included in the model. In addition to the 310 sub basins, 1432 channels were represented in the model from which potential flow estimates could be retrieved for many of the LRB tributaries. The subbasin map of the LRB SWAT model is shown in Figure 5.

Table 1. Datasets used in the LRB SWAT+ model

Data Type	Data	Data source/s
Topography	Digital elevation model (DEM)	NASADEM 30 m spatial resolution (https://portal.opentopography.org/dataCatalog?group=global)
Landuse	Landuse maps	ESA 10 m landcover (https://worldcover2021.esa.int/)
Soils	Soil map Soil properties	FAO/UNESCO soil map (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/)
Climate	Precipitation Temperature Solar Radiation Relative humidity Wind speed	Rainfall: MSWEP (https://www.gloh2o.org/mswep/) Other datasets: ERA5Land (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land)
Hydrology	Measured river discharge Actual Evapotranspiration data (ET)	Department of Water and Sanitation, South Africa (https://www.dws.gov.za/Hydrology/) WaPOR ET data (https://data.apps.fao.org/wapor/?lang=en)

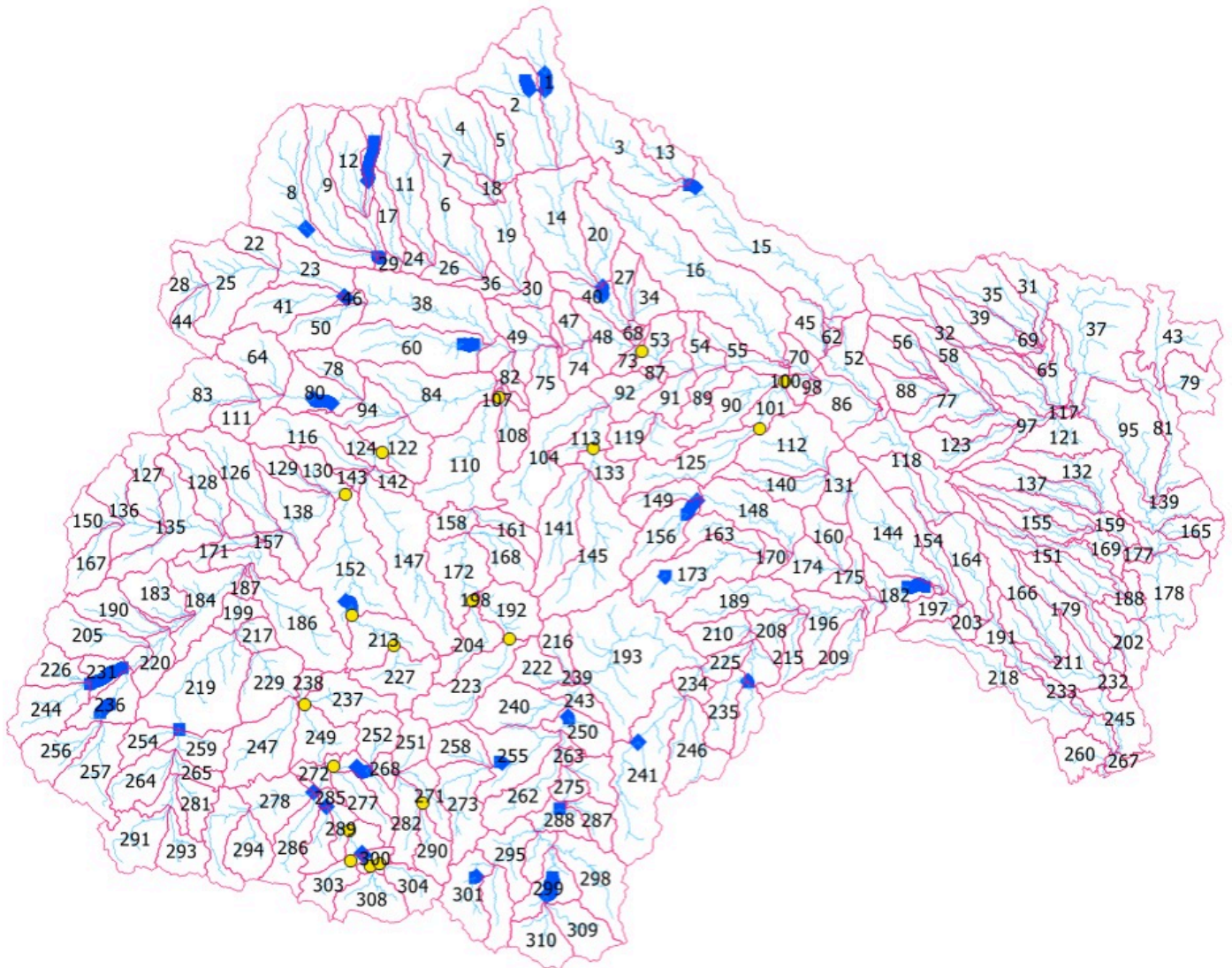


Figure 5. Sub-basin map of LRB represented in the SWAT+ model

Model calibration and evaluation

The calibration of the model was carried out using the freely available automatic calibration routine available within SWAT+. Discharge data for presently monitored gauging stations in South Africa were downloaded from the data portal of the Department of Water and Sanitation. The downloaded discharge data were analysed for consistency and outliers and cleaned to produce a calibration dataset. An example of a discharge data quality check to identify data inconsistencies is given in Figure 6. Discharge data from other countries in the LRB were not available at the time of calibration, so a multi-step calibration approach was carried out in which the model was calibrated for 17 locations mainly located in the South Africa part of LRB. A data acquisition request has been shared with all the riparian countries to obtain discharge datasets covering all the sub-basins. The calibration will be revisited when stakeholders make new datasets available.

In total, 17 discharge stations were initially shortlisted for model calibration. A detailed data review of these 17 discharge stations was conducted to identify artifacts in the discharge data like data gaps, outliers, and consistency between upstream and downstream stations (Figure 6). It can be seen from the encircled area with dotted lines that inconsistencies currently exist in the raw discharge data due to the presence of straight lines. From the 17 discharge stations (Figure 7) Only seven stations were selected and found reliable enough for final calibration, neglecting multiple sites in one subbasin.

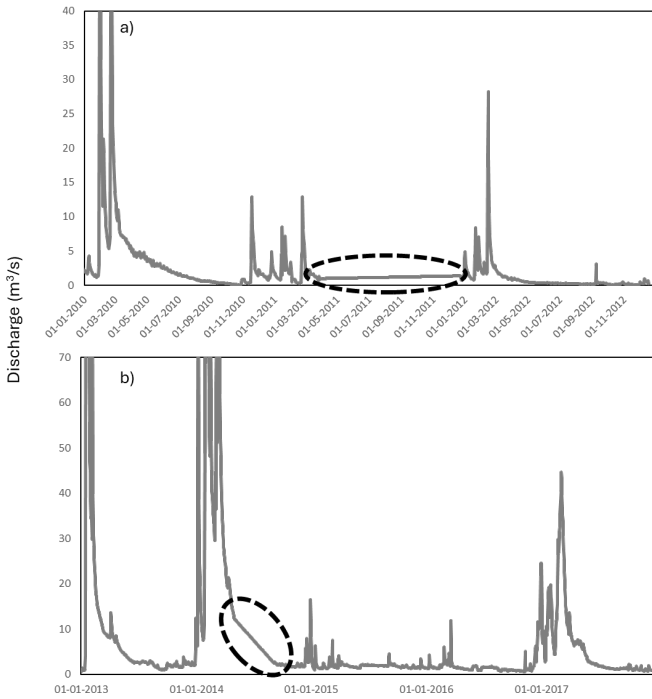


Figure 6. Discharge data assessment at the) Mutale River at Kruger National Park and b) Luvuvhu River at Mhinga showing inconsistencies in the raw data (shown within the dashed circles)

The SWAT+ model was calibrated using the SWAT+ Toolbox 1.0.5, a free tool for performing sensitivity analyses, calibration, and more. This tool is written in C# and available for the Windows operating system (Chawanda, 2021). The model was calibrated separately for several tributary rivers (sub-catchments) which were selected based on the availability of streamflow data.

Five criteria, including the Nash-Sutcliffe coefficient efficiency (NSE), relative percentage of bias (PBIAS), root mean square error (RMSE), correlation coefficient (r), and Kling-Gupta efficiency (KGE), were used to evaluate the model performance.

$$NSE = \frac{\sum_i (P_i - O_i)_i^2}{\sum_i (P_i - \mu_p)_i^2} \quad (1)$$

$$PBIAS = 100 \times \left[\frac{\sum_i^n (O_i - P_i)}{\sum_i^n O_i} \right] \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_i^n (P_i - O_i)}{n}} \quad (3)$$

$$KGE = 1 - \sqrt{(r - 1)^2 + \left(\frac{\sigma_P}{\sigma_O} - 1\right)^2 + \left(\frac{\mu_P}{\mu_O} - 1\right)^2} \quad (4)$$

where P is predicted; O is observed; n is sample size and bars denote mean, σ is the standard deviation, and μ the mean

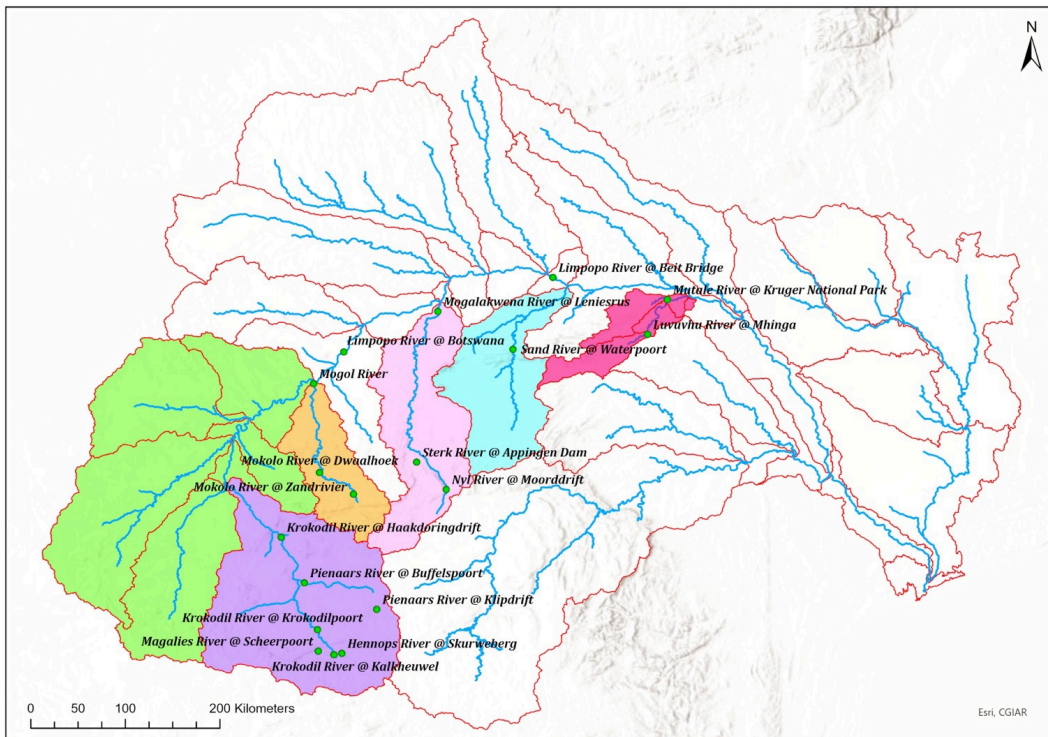


Figure 7. Location of calibrated sub-catchments of the LRB model (coloured) and 17 discharge gauges

RESULTS

Overall model performance

Table 2 presents the performance metrics of a hydrological model simulating river discharge at various stations. For the Limpopo River in Botswana, Pearson's correlation coefficient (r) is 0.67, indicating a moderate positive relationship between observed and simulated discharge. The Nash-Sutcliffe Efficiency (NSE) is 0.42, showing that the model has moderate predictive power. The Relative Percentage of Bias (PBIAS) is -7.5%, suggesting an underestimation of discharge by the model. The Root Mean Square Error (RMSE) is 22.06, reflecting the average error magnitude in the discharge predictions. This discharge outlet is located upstream in the LRB but located downstream of dams which are not represented in the model. Since the flow regimes are controlled dominantly by the reservoirs, incorporating its operating characteristics will improve the model simulations appreciably.

For the Crocodile River at Haakdoring Drift and BuffelsPoort, the r values are 0.75 and 0.68 respectively, with corresponding NSE values of 0.54 and 0.46, indicating better model performance at Haakdoring Drift. PBIAS values are -17.44% and -11.36%, respectively, with RMSE values of 16.55 and 7.71, suggesting better precision at BuffelsPoort. Both stations have Kling-Gupta Efficiency (KGE) values of 0.52. The

Mogalakwena River at Leniesrus shows a higher r of 0.78, NSE of 0.61, low PBIAS of -1.24 %, and an RMSE of 4.36, indicating strong model performance. The KGE is 0.68, further supporting this observation.

The Mokolo River at Mogol River station and Dwaalhoek have r values of 0.84 and 0.87, and NSE values of 0.67 and 0.69, respectively, indicating strong model performance. However, the PBIAS values of -28.39 % and -10.29 % suggest significant underestimation at the Mogol River station. The RMSE values are 10.43 and 7.99, with KGE values of 0.56 and 0.58, indicating better performance at Dwaalhoek. Overall, the model shows varying degrees of accuracy and precision across different stations, with generally better performance indicated by higher r , NSE, and KGE values, lower RMSE, and less negative PBIAS.

Performance Indicator	r	NSE	PBIAS	RMSE	KGE
Limpopo River at Botswana	0.67	0.42	(-7.5)	22.06	
Crocodile River at Haakdoring drift	0.75	0.54	(-17.44)	16.55	0.52
Crocodile River at BuffelsPoort	0.68	0.46	(-11.36)	7.71	0.52
Mogalakwena River at Leniesrus	0.78	0.61	(-1.24)	4.36	0.68
Mokolo River at Mogol River station	0.84	0.67	(-28.39)	10.43	0.56
Mokolo River at Dwaalhoek	0.87	0.69	(-10.29)	7.99	0.58

Table 2. SWAT+ LRB model performance assessment

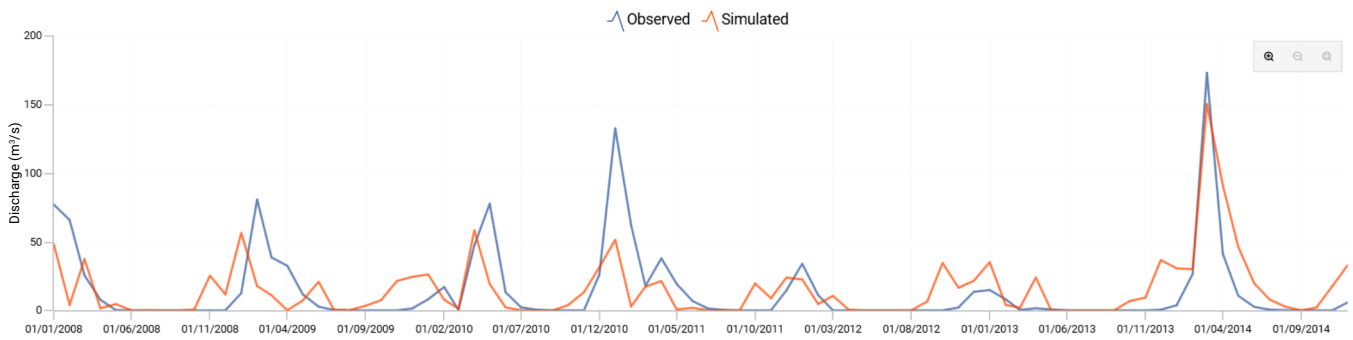


Figure 8. Observed vs simulated flows at a gauging station in Botswana

Model performance at individual calibration points

The following figures show graphical comparisons of in-situ observed and simulated flow series at seven stream gauging stations used for the LRB model calibration. The first is a discharge station located just downstream of the main Limpopo River, at the confluence with the Lephale River on the border between South Africa and Botswana (Figure 8). Important sub-basins of LRB, like the Crocodile River, are located upstream of this gauging station. The observed and simulated discharge at this gauging station show a general correspondence, with the model capturing the major peaks and troughs in observed discharge. However, there are noticeable discrepancies, particularly during the extreme events of January 2011, in which the model-simulated discharge substantially underpredicts the observed values. In the initial years of comparison, there exists a lag in the timing of peak discharge between observed and simulated values, evident from the 2009 and 2010 peak discharge values. Overall, the graph indicates that while the model captures the general trend of river discharge, periods of underestimation need to be addressed to enhance model accuracy. The simulated discharge values also indicate that the model response to the rainfall events is faster, as evident from the prominent rising limb of the hydrographs compared to the observed discharge values.

The calibration process utilized two discharge stations at BuffelsPoort (Figure 9) and Haakdongdrift (Figure 10) in the Crocodile River. The observed and simulated discharge at these two gauging stations in the Crocodile River exhibited good correspondence, with the model capturing the seasonal trends in observed discharge. However, the model consistently underestimated the peak discharge at both gauging locations by a significant amount (often > 50 %) during extreme rainfall events in 2005, 2008, 2011, and 2014. The factors causing the underestimation of discharge by the model need to be determined. The model's runoff generation initiates earlier than observed in the discharge events, leading to faster runoff contribution into the channel networks. Additionally, the underestimation of discharge in the Crocodile River could possibly result from the underrepresentation of extreme rainfall events in the MSWEP gridded rainfall precipitation data. Extreme events will be compared between MSWEP rainfall data and gauge dataset.

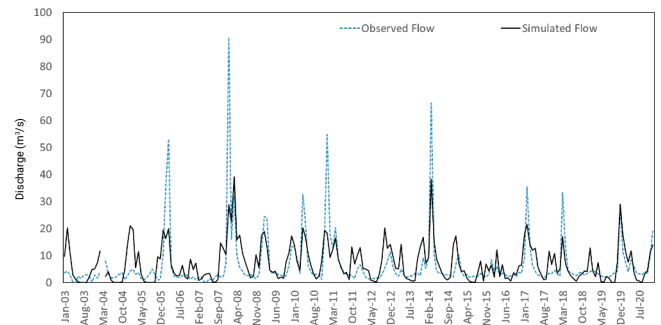


Figure 9. Observed vs. simulated flow at the BuffelsPoort station, Crocodile River

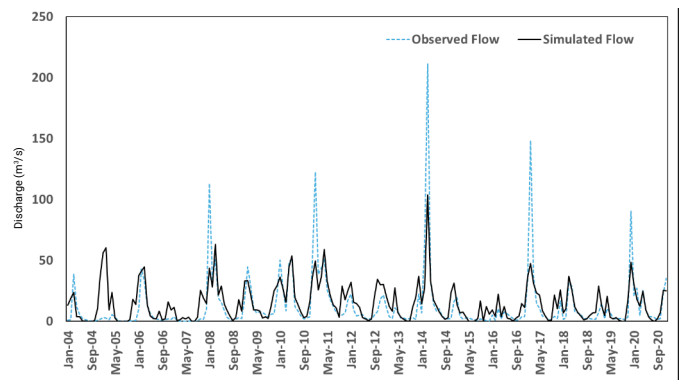


Figure 10. Observed vs. simulated flow at the Haakdongdrift station, Crocodile River

The graph at the Leniesrus station in the Mogalakwena River show good correspondence between the SWAT+ model simulation and observed values (Figure 11). The LRB SWAT+ model was able to capture the timing as well as the magnitude of the rainfall events appreciably. Two gauging stations Mogol (Figure 12) and Dwaalhoek (Figure 13) located in the Mokolo River were used for the calibration. In comparison with other calibration locations, Mogol and Dwaalhoek showed good model performance in terms of both timing and magnitude of the discharge from the extreme rainfall events. While the LRB model underpredicted discharge in Mokolo River too, the magnitude of underprediction is substantially lower in these two locations compared to other sub-basins like Crocodile. The 2014 event was the highest discharge event observed from the available gauge, which was significantly underpredicted. Slightly higher baseflow and a faster rising limb were observed consistently in the simulated hydrograph.

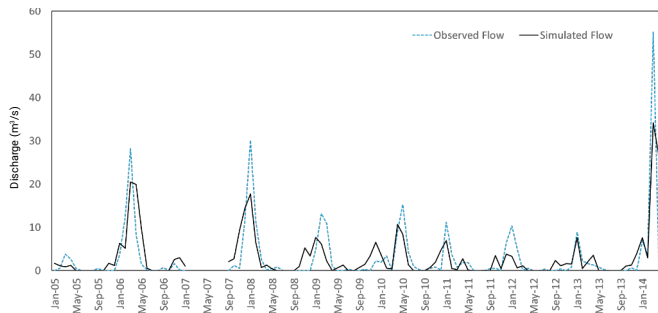


Figure 11. Observed vs. simulated flow at the Leniesrus station, Mogalakwena River

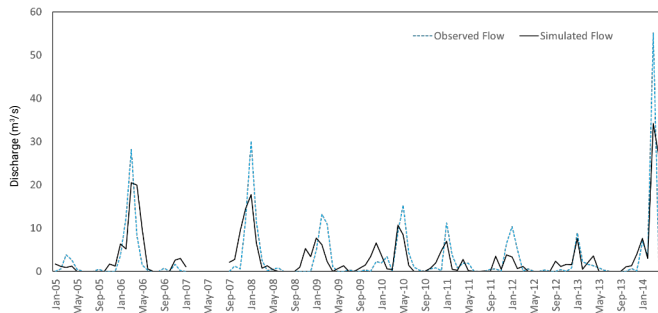


Figure 12. Observed vs simulated flows at the Mogol station, Mokolo River

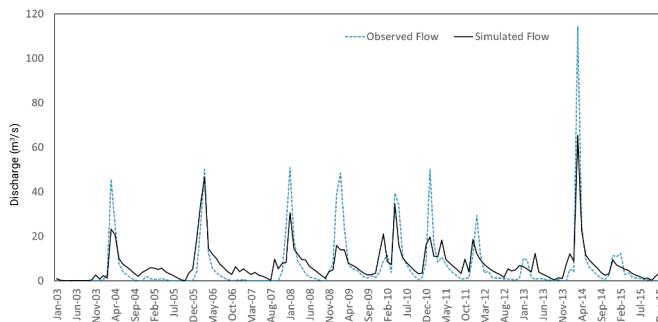


Figure 13. Observed vs simulated flows at the Dwaalhoek station, Mokolo River

Comparison of simulated and Observed evapotranspiration in one HRU

Figure 15 compares observed evapotranspiration (ET) data from the WaPOR (FAO) dataset with simulated ET data from the SWAT+ model for a specific Hydrological Response Unit (HRU). The graph shows a one-to-one linear relationship between the observed and simulated ET values, indicating a strong agreement between the two datasets. This alignment suggests that the SWAT+ model accurately captures the ET processes as recorded by WaPOR, with the points closely following the 45-degree line. This close match signifies the model's effectiveness in simulating ET, reinforcing its reliability for hydrological assessments in the HRU.

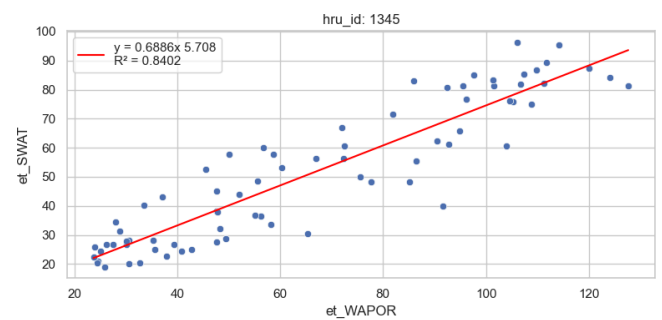


Figure 14. Comparison of evapotranspiration from WaPOR and SWAT+ LRB model

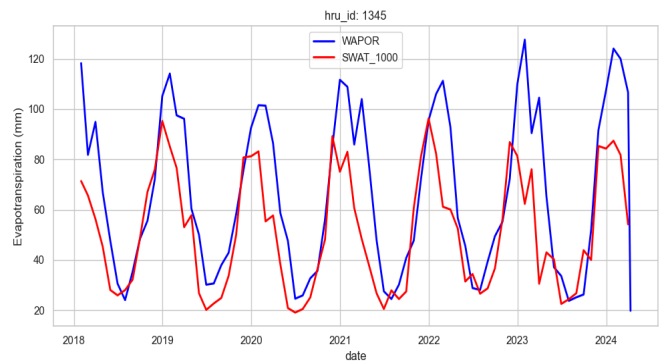


Figure 15. Time series comparison of SWAT+ ET and WaPOR ET data

APPLICATIONS

Deriving estimates of natural flow in the LRB under pristine conditions

Deriving estimates of natural flow in the LRB under pristine conditions

The water availability at a particular weir or reservoir located in the Limpopo River network depends on the available flow discharge of the river basin as well as the necessary flow to be released as the environmental flow. The determination of environmental flow is crucial, and it is calculated based on the natural flow conditions of the river network. Therefore, it is required to prepare long-term streamflow sequences for natural catchment conditions. The SWAT hydrological model can simulate the natural hydrological condition of the LRB when a digitized natural land cover map is available. To achieve this, all human impacts and related infrastructure, such as dams, weirs, diversion points, pumping stations, water supply abstractions, and irrigation schemes, were removed from the model configurations for present day conditions. It was not

possible however, to make changes to the distribution of vegetation types as they may have been in the past. Thereafter, the calibrated SWAT hydrological model was used to simulate the natural flow sequences in the LRB using a natural land cover map developed based on the methodology given below. The current land cover map was modified to depict natural land cover conditions (Figure 16). Spatial extraction techniques were utilized to identify reservoir shapes within the land use map, followed by Python-based replacement procedures to integrate surrounding natural values. In this case, the following modifications were made to the current land cover map.

The simulated mean annual runoff (MAR) of the Limpopo River at its outlet (near Xai-Xai) for the current landcover condition is 3148 million cubic meters (MCM), and the MAR in the natural land cover condition is 7882 MCM. This implies that the current-day net surface water impacts due to human activities in the LRB constitute about 60% of the total surface water resource. The following graph compares the historical flow series of the Limpopo River at its outlet (near Xai-Xai) in current land use conditions and the natural flow series simulated based on natural land cover conditions.

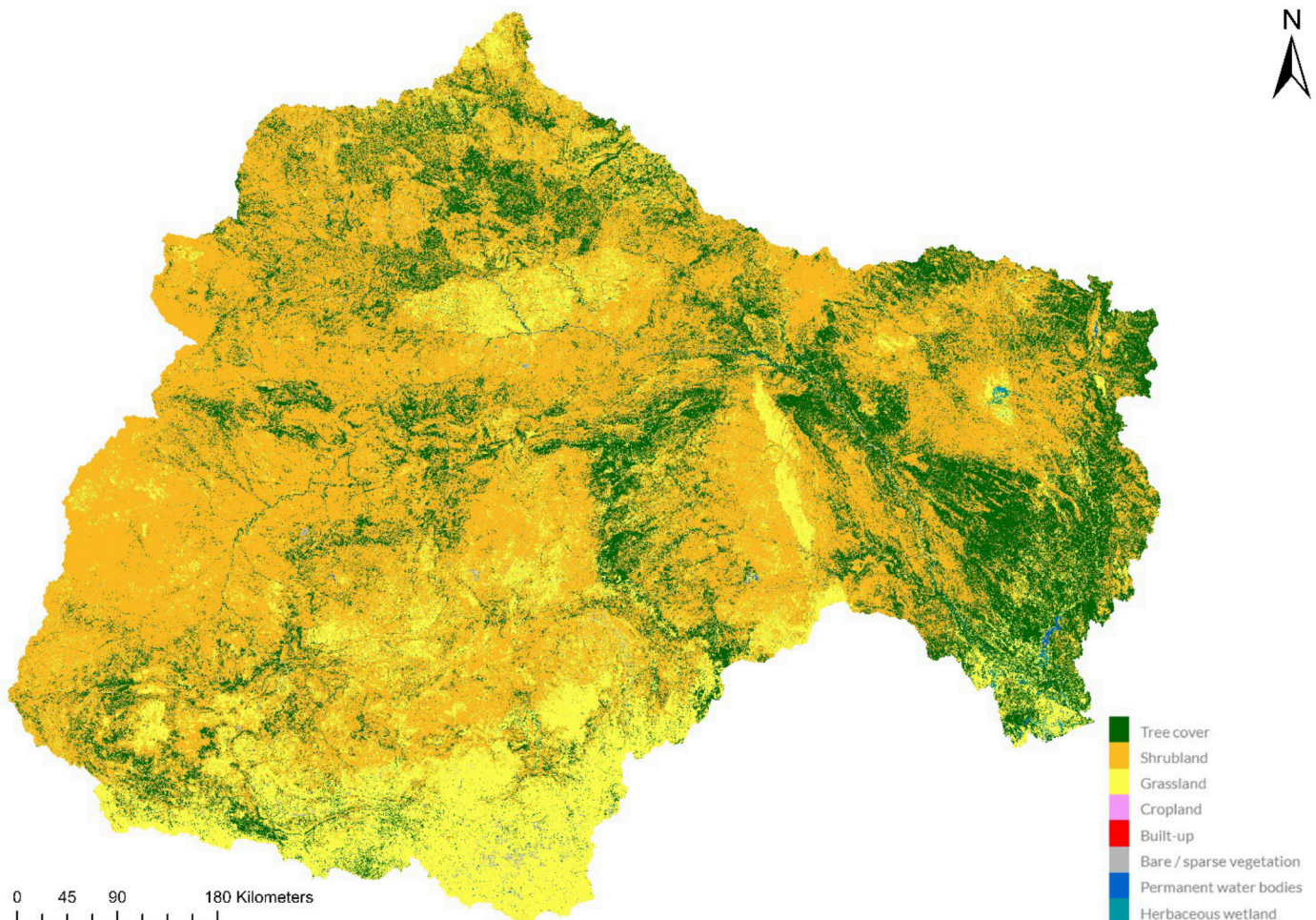


Figure 16. Modified ESA 10 m Landcover map representing LRB natural condition

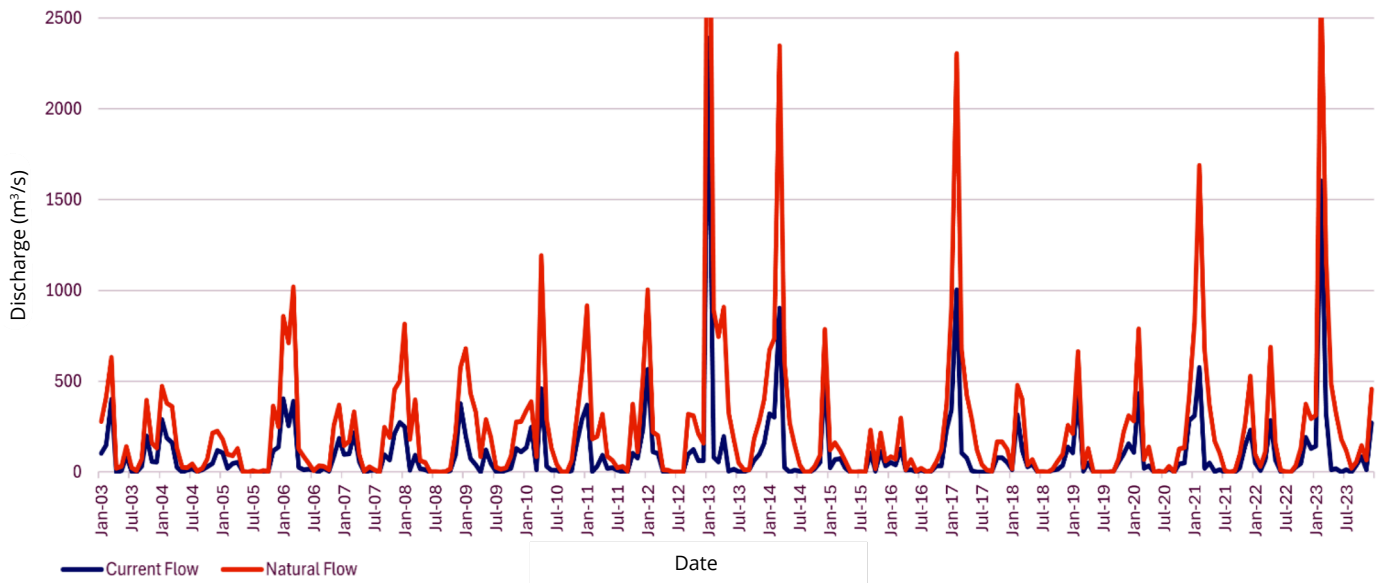


Figure 17. Comparison of current and natural flow in the LRB

The above graph shows that the peak flows (during the rainy period) in the current flow graph are substantially lower than those in the natural flow graph. This may be due to the attenuation effect of reservoirs in the current scenario, as the reservoirs store the flood inflow (as a retention storage when the reservoir is not in full condition) for use by water users such as agriculture and urban use during the dry periods. In addition, reservoirs tend to buffer discharge by temporarily storing water during flood events (above the spill level of the reservoir) which reduces the reservoir outflow (spillage) compared to the flood inflow.

Methodological frameworks for seasonal/sub-seasonal forecasting

We decided to utilize the widely used SWAT model to produce predictions of seasonal/sub-season water availability at the sub-basin level covering the entire LRB. SWAT is one of the most widely used hydrological models by various government agencies across the world owing to its simplicity in conducting the entire modelling exercise with GIS software like ArcGIS or QGIS. SWAT+ takes advantage of improvements in different model functionalities and parallel processing capability. The input datasets needed for the model setup were processed in QGIS interface using the QSWAT+ plugin. We leveraged a combination of in-situ datasets (where available) and globally available data sources as inputs for the SWAT+.

The activity employed a multi-stage calibration and validation process for the observed discharge, evapotranspiration and soil moisture to ensure dominant hydrological processes controlling the water balance in the LRB are correctly represented in the model. Automatic calibration algorithms like SWAT+ Tools, SWAT CUP or IPEAT were used to avoid biases associated with manual calibration strategies. The

model performance indicators were used to assess the performance of the model. These performance indicators include average river flow, r, NSE, PBIAS etc. The model was calibrated using SWATCUP (or manual adjustment of parameters).

With the model validated, forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal forecasting system (SEAS5) was integrated to predict water availability at the sub-catchment level. The overall framework incorporating modeling strategies and integration of weather forecast data is shown in Figure 18. This framework was further improved after discussion with LIMCOM and riparian country agencies. Discussion is currently underway with riparian country weather agencies to leverage the regional seasonal forecast for the southern African region to simulate water availability forecasts.

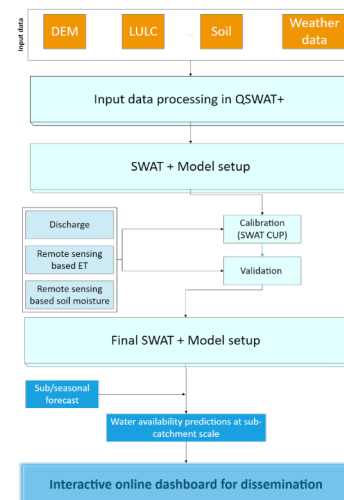


Figure 18. Seasonal water availability forecast framework for the LRB

CONCLUSIONS

This study developed a foundational LRB hydrological model using SWAT+ to serve as a basis for future applications. The model was calibrated and validated at seven locations primarily located in the South African part of LRB, and showed reasonable performance evident from the NSE values of 0.42 to 0.69. The LRB model could simulate trends in the observed discharge in all seven stations used for calibration. However, the model underpredicts the peak discharge significantly in the Crocodile River basin and Mokolo basin of the LRB. A preliminary comparison between SWAT+ model ET and WaPOR ET indicates a good correlation between the datasets in terms of temporal ET trends and magnitude. Additional data collection activities are currently underway to update the model with datasets on reservoir representation and characteristics, and to include additional calibration sites in the Olifants, Letaba, and other major subbasins of the LRB. Including reservoir operations and additional calibration sites will improve the model simulation appreciably and make it an ideal candidate for various river basin management applications.

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