The 2023 International Soil and Water Assessment Tool (SWAT) Conference
Session G1: Large-Scale Applications

Implementation of the SWAT Model for sustainable water management of the major river basins in Madagascar

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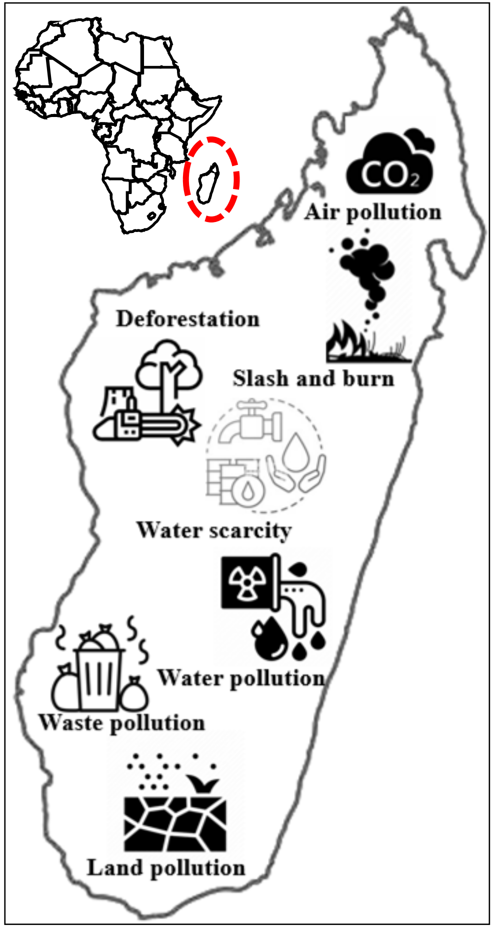
Introduction

Madagascar :

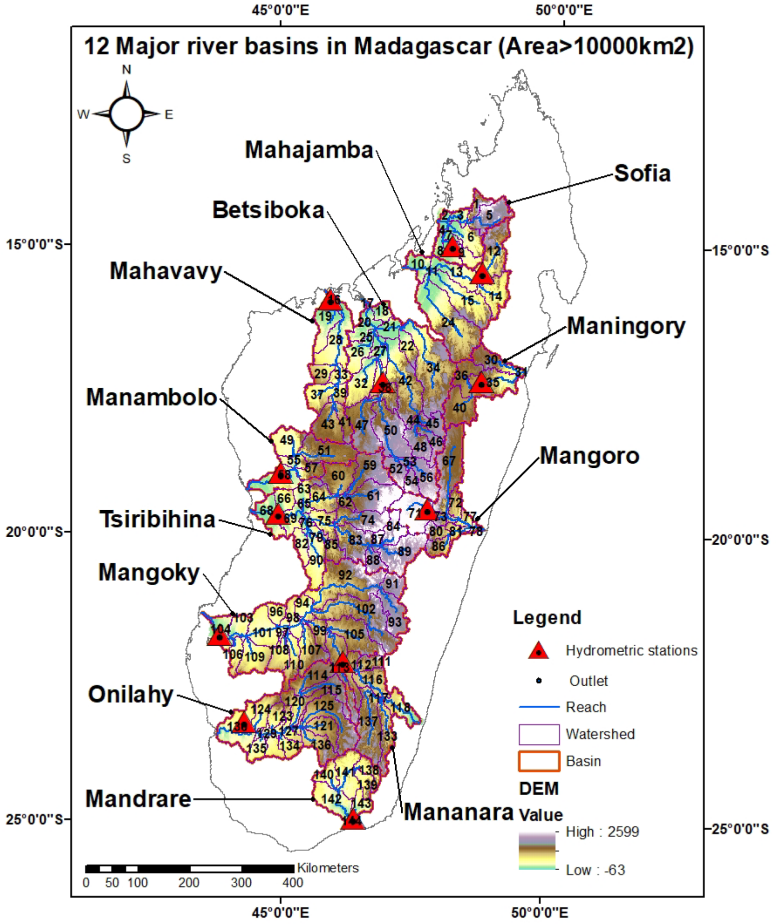


- East coast of Africa (*12°–25°S, 43°–51°E*);
- Population: 27million *(INSTAT, 2019)*;
- 2 main seasons: **wet/hot** (Nov-Apr), **dry/cool** (May-Oct);
- Annual precipitation 1500 mm/y; t 22.64°C *(Randriamarolaza et al., 2022)*;
- Annual precipitation decreases over most stations; Max. & min. temperatures increase up to 0.05°C /y and 0.04°C/y *(Raholijao et al., 2019)*;
- Hydrological processes and flow regimes poorly understood =>insufficient research and comprehensive data.

- INSTAT : Résultats Globaux Du Recensement Général De La Population Et De L'habitation De 2018 De Madagascar (RGPH-3) Tome 1, INSTAT-CCER, 2019; https://www.instat.mg/p/resultats-definitifs-du-rgph-3
- Randriamarolaza, L.Y.A., Aguilar, E., Skrynyk, O., Vicente-Serrano, S.M. and Domínguez-Castro, F., 2022. Indices for daily temperature and precipitation in Madagascar, based on quality-controlled and homogenized data, 1950–2018. International Journal of Climatology, 42(1), pp.265-288. https://doi.org/10.1002/joc.7243
- Raholijao, N., Arivelo, T.A., Rakotomavo, Z.A.P.H., Voahangin-dRakotoson, D., Srinivasan, G., Shanmugasundaram, J., Dash, I. and Qiu, J., 2019. Les tendances climatiques et les futurs changements climatiques a Madagascar-2019. Government of Madagascar, Antananarivo, Madagascar.[online] URL: https://www. primature. gov. mg/cpgu/wp-content/uploads/2019/11/Publication_FR_09_Sept_Version_Finale. pdf.
- Rakotoarimanana, Z.M.H and Rakotoarimanana, Z.H., 2022. A Review of Environmental Protection and Sustainable Development in Madagascar. J, 5(4), pp.512-531. https://doi.org/10.3390/j5040035

Study Area

Total Area: 320373.20 km²
Number of Subbasins: 144

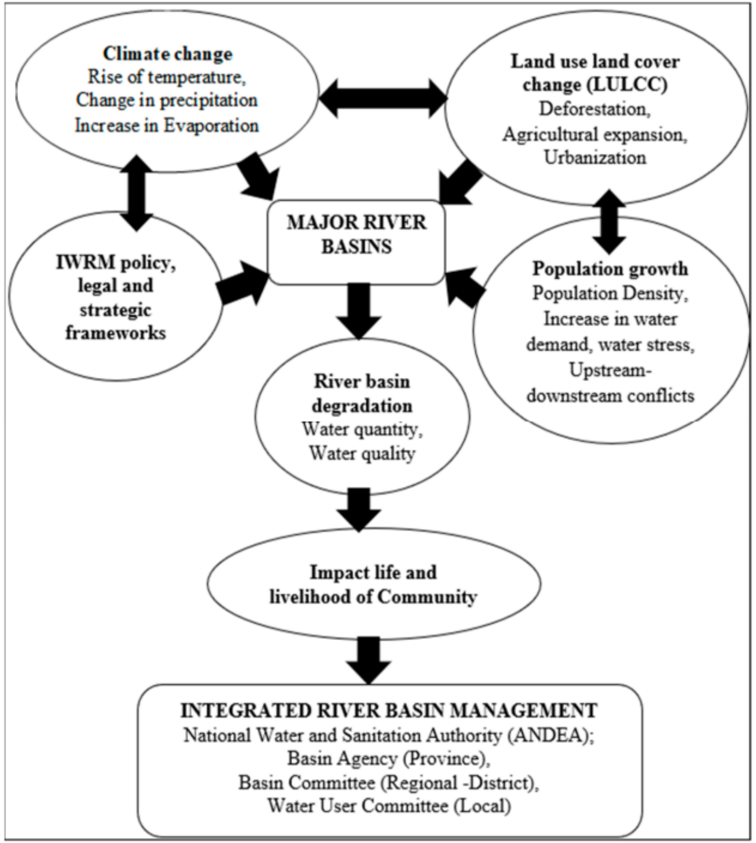


Basin Name	Lat. [deg.]	Lon. [deg.]	Elev Min. [m]	Elev Max. [m]	Drainage Area [km²]	Slope [%]	Longest path [km]	Stations
Sofia	-15.16	48.25	-3	1350	1904	9	145	Ankobakobaka
Mahajamba	-15.15	48.81	217	1759	4915	19	210	Antafiantsalama
Mahavavy	-16.01	45.91	-62	118	18620	2	54	Sitampiky
Maningory	-17.41	48.84	30	1517	9894	13	169	Andromba
Betsiboka	-17.30	48.36	725	1208	19300	13	150	Antsatrana
Manambolo	-19.15	44.93	-22	800	13070	6	164	Ambatolahy
Tsiribihina	-19.76	44.80	-20	458	47560	4	125	Betomba
Mangoro	-19.69	47.51	535	2593	5072	11	186	Tsinjoarivo
Mangoky	-21.74	43.92	-22	690	54100	3	124	Bevoay
Mananara	-22.39	46.23	622	1575	1981	11	142	Sahambano
Onilahy	-23.45	44.21	-22	637	32090	4	161	Tongobory
Mandrare	-25.08	46.37	-22	369	12520	4	36	Amboasary Sud

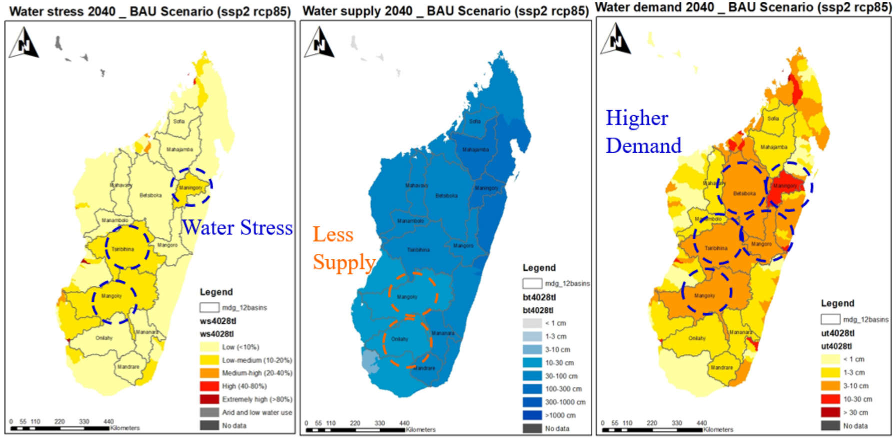
Source: Watershed delineation using ArcSWAT

Motivation

Threats to Basin Sustainability

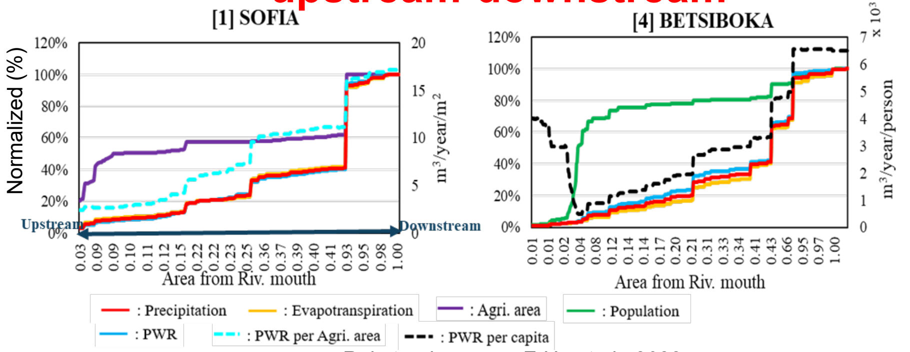


Risk of water scarcity



Rakotoarimanana, Z.H. and Ishidaira, H., 2022

Unequal spatial distribution upstream-downstream



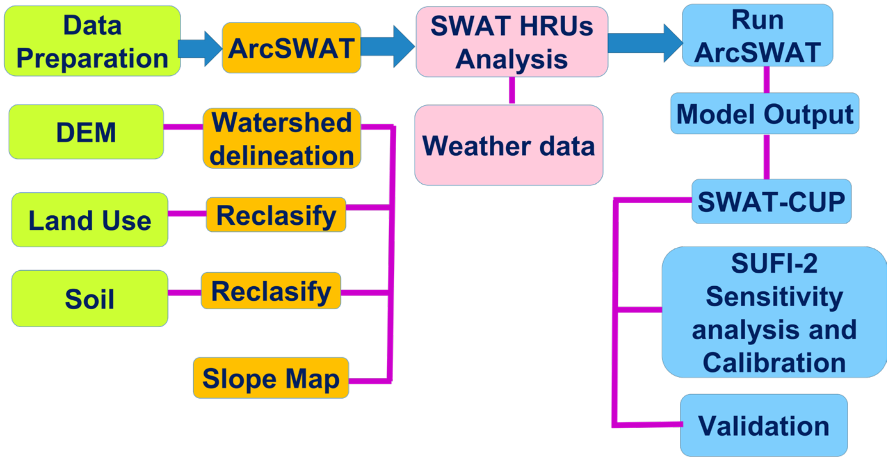
Rakotoarimanana, Z.H., et al., 2022

- Rakotoarimanana, Z.H. and Ishidaira, H., 2022. Analysis of River Basin Management in Madagascar and Lessons Learned from Japan. Water, 14(3), p.449. https://doi.org/10.3390/w14030449 .
- Rakotoarimanana, Z.H., Ishidaira, H., Magome, J., Souma, K. and Masutani, K., 2022. Assessment of Intra-Basin Water Resources: Case of the Major River Basins in Madagascar. Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research), 78(5), pp.I_107-I_115. https://doi.org/10.2208/jscejer.78.5_I_107.

Objectives

- To apply the SWAT model to analyze the streamflow & hydrological characteristics of the major river basins in Madagascar
- Assess the implications thereof for sustainable water management.

Materials and Methods



Data type	Description	Resolution/date	Source
Topography	Digital elevation model (DEM)	3s resolution (10x10 degree tiles)	HydroSHEDS database (Available at https://www.hydrosheds.org/)
Land-use map	Land-use classification	300 m resolution and 22 classes in 2020	European Space Agency (ESA CCI) (Available at https://www.esa-landcover-cci.org/)
Soil map	Soil type and texture	0-30cm and 30- 100 cm depth	Harmonized digital soil map of the world, Food and Agriculture Organization (FAO database) (Available at http://www.fao.org/)
Weather	Daily precipitation, maximum and minimum temperatures, relative humidity, wind, and solar radiation	38 km (daily) 1979–1999	National Centers for Environmental Prediction Climate Forecast System Reanalysis (NCEP/CSFR) **287 meteorological stations** (Available at https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr)
Discharge	Monthly observed runoff and point inlet	1979–1999	Madagascar National Meteorological and Hydrological Service / Global runoff database **12 hydrometric stations** (Available at https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Home)

SWAT 2012 & ArcGIS version 10.6.1

- **Warm-up period:** 3 years (1979-1981)
- **Simulation lengths:** 18 years (1982-1999)
- **Output timestep:** Monthly

SUFI-2 algorithm SWAT-CUP

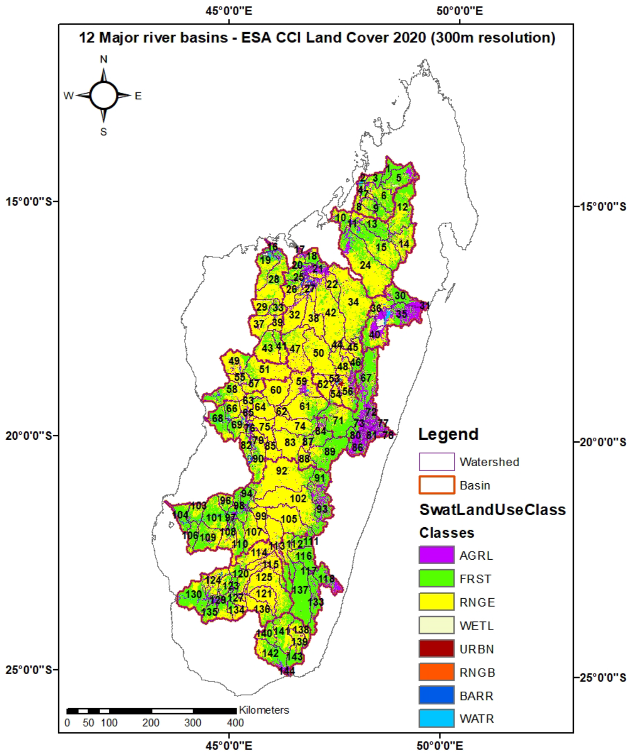
- **Model run:** 300 simulations
- **Objective function:** NSE= 0.5
- **Procedure**: Global sensitivity analysis

Model set-up

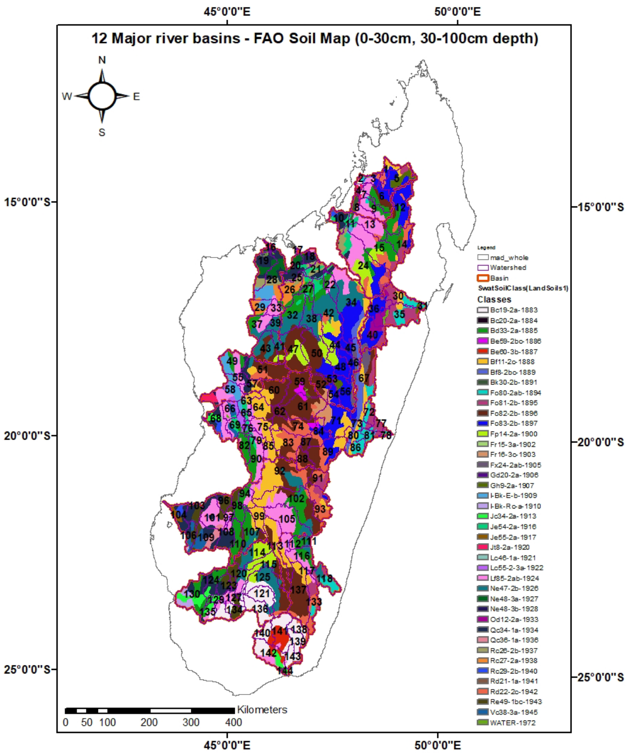
Hydrologic Response Unit (HRU)

Option Thresholds: 5 / 5 / 5 [%]
Number of HRUs: 1774

8 classes of land use



41 types of soils



Slope definition: 10 [%]

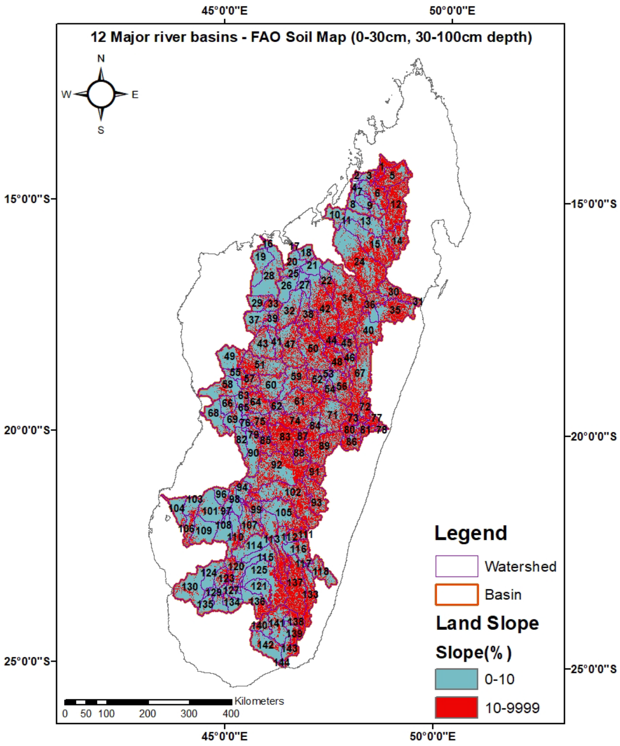
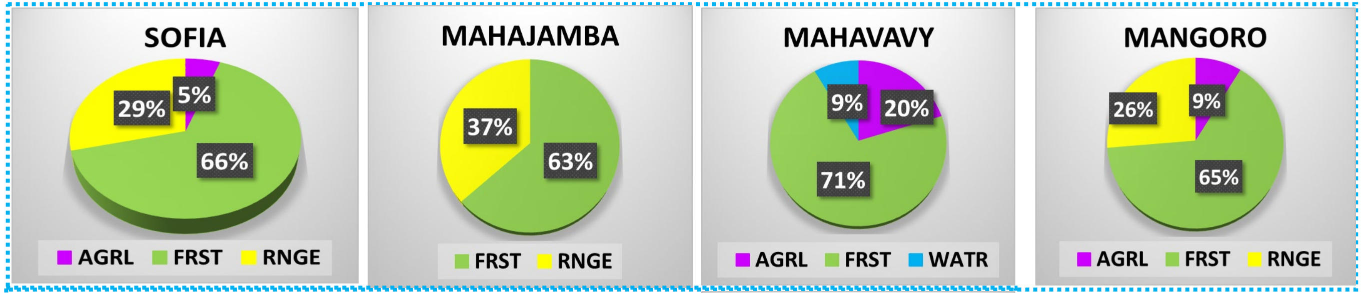
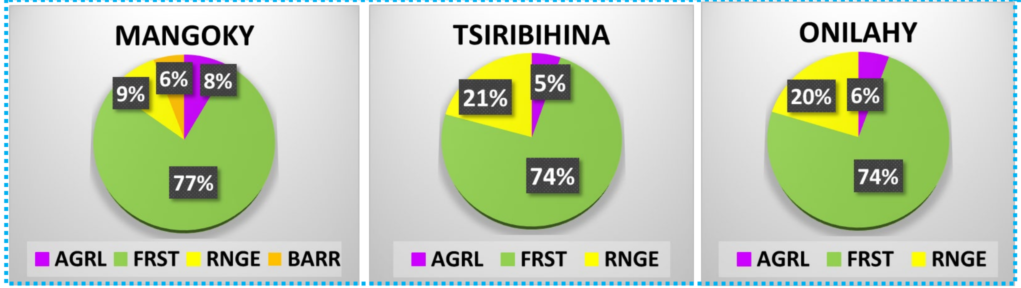


Figure: SWAT LU/LC Map/Soil Map/Slope Map

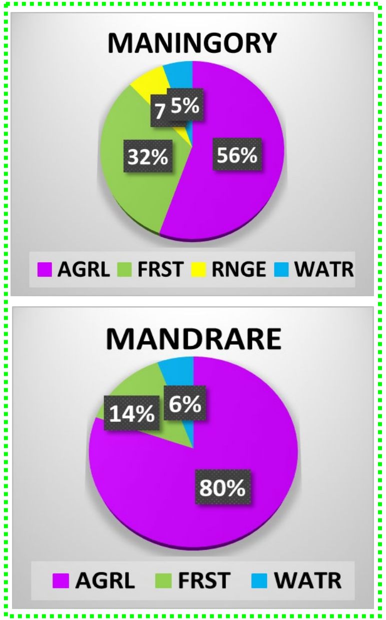
Land Use Summary of the Major River Basins

Forest-Mixed

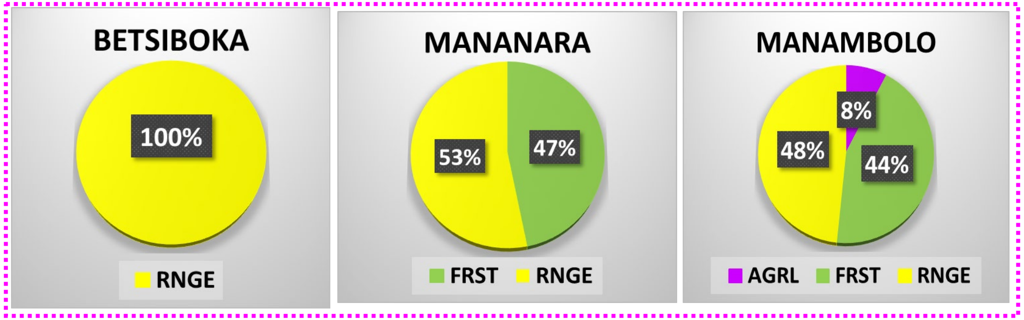


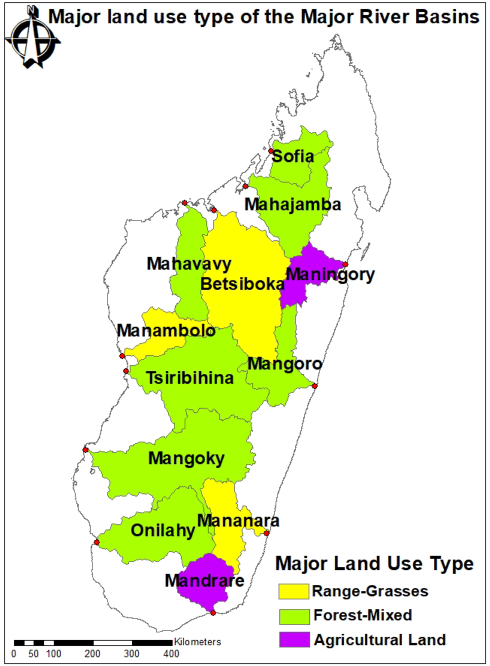


Agricultural Land



Range-Grasses





Performance ratings of hydrologic models for a monthly time step

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Performance rating	R^2	NSE	PBIAS %
Very Good	$0.7 < R^2 < 1$	$0.75 < NSE \leq 1.00$	PBIAS ≤ ±10
Good	$0.6 < R^2 < 0.7$	$0.65 < NSE \leq 0.75$	±10 ≤ PBIAS ≤ ±15
Satisfactory	$0.5 < R^2 < 0.6$	$0.50 < NSE \leq 0.65$	±15 ≤ PBIAS ≤ ±25
Unsatisfactory	$R^2 < 0.5$	$NSE \leq 0.50$	PBIAS ≥ ±25

Van Liew et al., 2003; Moriasi et al. 2007

P-factor ≥ 0.7 and **R-factor ≤ 1.5: satisfactory** for streamflow calibration

Abbaspour et al., 2007

- Van Liew, M.W. and Garbrecht, J., 2003. Hydrologic simulation of the little Washita river experimental watershed using SWAT 1. JAWRA Journal of the American Water Resources Association, 39(2), pp.413-426. https://doi.org/10.1111/j.1752-1688.2003.tb04395.x.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), pp.885-900.
- Abbaspour, K.C.; Rouholahnejad, E.; Vaghefi, S.; Srinivasan, R.; Yang, H.; Kløve, B. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. J. Hydrol. 2015, 524, 733–752. https://doi.org/10.1016/j.jhydrol.2006.09.014.

Results Parameters for calibration and their initial ranges

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Parameter_Name	Description	Min_value	Max_value
1:R__CN2.mgt	Soil Conservation Service (SCS) runoff curve number for moisture condition II	-0.2	0.2
2:V__ALPHA_BF.gw	Baseflow alpha factor (days)	0	1
3:R__SOL_AWC(..).sol	Available water capacity of the soil layer (mm mm-1)	0	1
4:V__ESCO.hru	Soil evaporation compensation factor	0	1
5:V__GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.2
6:V__SURLAG.bsn	Surface runoff lag time	0.05	24
7:V__GW_DELAY.gw	Groundwater delay (days)	0	500
8:R__OV_N.hru	Manning's "n" value for overland flow	0.01	30
9:V__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	0	500
10:V__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0	5000
11:V__RCHRG_DP.gw	Deep aquifer percolation fraction	0	1

*R: Relative (the existing parameter value is multiplied by 1+ a given value)
*V: Replace (the existing parameter value is replaced by a given value)

- **Six most sensitive parameters:** CN2, SOL_AWC, OV_N, ESCO, GW_DELAY, and RCHRG_DP.
- Findings consistent with the outcomes of a prior study in the Mangoky basin *(Rabezanahary et al., 2021).*

Rabezanahary Tanteliniaina, M.F., Rahaman, M.H. and Zhai, J., 2021. Assessment of the future impact of climate change on the hydrology of the Mangoky River, Madagascar using ANN and SWAT. Water, 13(9), p.1239.
https://doi.org/10.3390/w13091239

Modeling results after calibration &validation of monthly discharge

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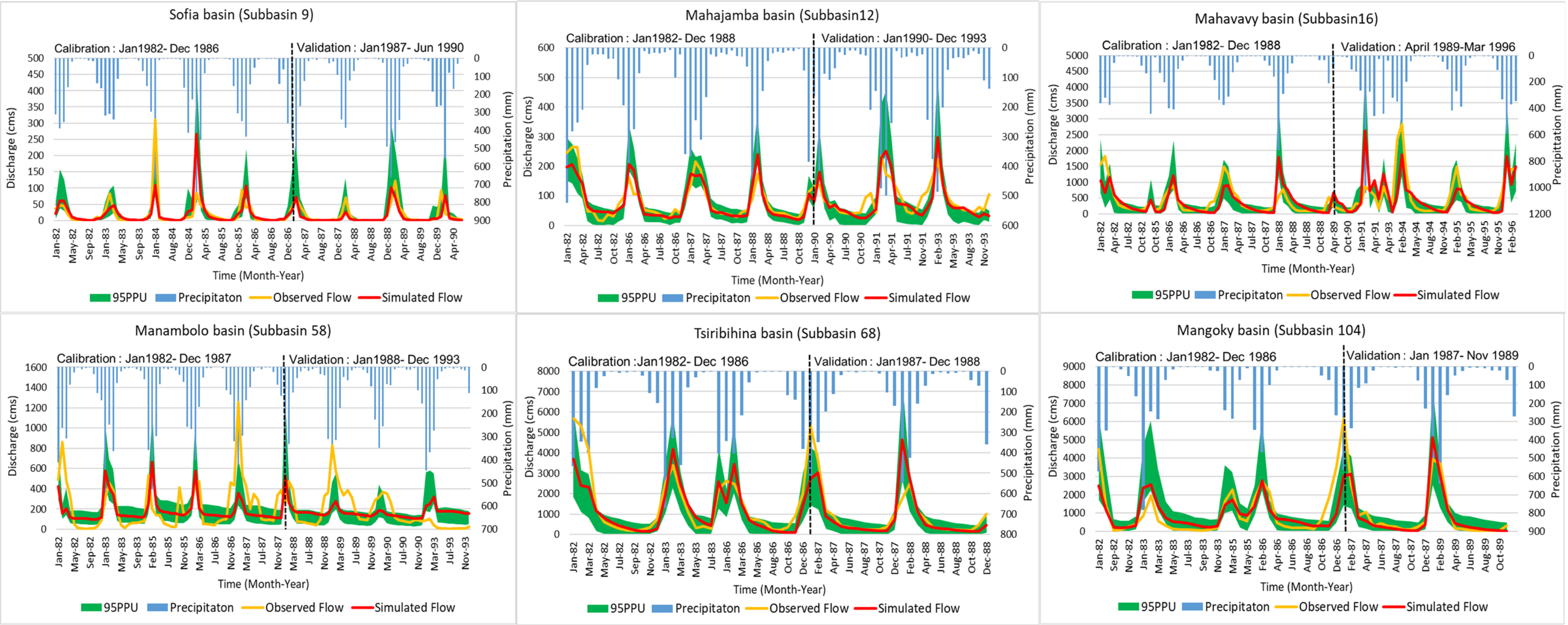
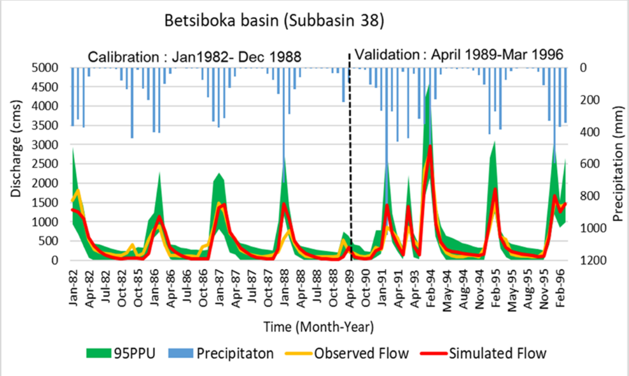
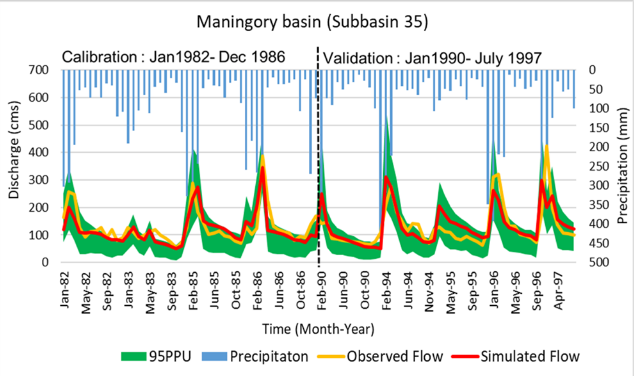
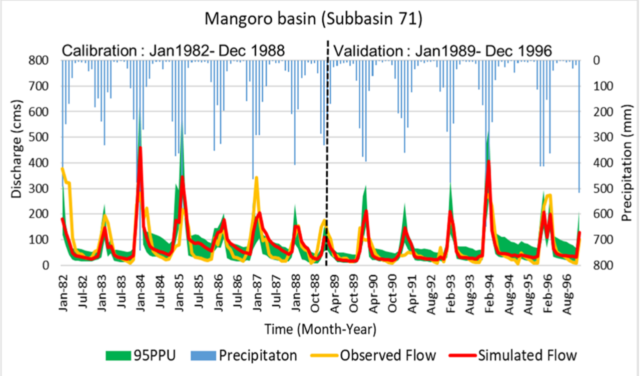


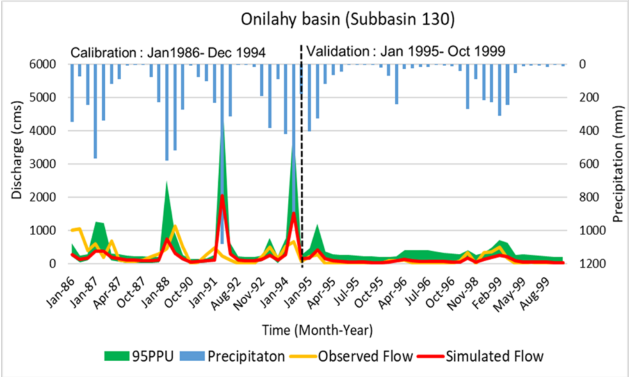
- **Streamflow:** highly variable and continuously changed over time (1982-1999);
- **Peak flows:** not accurately predicted by the SWAT model (Jan-Feb);
- **Overestimation:** Sofia, Mahajamba, Mahavavy, Manambolo, Mangoky, and Tsiribihina basins (0.5 < PBIAS<30.7)=> Basin located in the North, West, and Southwest

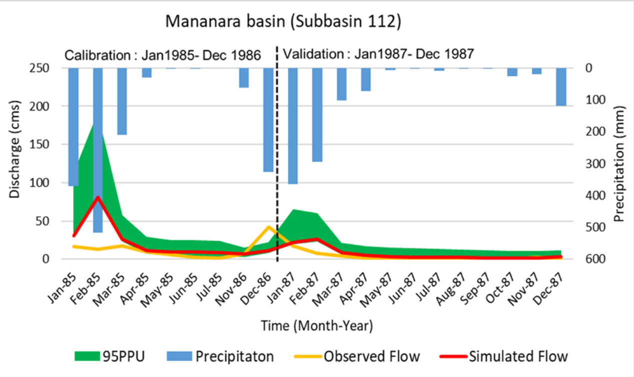
Modeling results (Cont.)

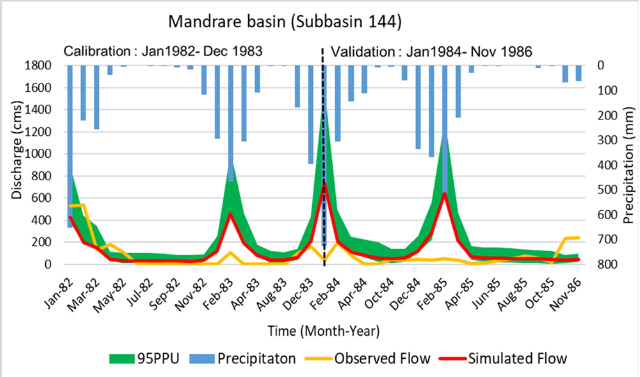










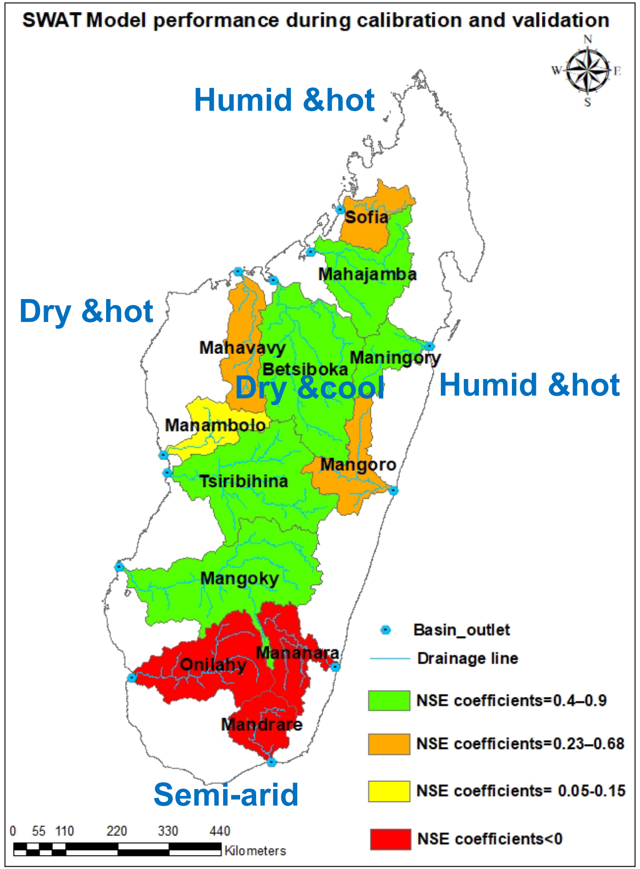


- **Under-estimation of peak flow**: Betsiboka, Maningory, Mangoro, Onilahy, Mananara, and Mandrare basins (-1.1< PBIAS<-130.2)=> Basin in the central highland, East, and South;
- Insufficient observed data & fewer observed flow covered by the 95PPU (in the South);
- **Streamflow:** increased rapidly in all basins from 1986.

Statistical parameters

BASIN NAME	CALIBRATION					VALIDATION				
	P-factor	R-factor	R^2	NSE	PBIAS	P-factor	R-factor	R^2	NSE	PBIAS
Sofia	0.72	0.72	0.34	0.23	7.1	0.83	1.31	0.49	0.43	30.7
Mahajamba	0.83	1.04	0.8	0.8	3	0.71	1.5	0.69	0.43	10.7
Mahavavy	0.86	1.19	0.47	0.4	10.9	0.8	1.01	0.44	0.4	3.4
Betsiboka	0.9	1.33	0.76	0.72	6.8	0.98	1.21	0.92	0.91	-1.8
Maningory	0.87	1.5	0.68	0.63	5.8	0.92	1.5	0.49	0.45	-1.5
Manambolo	0.41	0.94	0.18	0.15	15.4	0.48	1.01	0.06	0.05	0.5
Tsiribihina	0.87	0.92	0.72	0.69	16.5	0.92	0.89	0.58	0.54	11.2
Mangoro	0.78	0.97	0.45	0.42	-1.1	0.77	1.04	0.69	0.68	-1.1
Mangoky	0.79	1.3	0.52	0.51	3.7	0.96	0.77	0.78	0.77	13.6
Onilahy	0.43	1.58	0.03	-1.37	13.6	0.36	2.18	0.57	0.55	-13.5
Mananara	0.33	3.19	0.01	-3.83	-69.9	0.08	3.51	0.75	-0.51	-109.6
Mandrare	0.21	1.04	0.36	0.31	-20.6	0.4	3.07	0.01	-9.32	-130.2

(green)	Satisfactory
(pink)	Unsatisfactory



Results (NSE<0) consistent with the outcomes of the study carried out by Xie et al., (2012).

Xie, H., Longuevergne, L., Ringler, C. and Scanlon, B.R., 2012. Calibration and evaluation of a semi-distributed watershed model of Sub-Saharan Africa using GRACE data. Hydrology and Earth System Sciences, 16(9), pp.3083-3099. https://doi.org/10.5194/hess-16-3083-2012.

Flow Duration Curves

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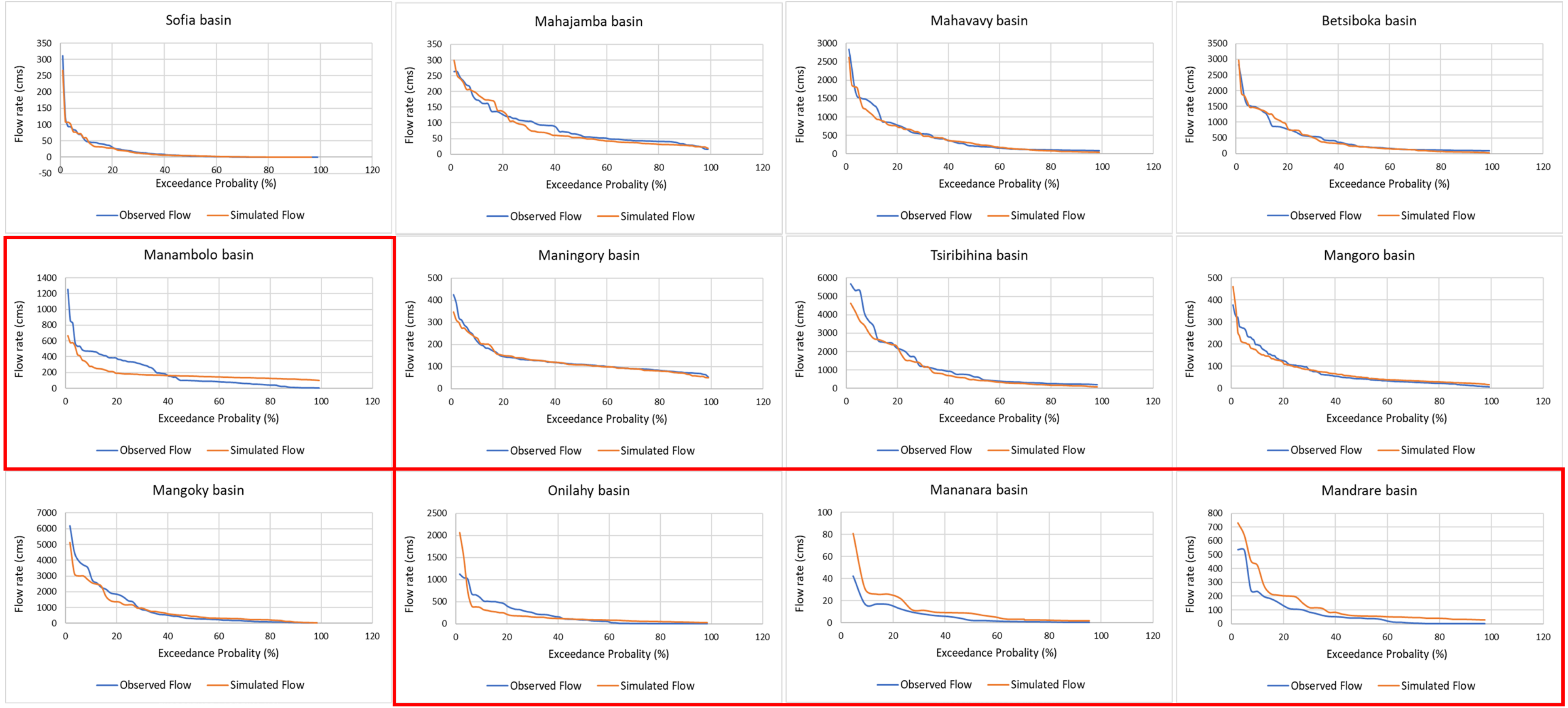
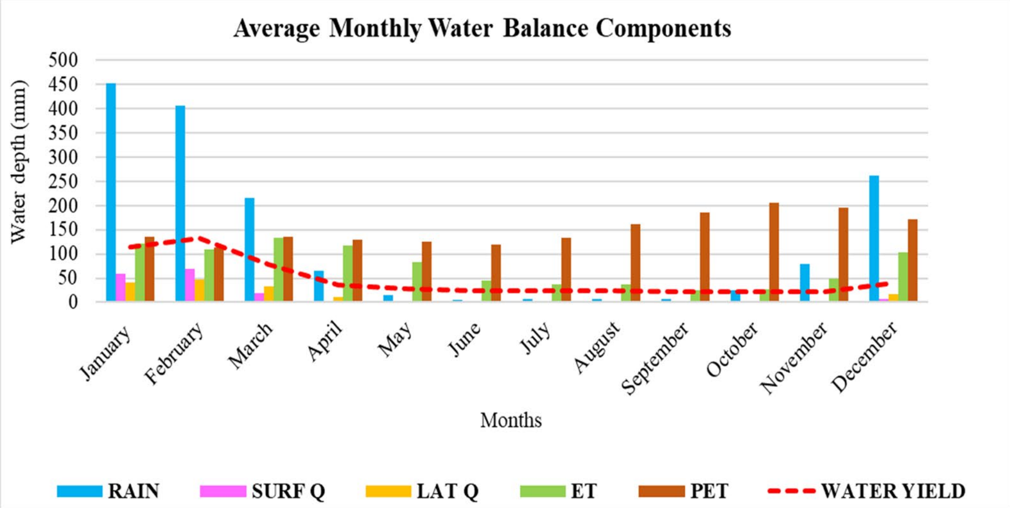
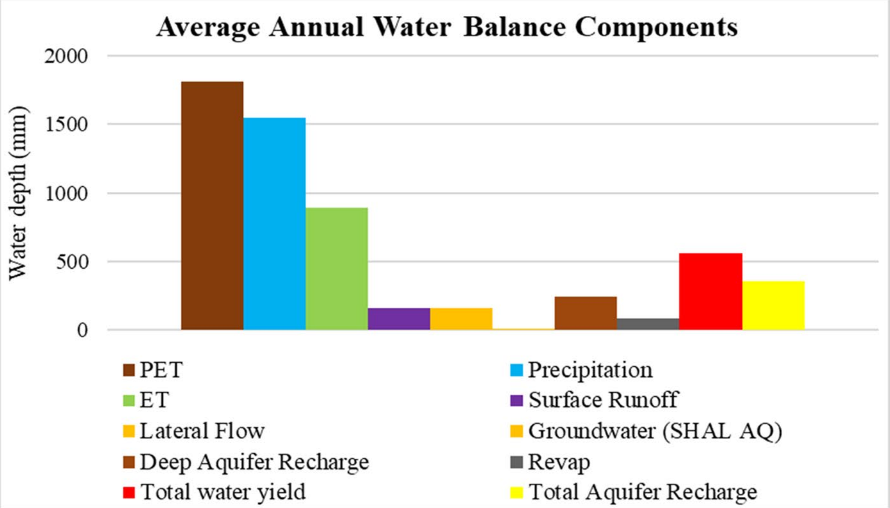
Flow duration curve of monthly flow for the major river basins (1982–1999)



Water Balance Components

Monthly and annual average water balance components after calibration for the entire watershed

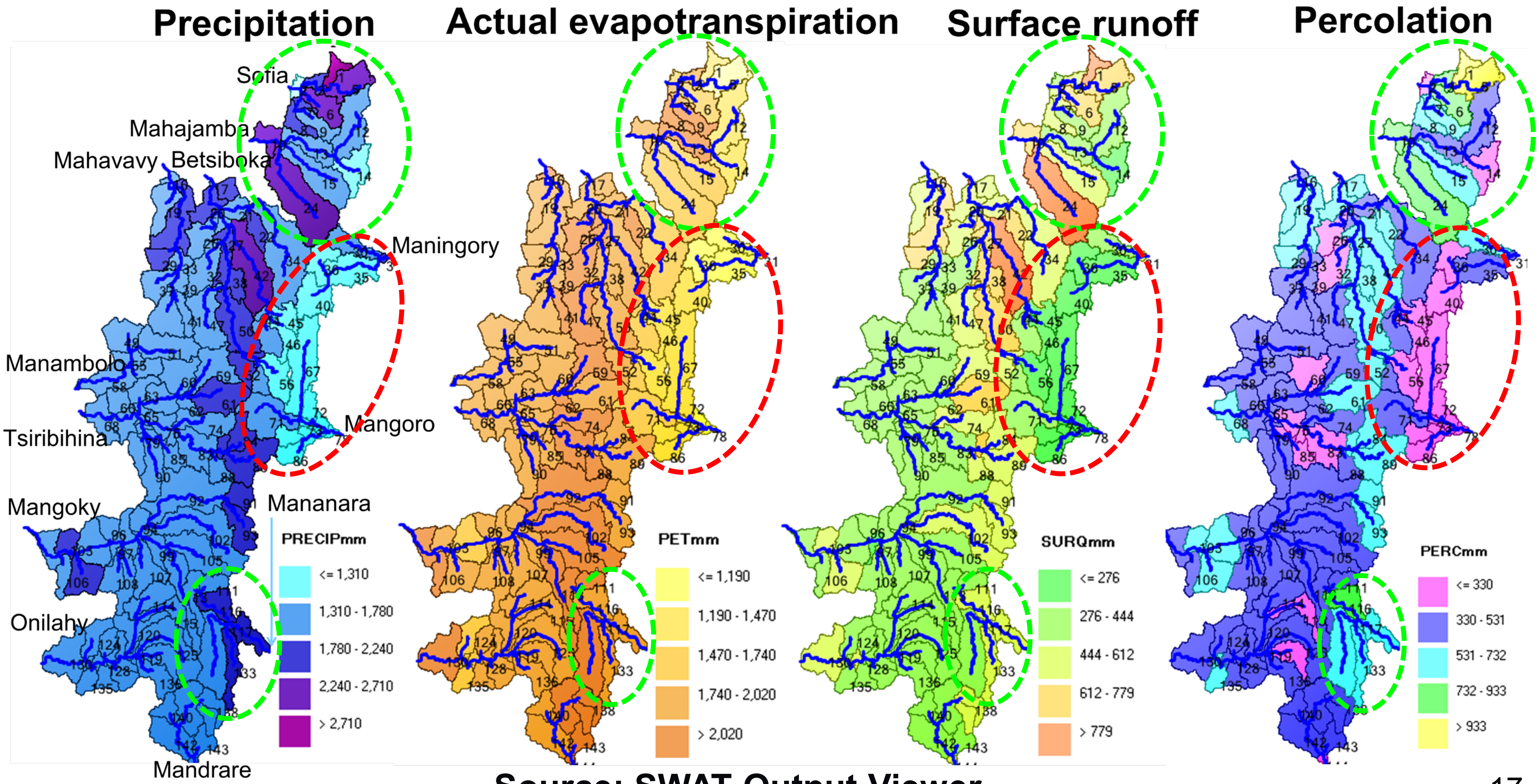




Ratios of the annual average of the total rainfall

ET	LatQ	GWQ	DAR	Revap
57%	10%	23%	16%	6%

Spatial visualization of SWAT outputs at the subbasin level at a yearly scale



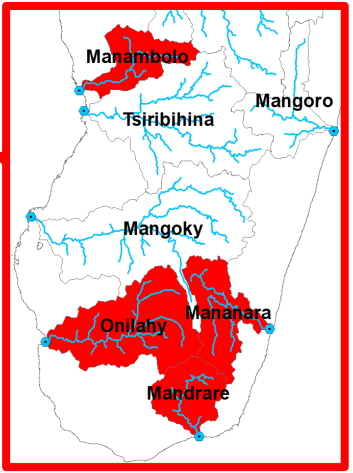
Source: SWAT Output Viewer

Conclusions and Recommendations

- The SWAT model efficiently simulated streamflow across the major river basins despite data insufficiency.

- Statistical metrics (P-factor, R- factor, NSE, R^2, and PBIAS) provided unsatisfactory results for Manambolo, Onilahy, Mananara, and Mandrare basins.

  => *Further work needs to be done for model enhancement.*

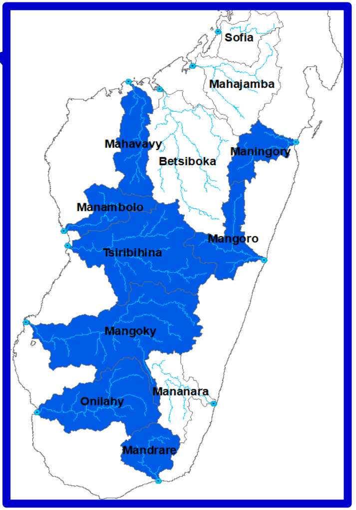


- NCEP-CFSR data provide reasonable agreements between the simulated and the observed streamflow

- Water resources are at risk of depletion in 8 basins :

Mahavavy, Manambolo, Maningory, Mangoro, Tsiribihina, Mangoky, Onilahy, Mandrare

=>*Develop water management plans appropriate to the specific characteristics of each river basin*



Limitations

- The quality and accuracy of the input data used to run the model (*Arnold et al., 1998a*);
- Challenges with observed discharge data used for calibration;
- SWAT model uncertainties, assumptions, & parameterization (*Jacomino and Fields,1997*).

Next step

- Improvement of the model (use of another rainfall data);
- Assess the potential effect of climate change on future water demand and supplies;
- Investigate the impact of LULC change on streamflow.

- Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development 1. JAWRA Journal of the American Water Resources Association, 34(1), pp.73-89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x
- Jacomino, V.M.F. and Fields, D.E., 1997. A critical approach to the calibration of a watershed model 1. JAWRA Journal of the American Water Resources Association, 33(1), pp.143-154.

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THANKS FOR YOUR KIND ATTENTION!

QUESTIONS AND SUGGESTIONS

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Soil & Water Assessment Tool SWAT