processes that are often unique to each watershed. It is possible that the performance of VegET model varies across HUC8 watersheds, and the single threshold ($R/P \leq 0.40$) filter applied to the CONUS-scale study may not represent the water balance characteristics of each watershed. However, the VegET model can be calibrated and optimized when finer scale spatial information is needed.

4. Case Study Applications

The spatially explicit Landscape Water Requirement Satisfaction Index (L-WRSI) is an indicator of landscape performance akin to the well-established WRSI for monitoring crop production based on the availability of precipitation and soil moisture to meet crop or landscape water requirements (ETc) during the growing season [22]. L-WRSI can be estimated as the ratio (%) of seasonal ETa to the seasonal ETc. Similar calculations are used for L-WRSI where Kcp is used instead of Kc to define the landscape water requirement phenology as follows:

$$\text{L-WRSI} = \frac{\sum ETa}{\sum ETc} \times 100 \tag{21}$$

$$ET_c = Kcp \times ET_o \tag{22}$$

where $\sum ETa$ is the sum of ETa (mm) for the selected time period (month, season, year); $\sum ETc$ is the sum of the landscape water requirement (mm) for the selected time period and denotes landscape-specific ETo after an adjustment is made to the reference crop ETo by the use of the LSP coefficient (Kcp). Kcp values define the seasonal water requirement patterns of the landscape.

Figure 14 illustrates the concept of the L-WRSI. The gray (ETc) and green (ETa) lines are the two components creating the L-WRSI. The difference between the two lines indicates the water deficit during insufficient precipitation, which leads to the reduction in the L-WRSI from 100%. The annual (January–December) and seasonal (May–September) cumulative deficit are represented by L-WRSI values of 85 and 89, respectively, i.e., 85% and 89% of the median landscape water requirement, met by precipitation, for the year and the season in 2018. The main deficit in the growing season was observed in July with a relatively low amount of precipitation. However, the 11% deficit for the season may not necessarily reflect an actual water deficit that would lead to a proportional yield reduction due to uncertainties in model inputs and assumptions; however, the relative magnitude in space and time could be used for drought monitoring and early warning by comparing the index across years and regions.

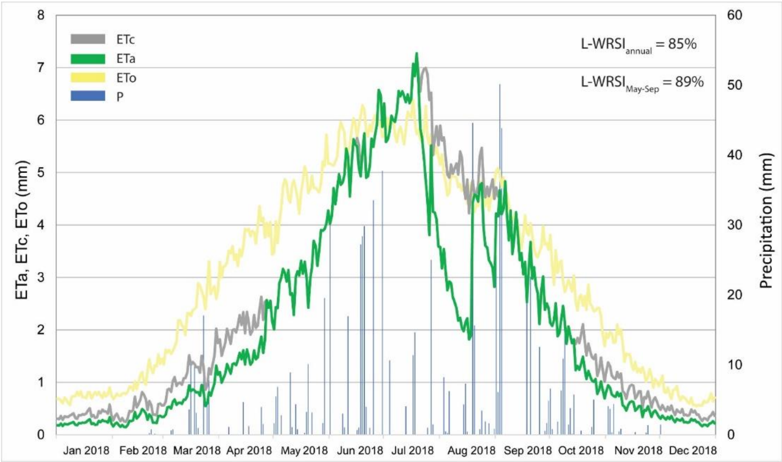

Figure 14. Illustration of the Landscape Water Requirement Satisfaction Index (L-WRSI) concept using daily precipitation (P), reference ET (ETo), actual evapotranspiration (ETa), and landscape water requirement (ETc) for a pixel near the AmeriFlux Station (US-Ne3) for 2018. Seasonal (89%) and annual L-WRSI (85%) indicate some level of dryness during the growing season and through the year.

The L-WRSI values for the CONUS and GHA were calculated and used to illustrate their agro-hydrologic applications for drought monitoring. L-WRSI is an integrated index that includes precipitation, atmospheric demand, phenology, and soil properties.

4.1. CONUS

Figure 15 shows seasonal L-WRSI for three years, namely 2012, 2016, and 2018. L-WRSI less than 100 indicates some form of water stress. Generally, L-WRSI > 95 is considered optimal and less than 80 indicates a serious precipitation shortfall that may lead to a substantial biomass and yield reduction for crops. A crop WRSI < 50 indicates crop failure and need for irrigation to grow crops. It is important to note that L-WRSI is calculated based on availability of moisture in the 1 m root-zone and does not take into account potential access to groundwater by deep-rooted trees and shrubs. This is one explanation why L-WRSI shows lower values (Figure 15) during the growing season in the southeast (e.g., Georgia), where the vegetation demand could be partially met by groundwater resources for the tree-dominated landscapes. It also explains the supplemental irrigation requirement for growing crops during the growing season in the region.

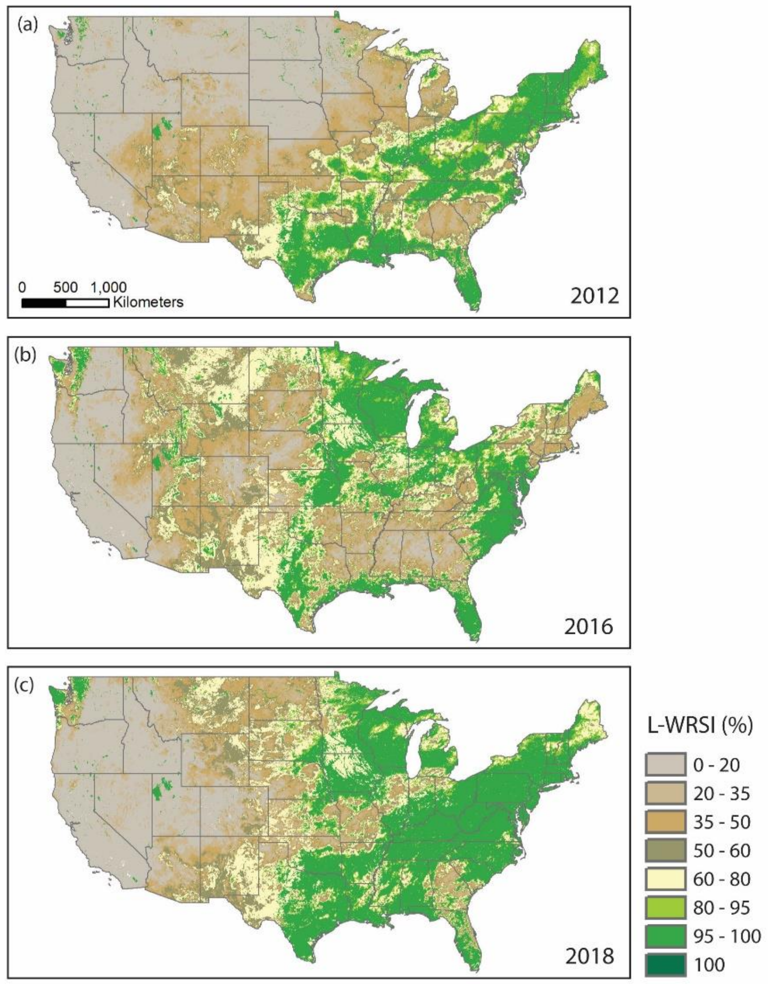

Figure 15. Growing season (May–September) Landscape Water Requirement Satisfaction Index (L-WRSI) for the conterminous United States for (**a**) 2012, (**b**) 2016, and (**c**) 2018. Values close to 100 (green) show availability of enough precipitation to meet crop requirements during the growing season. L-WRSI < 50 (brown tones) indicate severe moisture deficit in the top 1 m root zone to meet the expected water requirement of the landscape. The index does not account for access to groundwater or irrigation water applications.

For the country-wide assessment, L-WRSI was grouped into four qualitative categories of Good (L-WRSI > 95%), Fair (80–95%), Poor (50–80%), and Severe Damage (L-WRSI < 50%). A summary of the L-WRSI by croplands [56] of the CONUS (Figure 16) shows the drought year of 2012 had 66% of the CONUS under severe damage whereas 2016 and 2018 experienced severe damage to a lesser extent (26–27%). The extent observed in 2016 and 2018 may represent the areas that normally require irrigation for crop production. Such kind of metric would allow the expression of the impact of a drought year relative to a normal year. In this case, one could say the 2012 damage was twice as severe as that of 2018 (an average precipitation year).

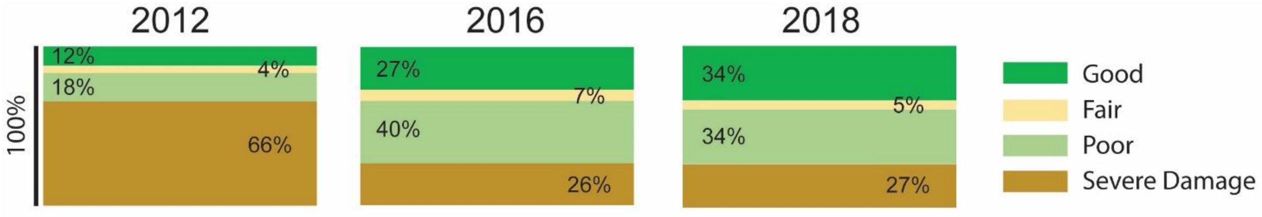

Figure 16. Summary of seasonal Landscape Water Requirement Satisfaction Index (L-WRSI) for crop areas by four broad categories for the conterminous United States (CONUS). The rectangular charts illustrate the percentage of the CONUS area that falls within the classes of Good (L-WRSI > 95%), Fair (80–95%), Poor (50–80%), and Severe Damage (L-WRSI < 50%) for each year.

4.2. GHA

L-WRSI was generated for the Greater Horn of Africa where frequent droughts create serious food insecurity challenges (Figure 17). In the GHA region, the L-WRSI is combined with other drought monitoring products such as NDVI and hydrologic indicators to develop the convergence of evidence framework needed for food insecurity assessment by FEWS NET. Figure 17 shows 3-month L-WRSI ending on the named month. For example, January 2018 L-WRSI comprises the ratio of ETa to ETc for the months of November 2017, December 2017, and January 2018. The spatial distribution of L-WRSI in the different seasons shows the complex nature of precipitation and vegetation pattern in the region. L-WRSI values can be summarized by district or watershed over a historical period to understand the relative performance of the landscape across regions and time periods.

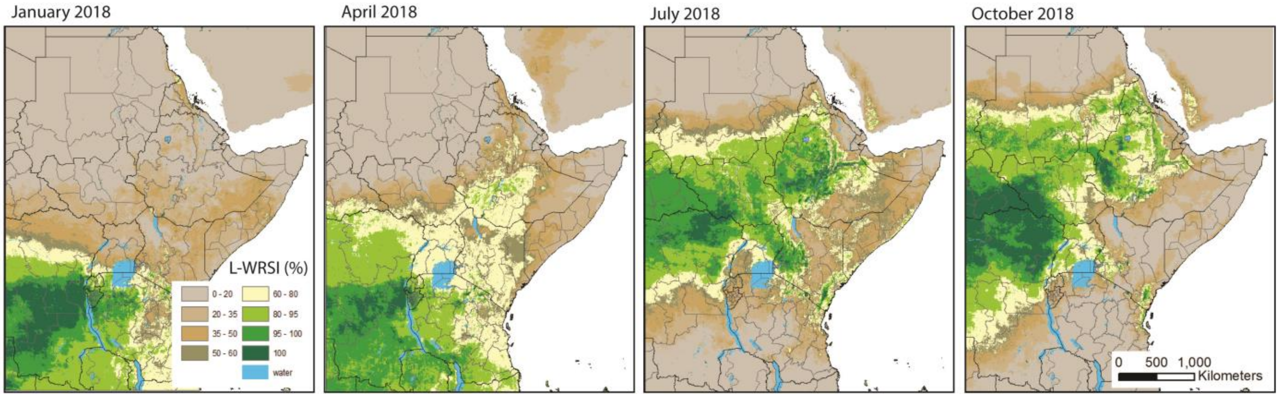

Figure 17. Landscape Water Requirement Satisfaction Index (L-WRSI) distribution in the Greater Horn of Africa using 3-month moving total for ETa and ETc during 2018. L-WRSI spatial patterns reflect the growing season dynamics across the region.

As opposed to the existing WRSI product of FEWS NET [22] for crop monitoring, the current continuous 3-month L-WRSI brings enhanced features of (1) the L-WRSI is continuous in space because the Kcp is generated from the NDVI-based LSP and does not depend on crop types or growing regions where the Kc is applied, (2) L-WRSI does not require estimation of start-of-season and end-of-season layers, which could introduce additional sources of uncertainty, making year-to-year comparison more reliable, and (3) because of the daily, year-round modeling, any desired time period can be simulated in the world instead of pre-specified seasons for a given region.

5. Conclusions

The main objective of this study is to present the updated agro-hydrologic VegET v2.0 model [29] along with performance evaluation results and drought monitoring applications over the conterminous United States and Greater Horn of Africa. A successful integration of a simple temperature-index based snowpack and melt process algorithm has been adapted to work with the VegET model.

Limited evaluation results indicate an encouraging performance in terms of capturing the timing and duration of snow accumulation and melt. Evaluation of soil moisture, ETa, and runoff estimations were reasonable in terms of capturing relative differences in space and time, indicating the usefulness of the model for drought monitoring purposes across diverse ecosystems using the highly integrated L-WRSI product. The operational implementation of the L-WRSI in the Greater Horn of Africa by the Famine Early Warning System Network can be expanded to a global coverage due to the readily available nature of gridded weather datasets and remotely sensed model parameters.

The spatiotemporal patterns of VegET ETa indicate that VegET could be used for the determination of net irrigation water use (blue water) when combined with energy balance models that estimate total ETa by quantifying the green water contribution from precipitation and soil moisture.

With continued evaluation and improvement, the VegET model can also be used to help improve flood forecasting because of the unique inclusion of the readily available land surface phenology (LSP) that accounts for vegetation dynamics in hydrologic modeling, without requiring specification of land cover types.

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