Preliminary Results: Water Yield for Linthipe, Malawi.

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1. Introduction

We use the InVEST Tier 1 hydrological model to estimate mean actual evapotranspiration and water yield per sub-watershed (6 sub-watersheds) for the Linthipe region, Central Malawi. Soil depth, precipitation and plant available water content come from the best publicly available data published by the food and agriculture organization (FAO-UN). Evapotranspiration data is published by the CGIAR consortium, and land use land cover (LULC) data and watershed delineations are provided by Professor Leo Zulu, Michigan State University. The Linthipe watershed has an area of 8,885 km^2 and is divided into 6 sub-watersheds (Figure 1). The analysis is performed at an annual time frame. More efforts have to be done to calibrate these models to account for groundwater-surface interactions while also validating results with more accurate hydrological models.

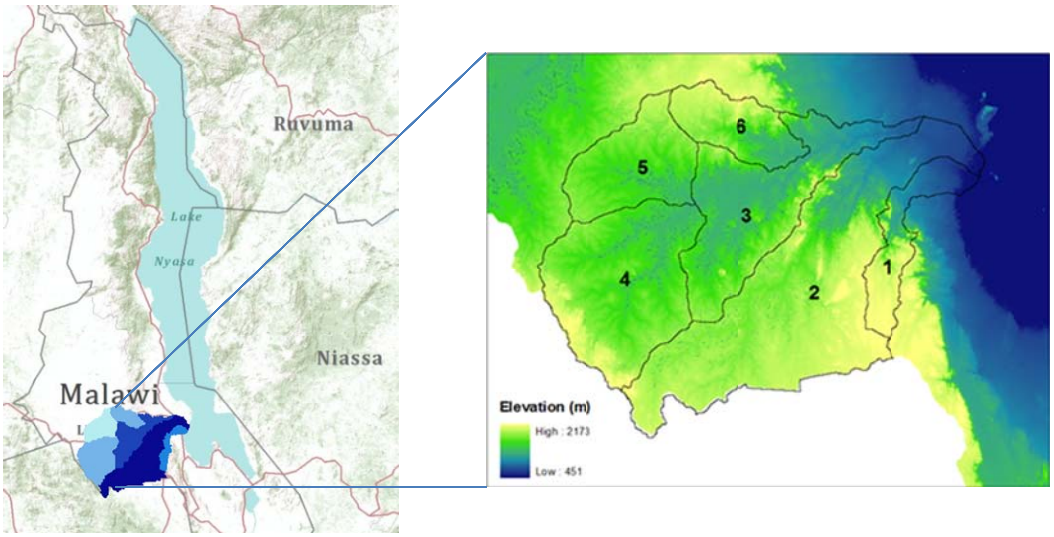


Figure 1. Main Watershed and Subwatersheds for the Linthipe Area, Central Malawi.

2. Data

Soil depth is a raster data set (FAO-UN 2007) with an average soil depth value for each cell (mm; 10*10 km) containing a dominant and subdominant soil type (very shallow, shallow, moderately deep, deep and very deep) and assuming dominant soil covers 65% of the pixel (dominant soil inside the pixel should be >50% and less than 80%). Precipitation (FAO-UN 1961-1990) is also a raster data set in mm and a 10*10 km spatial resolution. Plant available water content (PAWC; FAO-UN 2007) assumes that the dominant soil depth covers 60% of the pixel (mm/m; 10x10 km) and divides the data set into 9 different classifications of soil moisture capacity. Evapotranspiration comes from the *Global Potential Evapo-Transpiration (Global-PET)* and *Global Aridity Index (Global-Aridity)* with a high resolution average soil depth value for each cell (mm; 1*1 km). Please refer to appendix A for more detailed information on these data.

Polygon images for land use land cover, watersheds and sub-watersheds were provided by Professor Leo Zulu, Michigan State University. Land use codes, root depth and the plant evapotranspiration coefficient (etk) for each land use land cover class were estimated using InVEST's base data and Siebert *et al's'* quantification of blue and green virtual water contents in global crop production.[i]

3. Methods

Soil depth and PAWC data that were not published in mm, but in different depth and soil moisture capacity classifications, were transformed to mm by using the average of the upper and lower bounds for each classification (dominant and subdominant classes) and assigning each pixel either 65% of the weight (for the dominant soil depth) or 60% (for the dominant soil moisture) depending on their classification. Sensitivity analyses were done to investigate how changes in the assumptions of soil depth and plant available water content would drive the water yield results. In the first sensitivity, PAWC is held constant at the mean while we vary soil depth (lower bound, mean and upper bound) and in the second sensitivity we hold soil depth constant and vary PAWC. Sensitivities are performed because the data is not published in mm, but rather in different class groups where the user has to assume depth for a particular pixel.

The InVEST water balance model assumes that water yield can be estimated by the local interaction of fluctuating precipitation and potential evapotranspiration given the water storage properties of the soil (*Budyko curve*): [ii]

$$Y_{jx} = \sum \left(1 - \frac{AET_{xj}}{P_{xj}}\right) P_{xj}\, A_{xj} \qquad (1)$$

Where AET_{xj} is annual evapotranspiration on parcel x with land use land change (LULC) category j, P is annual precipitation on parcel x with LULC j, and A_{xj} is the area of x in LULC j.[iii] In particular, the model determines the annual amount of precipitation that does not evapotranspire (water yield) for each parcel on the landscape.[iii] The model runs at the pixel level and averages these outputs at the sub-basin level. It takes into account the evapotranspiration partition of the water balance as well as plant available water content, soil texture, soil depth and seasonality factors (in the form of z, a calibration factor). Because the PAWC (*mm* of water/*m* of soil) depends on soil depth (increasing soil depth reduces the PAWC) and evapotranspiration is affected by soil depth, we expect to see changes in the water yield by varying both soil depth and PAWC.

4. Results

4.1 Water Yield

Sub-watershed 2 contributes the most total volume (it also has the largest area: 3,274 km^2), followed by sub-watersheds 3 and 4 (Table 1; Figures 2, 3 and 4). Considered as a whole, the Linthipe Watershed has an *annual* water yield of 3.2 billion cubic meters of water (precipitation that does not evapotranspire). However, sub-watershed 6 is the one that contributes more water yield volume per hectare (m^3/hectare) and per sub-watershed (mm); it is also the sub-watershed with the smallest area (616 km^2). Choosing a lower soil depth value results in a higher water yield and there is a 4.9% and 2% difference between the mean total water yield and the lower and upper bounds respectively. Sensitivities on plant available water content provide similar results: reducing and increasing plant available water content led to a 3.8% increase and a 3.7% decrease in water yield respectively (Table 2).

4.2 Evapotranspiration

Sub-watershed 2 has the largest mean actual evapotranspiration of precipitation (also has the largest area) while sub-watersheds 5 and 6 have the lowest (Figures 5 and 6). At the same time, sub-watersheds 5 and 6 have the lowest mean actual evapotranspiration per sub-watershed (mean fraction of precipitation that actually evapotranspires at the sub-basin level).

Table 1. Soil Depth: Sensitivity Analysis

	Total Water Yield (m^3)			Mean Water Yield (m^3/hectare)		
Sub-Watershed	Lower Bound	Mean	Upper Bound	Lower Bound	Mean	Upper Bound
1	246,976,688	233,938,144	226,978,288	4,282	4,056	3,935
2	1,322,988,800	1,260,186,880	1,230,998,912	4,040	3,848	3,759
3	729,068,416	701,573,568	692,680,640	4,515	4,344	4,289
4	591,357,760	563,025,536	549,248,512	3,197	3,044	2,969
5	256,304,336	238,017,712	235,770,528	2,688	2,497	2,473
6	281,723,712	269,758,048	265,440,736	4,569	4,375	4,305
Sum	3,428,419,712	3,266,499,888	3,201,117,616	23,291	22,164	21,730

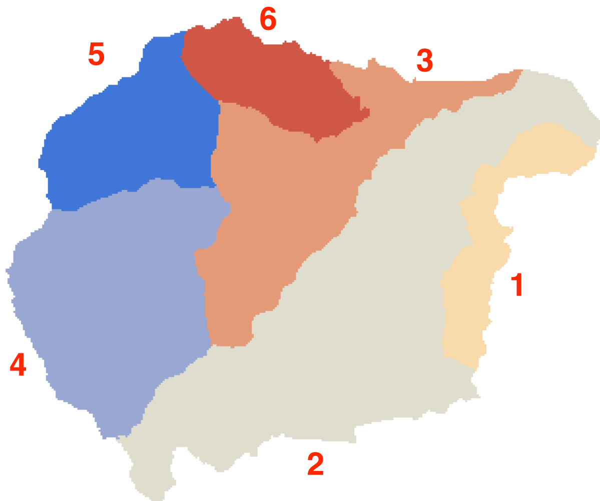
*InVEST estimation performed holding mean plant available water content constant and varying soil depth.

Table 2. Plant Available Water Content: Sensitivity Analysis

	Total Water Yield (m^3)			Mean Water Yield (m^3/hectare)		
Sub-Watershed	Lower Bound	Mean	Upper Bound	Lower Bound	Mean	Upper Bound
1	240,837,680	233,938,144	226,487,728	4,175	4,056	3,927
2	1,307,055,104	1,260,186,880	1,215,663,104	3,991	3,848	3,712
3	725,237,760	701,573,568	679,656,128	4,491	4,344	4,209
4	586,967,936	563,025,536	540,524,672	3,173	3,044	2,922
5	251,237,776	238,017,712	226,242,192	2,635	2,497	2,373
6	279,070,016	269,758,048	261,834,688	4,526	4,375	4,247
Sum	3,390,406,272	3,266,499,888	3,150,408,512	22,991	22,164	21,390

*InVEST estimation performed holding mean soil depth constant and varying plant available water content.

Mean Water Yield per Sub-Watershed: Base Case



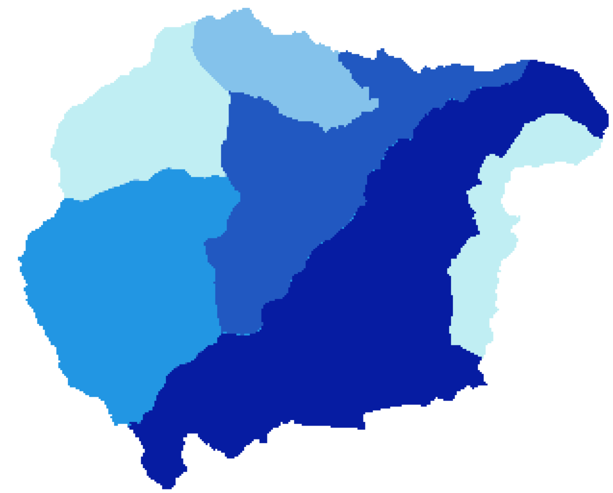


Fig 2. Water yield volume per hectare per sub-watershed (m3/hectare)

- 4,375.80
- 4,344.82
- 4,056.30
- 3,848.70
- 3,044.33
- 2,497.12

Fig 3. Mean water yield per sub-watershed (mm)

- 437.58
- 434.48
- 405.63
- 384.87
- 304.43
- 249.71

Fig 4. Total water yield per sub-watershed (m3)

- 153,941,664 - 238,017,712
- 238,017,712.1 - 414,134,528
- 414,134,528.1 - 621,463,488
- 621,463,488.1 - 803,541,440
- 803,541,440.1 - 1,328,160,512

0 35,500 71,000 142,000 Meters

1 centimeter = 16,973 meters

N W E S

Mean Actual Evapotranspiration per Sub-Watershed: Base Case

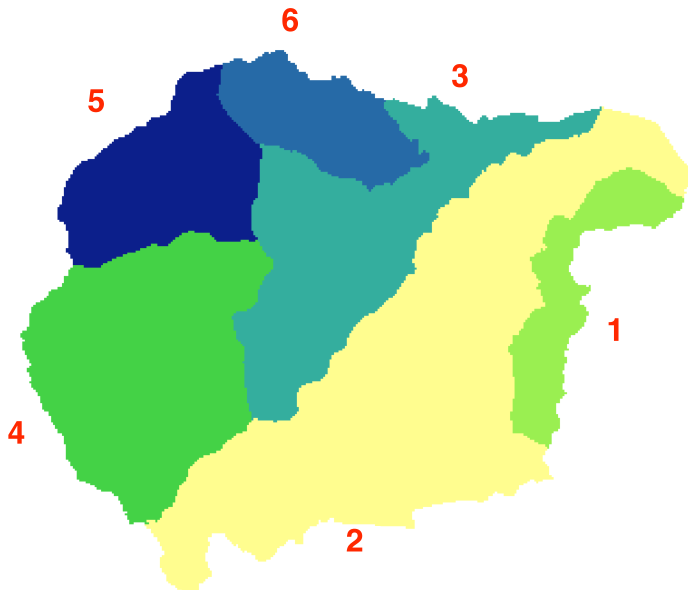


Fig 5. Mean actual evapotranspiration of precipitation (in mm).

- 682.26
- 676.53
- 671.36
- 670.15
- 644.62
- 624.28

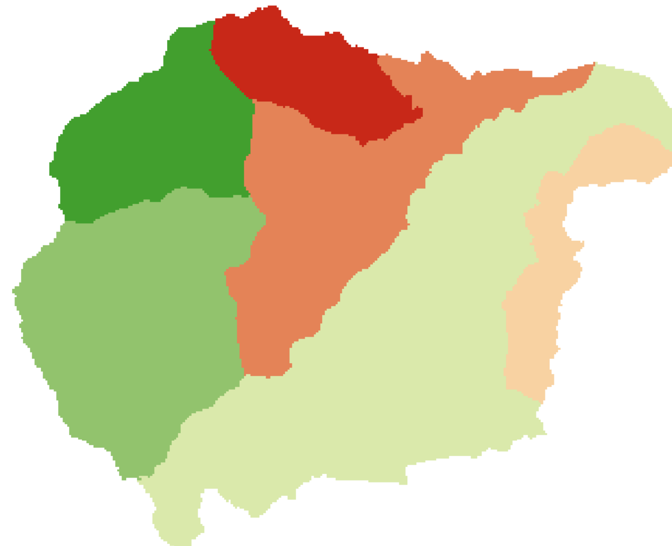


Fig 6. Mean actual evapotranspiration per sub-watershed (mean fraction of precipitation that actually evapotranspires at the sub-basin level).

- 0.59
- 0.60
- 0.62
- 0.64
- 0.68
- 0.71

0 31,000 62,000 124,000 Meters

1 centimeter = 14,943 meters

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5. Discussion

We used the InVEST Tier 1 hydrological model (water yield) to estimate total volume (m^3), volume per hectare (m^3/hectare), and mean volume per watershed (mm). The sensitivity results suggest that there is little percentage change in water yield as a result of choosing either lower, mean or upper bounds for soil depth and plant available water content. However, although these percentage differences might be small, it is important to note that these changes in water yield could have significant impacts in the amount of water that is available for irrigation and hydropower. Clear guidelines should be delineated by InVEST (and the user) so as to make sound assumptions and avoid early mistakes that could cascade into later steps of the analysis.

The second sub-watershed has the largest total water yield and mean evapotranspiration, but it also has the largest area. Sub-watershed 6 has the largest water yield volume per hectare (m^3/hectare) and mean water yield (mm) per sub-watershed as well as the smallest area. Large total water yields and evapotranspiration could be attributed to large areas, but stream flow data, topography and other factors should be integrated in the spatial analysis (and hydrological analysis) to better understand differences in water yield across Linthipe's watersheds. Better (empirical) information on the coefficients that go into the land use land cover biophysical table (root depth and *etk*) are needed to increase the accuracy of these results.

Further limitations from 'Natural Capital: Theory and Practice of Mapping Ecosystem Services':

1. The Tier 1 model can estimate relative contributions but will likely misrepresent the integrated watershed response.
2. Does not incorporate sub-parcel spatial variability of soil water storage capacity and synchronicity of the energy-precipitation cycles on the water balance.
3. Doesn't explicitly model groundwater.
4. Annual timeframe: hydrological demands occur in a matter of days and representing hydrology as an annual output can lead to large errors of interpretation.

A way to deal with uncertainty would be to incorporate Monte Carlo analysis (or Bootstrapping) in order to introduce random variation around expected values of environmental conditions initially and later on to prices, input availability and farmer behavior (in the water scarcity and allocation InVEST models).

6. Appendix A: Data Characteristics

1. Soil Depth:

Source: FAO – UN 2007.

Characteristics: GIS raster dataset (ESRI GRID) with an average soil depth value for each cell (mm).

Assumptions: Assume that the dominant soil covers 65% of the pixel. A dominant soil inside the pixel should be > 50% and less than 80%. Our assumptions are based on previous assumptions determined by the FAO. It has to be determined whether we use half the soil depth for each definition by the FAO and we assigned higher and lower proportions to the dominant soil type as sensitivities. i.e. dominant soil type could be characterized by 60%, 65%, 70% and 75%.

The raster dataset of effective soil depth has a spatial resolution of 5 * 5 arc minutes and is in geographic projection. Information with regard to soil depth was obtained from the "Derived Soil Properties" of the FAO-UNESCO Soil Map of the World which contains raster information on soil properties. The effective soil depth is the depth to which micro-organisms are active in the soil, where roots can develop and where soil moisture can be stored. As such it is an essential indicator of soil health.

Structure of the attributes
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The first digit indicates the dominant class. The second digit indicates the associated class. The same classes are used in the first and second digit, except that a zero as second digit indicates that the class pointed by the first digit occurs in >80% of the pixel.

Depth

1: Very shallow (<10 cm)
2: Shallow (10 ? 50 cm)
3: Moderately deep (50 ? 100 cm)
4: Deep (100 ? 150 cm)
5: Very deep (150 ? 300 cm)
97: Water
99: Missing data

2. Precipitation data:

Source: FAO – UN. Rainfall Monitoring for the African Continent.

Maps on monthly total rainfall amount (in millimeters) and monthly rainfall percentage of normals 1961-1990 (in percentage) from August 2004 to October 2008. An interpolation method (Kriging) is applied to input data.

Data input for rainfall maps are provided by Global Precipitation Climatology Centre (GPCC) operated by the Deutscher Wetterdienst (DWD, National Meteorological Service of Germany). GPCC First Guess Product, gauge-based gridded monthly precipitation data sets for the global land surface, at spatial resolutions of 1.0 x 1.0 degrees geographical latitude by longitude are used.

The First Guess Product of the monthly precipitation anomaly is based on interpolated precipitation anomalies from about 6,000 stations worldwide. Data sources are synoptic weather observation data (SYNOP) received at DWD via the WMO Global Telecommunication System (GTS) and climatic mean (mainly 1961-1990) monthly precipitation totals at the same stations extracted from GPCC s global normals collection. An automatic-only quality-control (QC) is applied to these data. Since September 2003, GPCC First Guess monthly precipitation analyses are available within 5 days after end of an observation month.

3. Plant Available Water Content

Source: FAO – UN. Soil Moisture Capacity (mm water/ m soil)

Assumptions: Assume that the dominant depth covers 60% of the pixel. We need to make assumptions about the maximum water content (mm/m) of soil. The maximum water content value is 200 (mm/m). Wetland's are not classified in the analysis. We assume that the maximum water content is somewhere between 1000(mm/m) –overly saturated- and a PAWC > 200 mm. Hence we assume 600 (mm/m) as the maximum PAWC. Sensitivity analyses have to be performed on choosing different PAWC values (different proportions) for different pixels.

The raster dataset of soil moisture storage capactity has a spatial resolution of 5 * 5 arc minutes and is in geographic projection. Information with regard to soil moisture was obtained from the "Derived Soil Properties" of the FAO-UNESCO Soil Map of the World which contains raster information on soil properties.

This parameter indicates the amount of soil moisture that can be stored between field capacity and wilting point and is presumed to be available to plants. It is calculated on the basis of soil depth and textural class. The dataset is available for download (below) in both ASCII and ESRI GRID formats. A layer (.lyr) legend (.avl) and excel file are provided in the downloads.

Structure of the attributes
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The first digit indicates the dominant Smax class (60% of the cell). The second digit indicates the associated (40% of the cell) class. When the second number is 0, this indicates that the whole cell is made up by the Smax class indicated by the first number.

Soil Moisture Capacity

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The classes are:
1: Wetlands
2: > 200 mm/m
3: 150 - 200 mm/m
4: 100 - 150 mm/m
5: 60 - 100 mm/m
6: 20 - 60 mm/m
7: < 20 mm/m
97:Water

99:Glaciers, Rock, Shifting sand, Missing
data

4. Average Annual Potential Evapotranspiration

Source: CSI CGIAR GeoPortal

Characteristics: GIS raster dataset (ESRI GRID) with an average soil depth value for each cell (mm).

Assumptions: Not required for this data.

The *Global Potential Evapo-Transpiration (Global-PET) and Global Aridity Index (Global-Aridity)* datasets provide high-resolution global raster climate data related to evapo-transpiration processes and rainfall deficit for potential vegetative growth. The Global-PET and Global-Aridity datasets are provided for non-commercial use in standard ARC/INFO Grid format, at 30 arc seconds (~1km at equator), to support studies contributing to sustainable development, biodiversity and environmental conservation, poverty alleviation, and adaption to climate change globally, and in particular in developing countries.

5. Average Annual Potential Evapotranspiration

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7. References

[i] Siebert, Stefan, Doll, Petra. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. 2009. *Journal of Hidrology*. 384 (2010) 198-217.
[ii] Milly, P.C.D. Climate, soil, water storage, and the average annual water balance. 1994. *Water Resources Research*. 3(7), 2143-56.
[iii] Kareiva, P., Tallis, Heather, Rickets H. *et* al. *Natural Capital: Theory and Practice of Mapping Ecosystem Services*. Oxford University Press (2011).