Evaporation Estimation over the Upper Blue Nile Basin by combining Satellite Observations and River Flow Gauges

Massachusetts Institute of Technology

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Introduction

The upper Blue Nile basin is one of the main tributaries of the Nile river. The area of the basin is 176, 000 km^2 which represents 5% of the total Nile River basin drainage area. However, its flow contribution is 60% of the total flow measured at Aswan. The upper Blue Nile basin is the

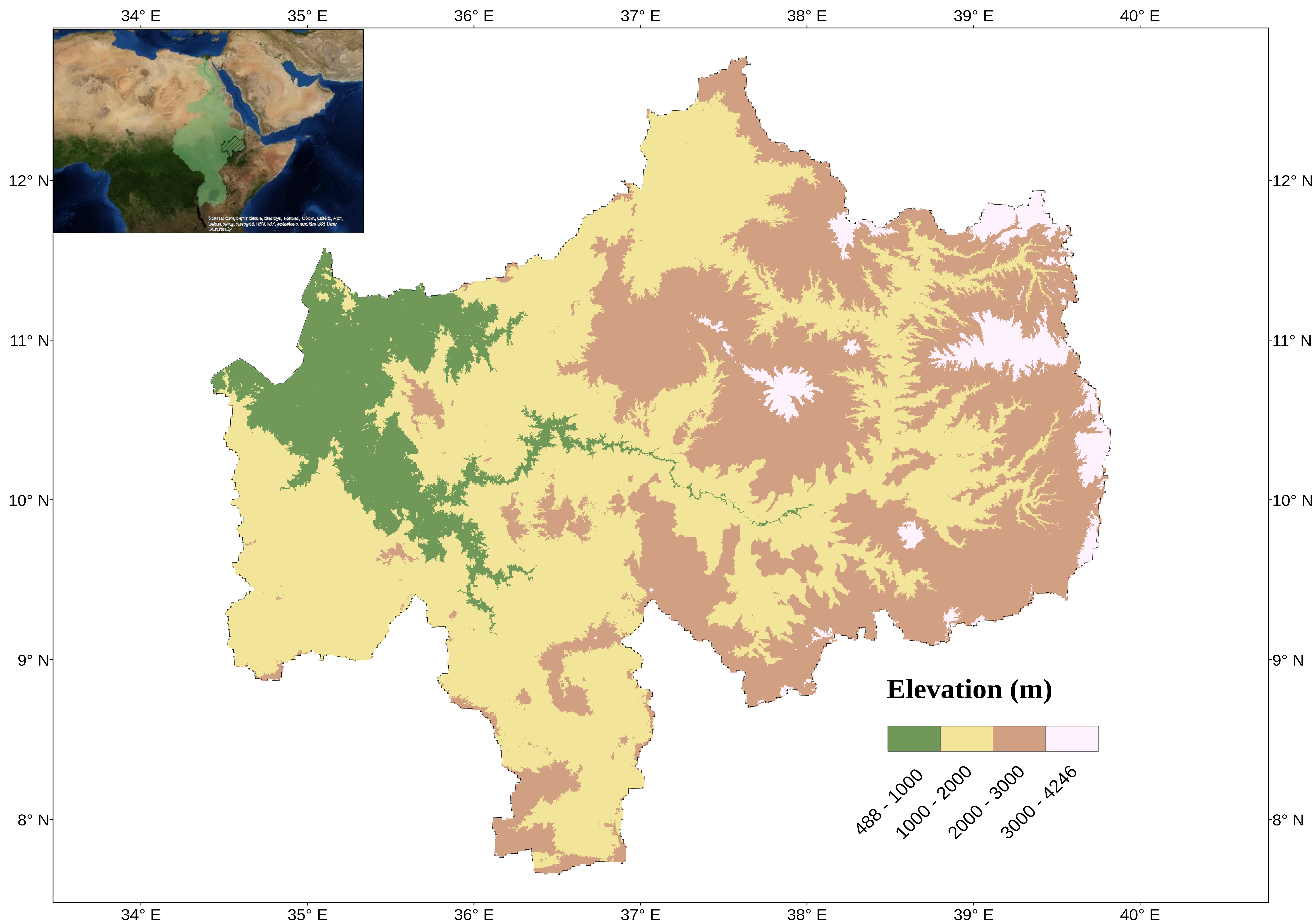

Figure 1: Topographic map of the upper Blue Nile basin

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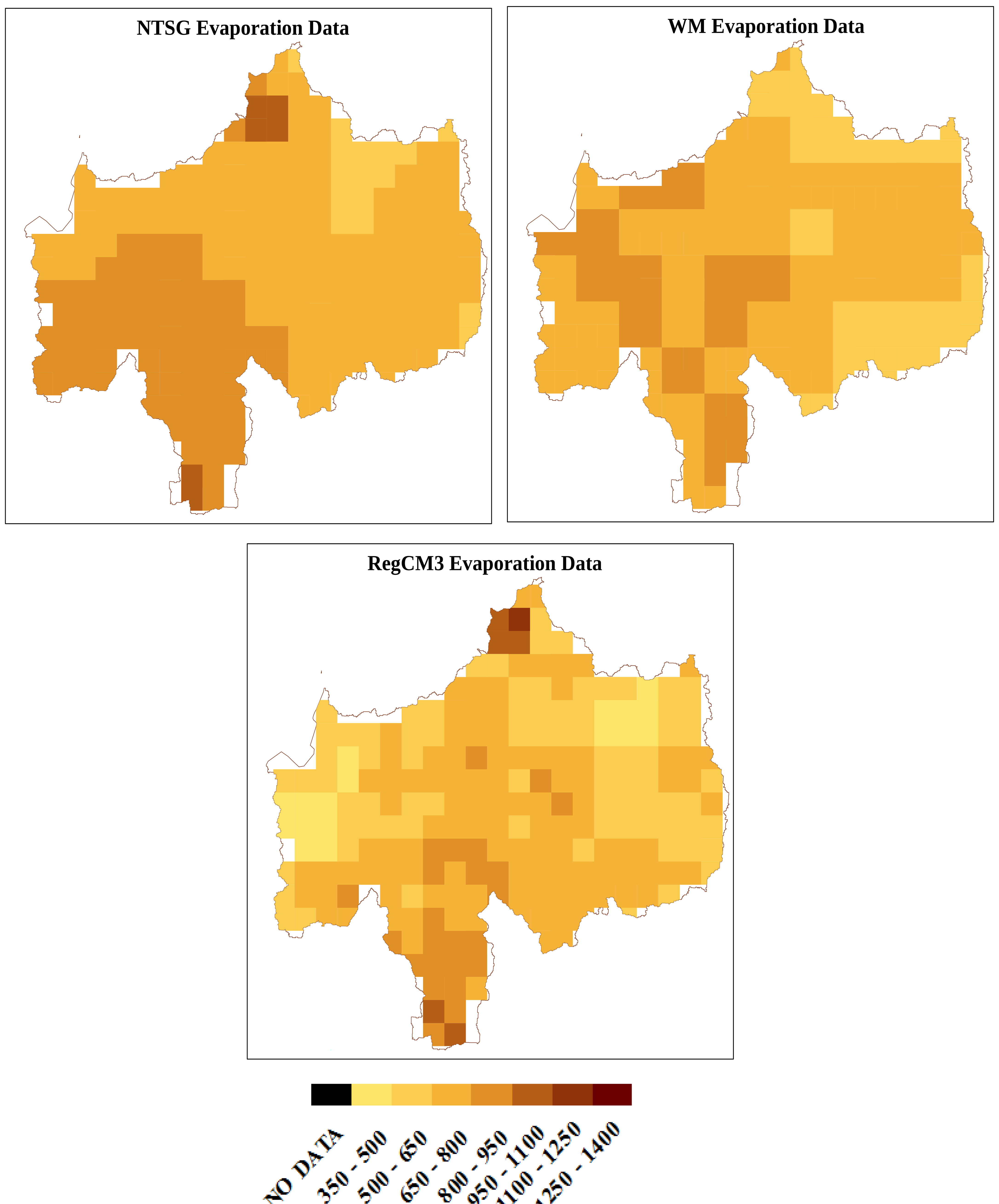
Introduction

The evaporation is generally underestimated over the upper Blue Nile basin. The basin's annual water budget can not be balanced using these datasets with an error of 30% of the mean annual precipitation.



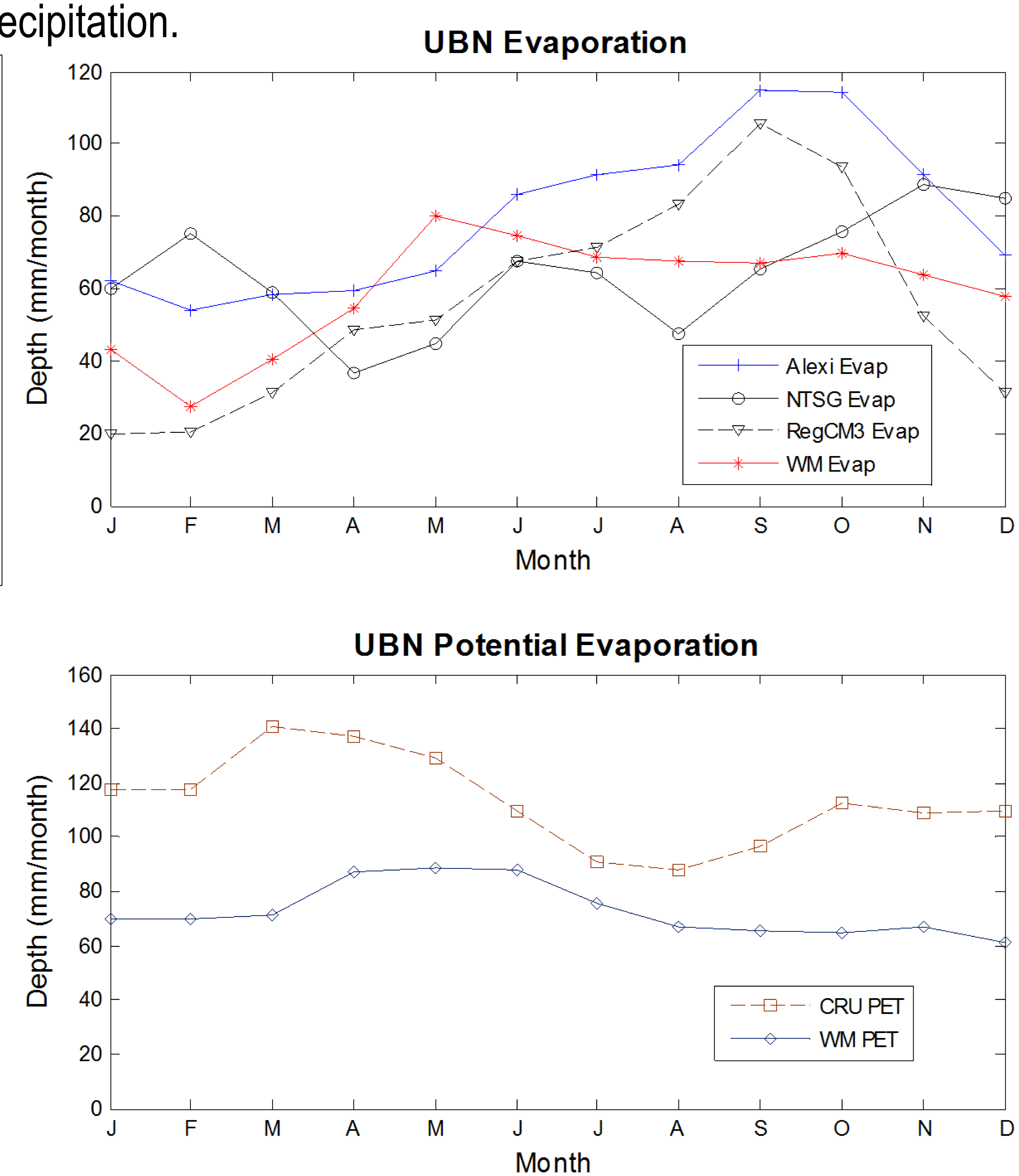


Figure 2: Comparison between the temporal and spatial distribution of several global evaporation datasets

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Data

In this analysis we use the following data:

(i)TRMM v7 Multi-satellite Precipitation Analysis (TMPA) 0.25° × 0.25° resolution 3B42 (Huffman et al., 2007)
(ii)CRU TS 3.1 potential evaporation dataset (Mitchel and Jones, 2005)
(iii)GRACE Terrestrial water storage (Chambers, 2006)
(iv)WM Evapotranspiration data (Willmot and Matsuura, 2011)
(v)Cropland and Pasture data 1700-2007 (Ramankutty and Foley, 1999)
(vi)Dominant Flow Routing (DRT) algorithm (Wu et al., 2011)
(vii)HWSD Water holding capacity (FAO, IIASA, ISRIC, ISSCAS & JRC, 2009)
(viii)NASA-SRB surface shortwave and longwave radiation (Darnell et al.,1996; Gupta et al., 1999)

Methodology

An optimization model is formulated to minimize the weighted mean-squared deviation of the estimated hydrological variables from the input data for a typical year over the upper Blue Nile Basin.

$$Min\left[\sum_m\sum_n w_P \times \delta^2_{P_{n,m}} + \sum_m\sum_n w_{PET} \times \delta^2_{PET_{n,m}} + \sum_m\sum_n w_{ET_{crop}} \times \delta^2_{ET_{crop_{n,m}}} + \sum_m\sum_n w_{ET_{noncrop}} \times \delta^2_{ET_{noncrop_{n,m}}} + \sum_n w_S \times \delta^2_{S_{n,m}} + \sum_m\sum_n w_R \times \delta^2_{R_{n,m}}\right]$$

Where:

$$\delta_{P_{n,m}} = \frac{1}{\overline{P}}\left[\overline{P_{n,m}} - P_{n,m}\right]$$: pixel precipitation misfit

$$\delta_{R_{n,m}} = \frac{1}{\overline{R}}\left[\overline{R_{n,m}} - R_{n,m}\right]$$: pixel run-off misfit

$$\delta_{PET_{n,m}} = \frac{1}{\overline{\overline{PET}}}\left[\overline{PET_{n,m}} - PET_{n,m}\right]$$: pixel potential evaporation misfit

$$\delta_{S_{n,m}} = \frac{1}{\overline{S}}\left[\overline{S_{n,m}} - S_{n,m}\right]$$: pixel basin storage misfit

$$\delta_{ET_{crop_{n,m}}} = \frac{1}{\overline{\overline{ET_{crop}}}}\left[\overline{ET_{crop_{n,m}}} - ET_{crop_{n,m}}\right]$$: pixel crop- evapotranspiration misfit

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Physical and Hydrological constraints

- The monthly pixel water balance:

$$\Delta S_{n,m} = P_{n,m} + Q_{in_{n.m}} - ET_{n,m} - Q_{out_{n.m}}$$

- The tributary flow constraint:

$$Q_{in_{n.m}} = \sum_{trib} \left(\Delta t \times \left(P_{n,m} - ET_{n,m} - \Delta S_{n,m} \right) \right)$$

- The basin outflow flow constraint:

$$R_{m,g} = \sum_{g} Q_{out_{g.m}}$$

- The Evapotranspiration constraint:

$$ET_{n,m} = ET_{crop_{n.m}} + ET_{noncrop_{n.m}} + ET_{Lake_{n.m}} \quad \& \quad ET_{crop_{n.m}} = K_{crop_{n.m}} \times PET_{n,m} \times \frac{A_{crop_n}}{A_n}$$

- The Radiation constraint:

$$ET_{n,m} \times \lambda \leq Rad_{net_{n.m}}$$

- The storage threshold and non-negativity constraints :

$$\Delta S_{\min} \leq \Delta S_{n,m} \leq \Delta S_{\max}$$

$$S_{n,m} \leq S_{threshold}$$

$$S_{n,m}, P_{n,m}, R_{m,g}, Q_{in_{n.m}}, Q_{out_{n.m}}, PET_{n,m}, ET_{n,m}, ET_{crop_{n.m}}, ET_{noncrop_{n.m}}, ET_{Lake_{n.m}} \geq 0$$

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Physical and Hydrological constraints

Several flow stations were added to the optimization model to enhance the model flow routing. The basin is divided into 5 sub-basins to investigate the spatial and temporal evaporation trend variation between the 5 sub-basins.

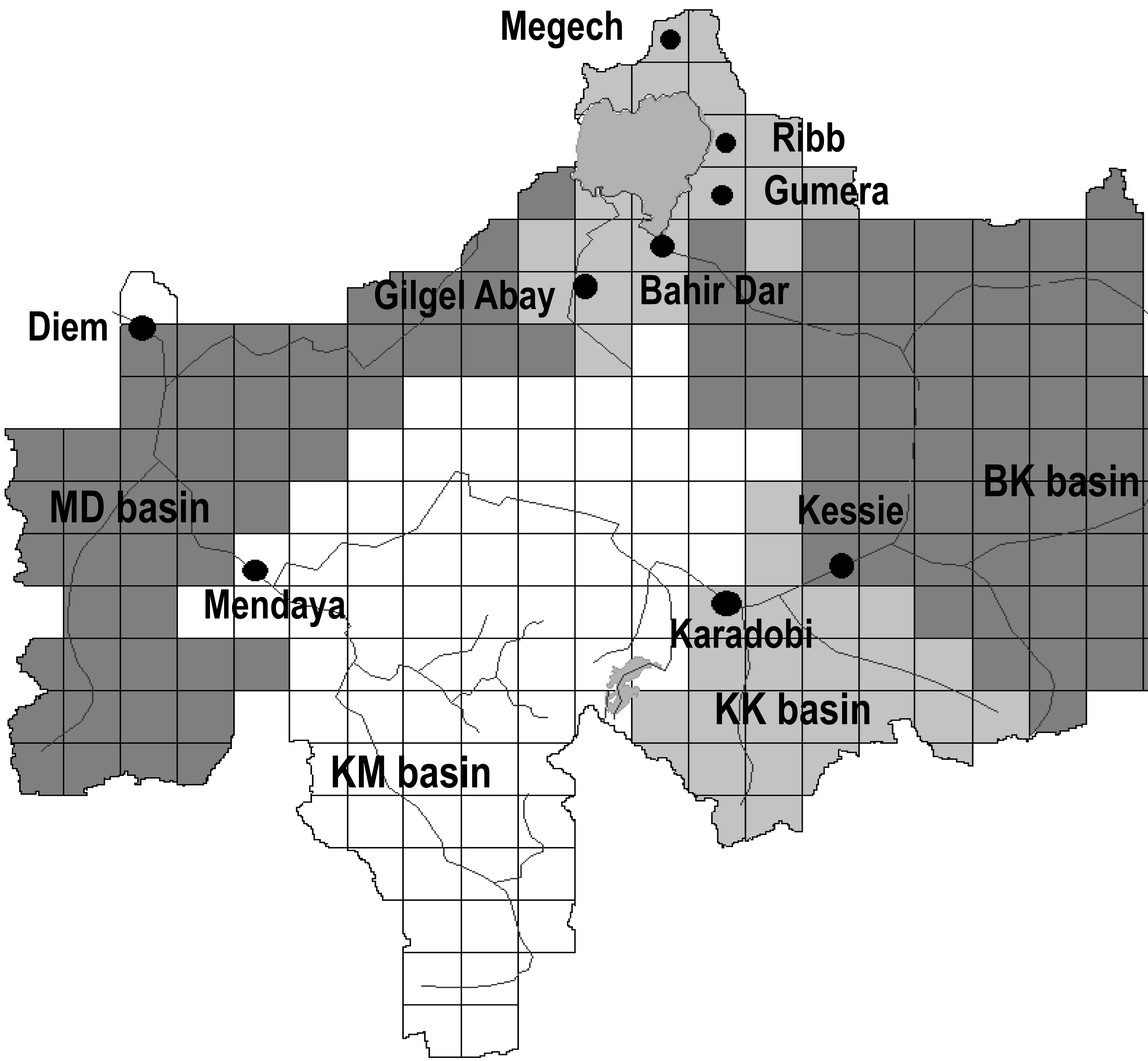

Figure 3: Flow gauge stations locations and the sub-basins created

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Model Results

A comparison between the spatially averaged input and assimilated hydrological variables is shown in Figure 4. The model finds that TRMM overestimates precipitation by 9%. It was found that the model annual evaporation estimate agrees with the ALEXI evaporation product (Anderson et al., 1997). However the spatial distribution

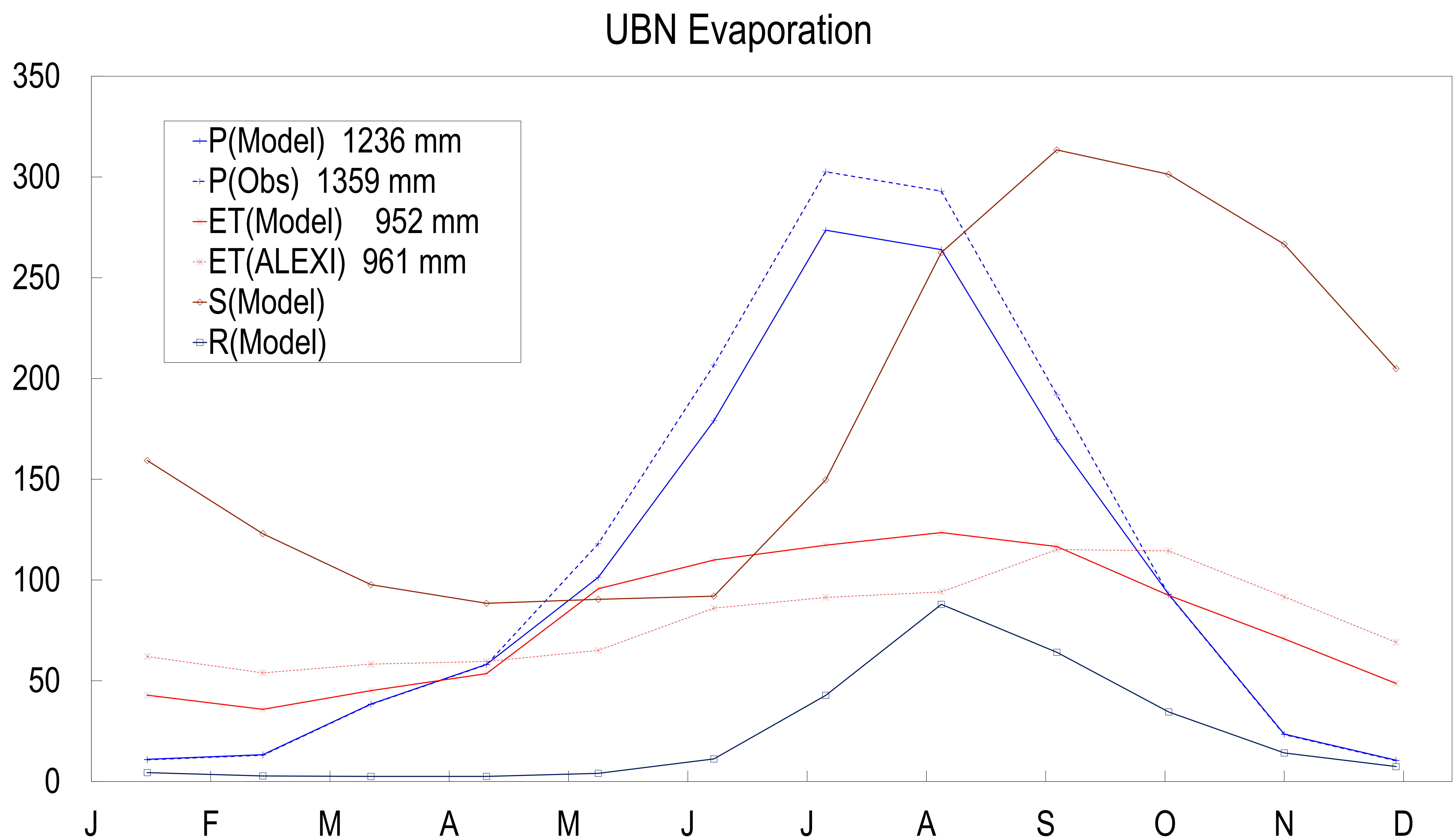

Figure 4: The temporal distribution of the upper Blue Nile basin water budget depths

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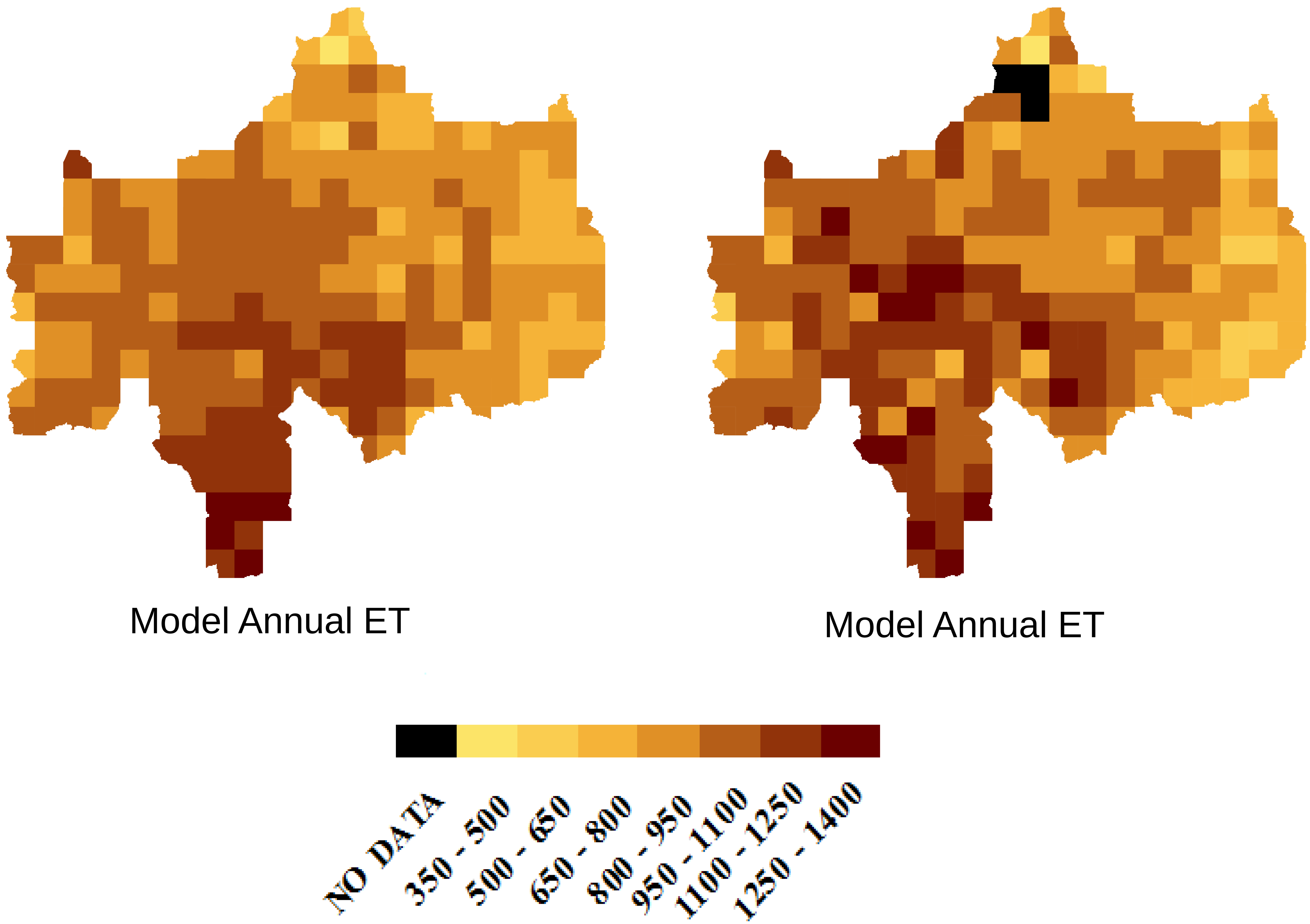

Figure 5: A comparison between the spatial distribution of the model and ALEXI product annual ET

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Model Results

The climatology of the sub-basins is quite different, the western basins are generally wetter than the eastern highlands. The evaporation over the BK and KK sub-basins has a higher seasonal pattern where it peaks around the rainy season while the peak evaporation extends over 5 months in the MD and KM.

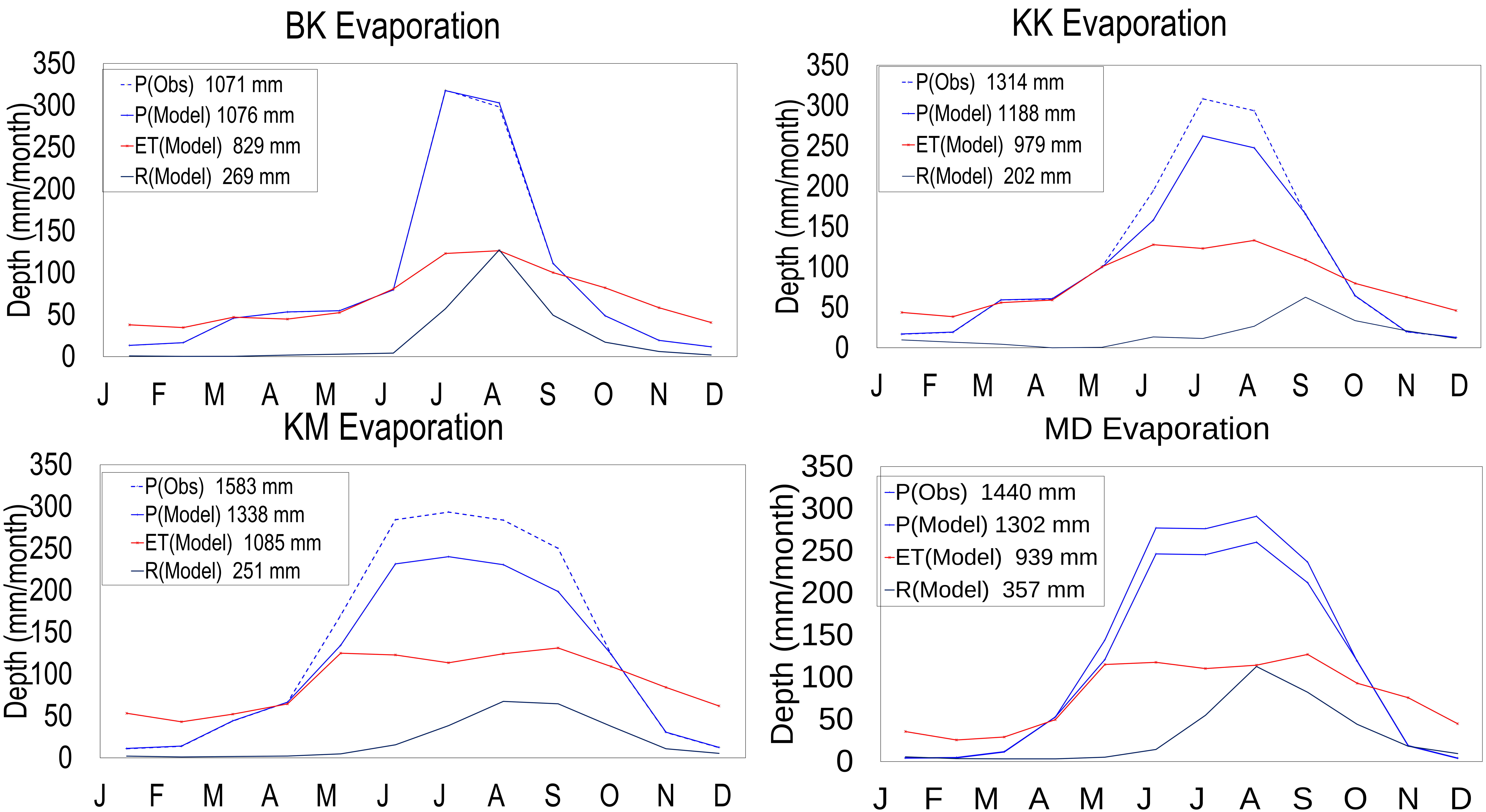

Figure 6: The temporal distribution of the sub-basins water budget depths

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Model Results and Discussion

The model results highlight the role played by natural vegetation in the basin's water budget. Natural vegetation generally evaporates higher than the current upper Blue Nile croplands.

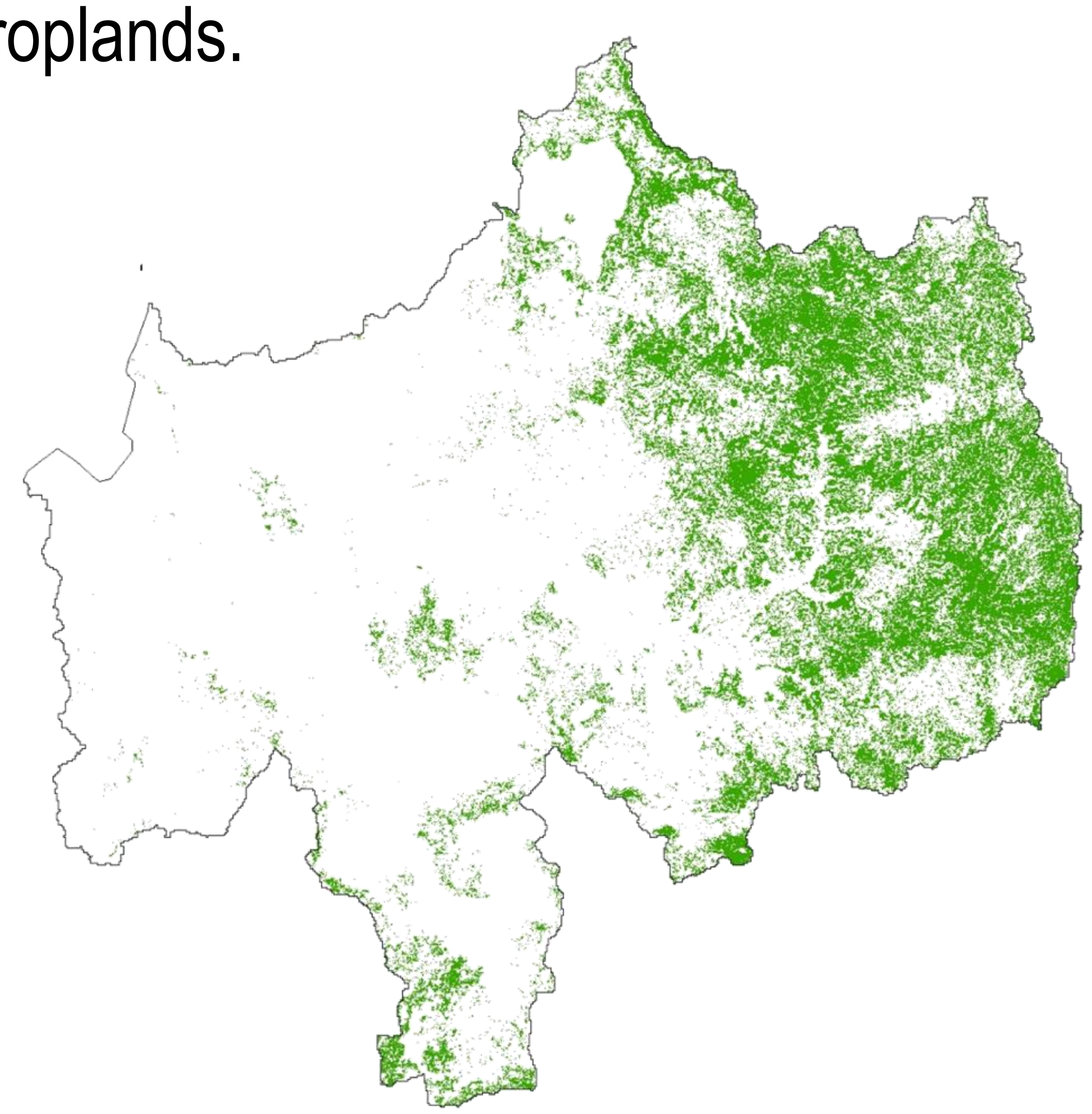

Figure 7: MODIS 2009 Crop land use

Summary of Results

Table 1. Comparison between the annual water budget depths over the UBN

Depth (mm)	Data	Model	% Change
Precipitation	1362	1429	9
Evapotranspiration	656	952	45
Runoff	276	278	0.8

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Summary of Results

Table 2. Summary of the annual water budget depths for 5 sub-basins

Depth (mm)	BD_Kes	Kes_Kar	Kar-Man	Man_Die
Precipitation	1076	1188	1338	1302
Evapotranspira	829	979	1085	939
Runoff	269	202	251	357
RC %	25	17	19	27

Conclusions

1.The available global satellite evaporation datasets generally underestimate the evaporation from the upper Blue Nile basin.

2. Natural vegetation plays the most important role in the hydrological budget of the upper Blue Nile basin.

3.The current croplands and cropping patterns are more water efficient than the natural vegetation in the upper Blue Nile basin

References

Conway, D., 1997, A water balance model of the Upper Blue Nile in Ethiopia, Hydrological Sciences Journal, 42(2), 265-286

Conway, D. (2000), The Climate and Hydrology of the Upper Blue Nile River. The Geographical Journal, 166: 49–62.

McLaughlin, D. (1995), Recent developments in hydrologic data assimilation, Rev. Geophys.,33(S2), 977–984

Ramankutty, N., and J. A. Foley (1998), Characterizing patterns of global land use: An analysis of global croplands data, Global Biogeochem. Cycles, 12(4), 667–685

Ramankutty, N., and J. A. Foley (1999), Estimating historical changes in global land cover: Croplands from 1700 to 1992, Global Biogeochem. Cycles, 13(4), 997–1027

Tafesse, T., 2001, The Hydropolitical Assessment of the Nile Question: An Ethiopian Perspective, Water International, 26(4), 1-11

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