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The use of satellite images for evaluating a SWAT model: Application on the Vit Basin, Bulgaria

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Abstract: Remote sensing has become an indispensable source of input data and parameters estimation for environmental modelling. In the presented study evapotranspiration (ET) and leaf area index (LAI) were derived from satellite images and used for the evaluation of a hydrological model. Such applications can help to identify simulation inaccuracies and optimize the performance in areas with limited data availability. Moreover daily observations can provide useful information on agricultural management measures, such as harvesting dates. The Soil and Water Assessment Tool (SWAT) was chosen to model the Vit River catchment (area 3200 km²), which is located in the North of Bulgaria. SWAT is an integrated river basin model that performs the calculations on the scale of hydrological response units (HRUs), which are generated by a unique combination of land use, soil type and land slope. This approach allows a high discretization of the entire basin and enables the plot of results in detailed maps. The main objectives were to evaluate the predictions for ET and LAI by visual comparison of the model output with remotely sensed data. The evaluation showed that estimates for ET tend to be slightly underestimated, while those for LAI were visibly overpredicted. Furthermore a very distinct zoning effect of the results into clusters with similar values was observed. Those zones were identified as areas to which SWAT had assigned the same climatic conditions. On the contrary the satellite images were clearly following the land-use pattern of the basin and were showing uniform values for the different types of vegetation. It was concluded that in SWAT, climate showed a considerably greater impact on the ET and LAI simulations than different land-use or vegetation types, which was an unexpected phenomenon that needs further investigation.

Keywords: SWAT; remote sensing; evapotranspiration; leaf area index; Vit Basin

1 INTRODUCTION

Along with the increase of computational power the performance of hydrologic models has improved significantly and simulation outputs have become an essential part in watershed management. Remote sensing (RS) provides temporally dynamic and spatially explicit information on land surface characteristics [Zhang et al. 2011]. Thus the implementation of such data in physically-based models can be of great benefit, especially for river basins with poor data availability. Most studies use RS products to define the geometry, drainage network and land use of a watershed but also to parameterize hydrological variables such as leaf area index [Boegh et al., 2004] or soil moisture [Houser et al., 1998]. The use of RS to calibrate or evaluate a hydrological model however has been studied only by few researchers [Immerzeel and Droogers, 2007].

Within the scope of the EU funded 'EnviroGRIDS@BlackSeaBasin' project, which among others, aims to provide analyzed, processed and visualized information about the freshwater resources of the Black Sea Basin to decision makers and the public, the watershed scale model SWAT (Soil and Water Assessment Tool) was applied to the Vit River, which is located in the north of Bulgaria and is a direct tributary to the Danube. Calculations in SWAT are performed on a high level of spatial discretization, which allows plotting the results in detailed maps covering the entire basin. Satellite images can be then used for a visual comparison of specific outputs at different points in time. This approach enables the evaluation of the model for various parameters on a large scale rather than at single control points. It is therefore very useful for recognizing weaknesses and providing solutions at the same time.

The purpose of this study is to evaluate the performance of SWAT in simulating evapotranspiration and leaf area index in watersheds with limited data availability and quality, with the intention of providing useful information to researchers concerning model adaption and/or optimization.

2 THE VIT BASIN

The Vit basin stretches out from the Balkan Mountains northwards through the hilly Danubian Plane down to the Danube River itself. The total length of the river Vit is around 159km and the average channel slope is about 1.2%. The catchment area is 3200km², while the average width is only 20.5km. The mean annual discharge at the mouth is 19,18m³/s. The distribution of annual runoff is dominated by the seasonal characteristics of the moderate continental climatic conditions. Typically winter months come along with a snow cover in the mountainous areas. Precipitation occurs during spring, early summer and autumn. In summer however the rain events are from short duration and high intensity. The maximum discharge of the river can be observed during spring. The precipitation rates in the watershed vary from 500mm in the north to more than 1100mm in the south. The highest values are measured in June (55–75mm), while February and March are the driest months. The total mean annual precipitation in the basin is 780mm. The average annual temperature is 12°C, reaching a maximum of 25°C in summer (June to August) and a minimum of about 0°C in winter months (December to February). Areas used for agricultural purposes have the greatest share (ca. 60%) in the watershed. Around 30% of the basin is covered by

forest (deciduous broadleaf forest – 22%, mixed forest – 6% and evergreen needle forest – 1%). The remaining area is shared by shrubland, grassland, wetlands, industry and urban areas. The main soil types in the basin are Chernozems, Luvisols, Planosols and Kastanozems.

3 METHODS AND MATERIALS

3.1 Theoretical description of SWAT

The Soil and Water Assessment Tool – SWAT [Arnold et al., 1998] is an open source watershed scale, semi-distributed hydrological model developed by the USDA – Agricultural Research Service in the early 1990s. It uses physically-based input such as topography, soil properties, land cover and weather data to simulate the impacts of land management practices on water quantity and quality. The model can predict water flow, sediment transport, nutrient cycling and crop growth on a yearly to hourly time-step for continuous long-term simulations in large and complex watersheds [Neitsch, et al., 2001]. SWAT has a graphical user input interface (ArcSWAT) for the definition and storage of hydrologic features, as well as the organization and manipulation of the related spatial and tabular data. SWAT subdivides a watershed into subbasins which are then further discretized into hydrological response units (HRUs). A HRU has a unique combination of land use, soil type and land slope. Calculations concerning surface runoff, plant growth and water quality are performed at the lowest level of aggregation and afterwards summed up for each subbasin. The simulated water flow, nutrients and sediment loading are then routed through the river using the Muskingum method. Climate data is assigned to each subbasin using the information from the station nearest to the centroid of the same.

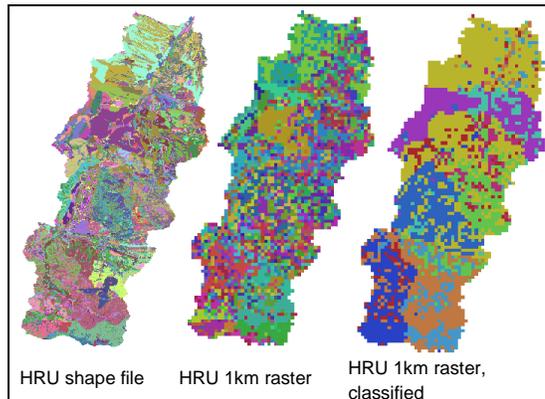
The terms evapotranspiration and leaf area index are closely interrelated in SWAT. Actual evapotranspiration is calculated after potential evapotranspiration has been determined. The components of actual evapotranspiration; evaporation of intercepted rainfall, transpiration, sublimation and evaporation from the soil are computed separately. Potential evapotranspiration can be modeled using the Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestley and Taylor, 1972) or Hargreaves method according to data availability. For this study the Penman-Monteith method was selected. Leaf area index is calculated as a function of Potential Heat Units (PHUs). The Heat Unit (HU) theory postulates that plants are accumulating as many heat units as the average daily temperature (heat) lies above the minimum base temperature (i.e. 5°C) required for a certain plant to grow until they reach maturity and get harvested.

3.2 Model application

Using ArcSWAT the Vit basin was delineated and subdivided into 20 subbasins and 1538 HRUs. The Digital elevation model (DEM) with a spatial resolution of 90mx90m was obtained from Shuttle Radar Topography Mission (SRTM) data. A scanned soil map of Bulgaria (1:400000), available from the European Soil Portal was digitized and related to the soil database provided by the project. The land use map is an average of annual MODIS land cover products for the years 2001, 2006 and 2008 and has a resolution of 1km². Weather data was derived from daily records of four climatic

stations (min/max temperature, wind speed and relative humidity) and nine rainfall gauges available over a period of 10 years (2000-2009). Solar radiation was estimated using the weather generator (WGN) and a dataset provided by enviroGRIDS. The WGN applies different statistical approaches to simulate missing data from a core set of basic properties such as monthly averages, standard deviations and others.

As proposed by Neitsch et al. (2002) the first two years of the simulation (2000-2001) were used as “warm-up” in order to stabilize the model and estimate correctly initial conditions such as soil moisture, groundwater level, nutrient content and others. Calibration was carried out for the period between 2002 and 2005, while validation was performed for 2006-2009. Daily records from five control gauges were available for model optimization, however due to data quality special attention was paid to only two of them (hms21650 and hms21750). Three different quantitative statistics were used to assess the goodness of the simulation; the Nash – Sutcliffe efficiency (NSE), the percent bias (PBIAS) and the coefficient of determination (R^2). The statistics showed good results for monthly (NSE of 0.83 and 0.82) as well as daily (NSE of 0.66 and 0.54) stream flow predictions during calibration. The validation period was less satisfactory for simulations on a daily time step (NSE of 0.30 to 0.39) but monthly averages were still adequate (NSE of 0.66 and 0.72). A great share of model failure



was attributed to insufficient data quality and availability.

The outputs for evapotranspiration and leaf area index were extracted from the database and attributed to the hydrological response units. The shape files were then converted to raster images with 1 km resolution and aggregated into classes in order to enable a better comparison with the satellite images (compare fig. 1).

Figure 1. Illustration of process applied to prepare HRU results for comparison with satellite images

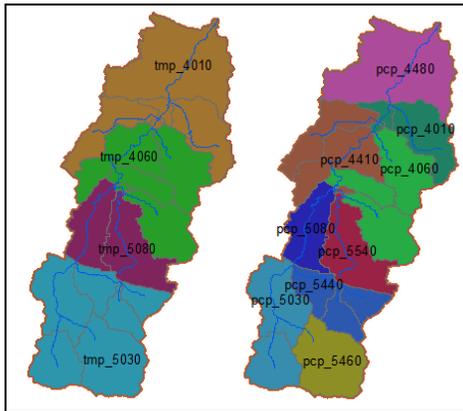
3.3 Remotely sensed data

The ET products (MOD16A2) used in this study represent all transpiration by vegetation and evaporation from canopy and soil surfaces, expressed in 1-dimensional vertical mm/day units. ET is computed globally every 8 days at 1km scale, using MODIS landcover, FPAR/LAI data and global surface meteorology from the Global Modelling and Assimilation Office. The LAI images (MOD15A) are Version-5 MODIS/Terra LAI products composited every 8 days at 1-kilometer resolution on a Sinusoidal grid. They have been validated at stage 2, meaning that the accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts. According to the Center for Earth Resources Observation and Science (EROS) these data are ready for use in scientific publications. To preserve information content of input data, LAI is retrieved directly from MODIS channel data.

4 RESULTS AND DISCUSSION

Before proceeding with the evaluation it should be noted that the model was not calibrated towards plant growth and respectively leaf area index. Moreover potential evapotranspiration was determined using solar radiation which was statistically estimated and not actually observed.

The results for ET and LAI were assessed for two different years, for a considerably wet year (1301mm) and for an average year (757mm). The outputs during the year with average climatic conditions (2006) were visibly closer to the remotely sensed estimates for both parameters. The temporal distribution of the predictions matched pretty well the overall trend of low values in winter, increasing rates during spring and summer and decreasing values towards autumn and winter. However in 2005, the model failed in simulating the seasonal variability of LAI. Moreover a remarkable difference in spatial distribution was observed for both years and parameters. While remotely sensed ET and LAI were clearly following the land use pattern of the basin, the visual assessment of the simulated outputs showed a very distinct clustering of the results into areas with similar values.



Those areas were not based on the land use type but on climatic conditions. In particular this means the basin was subdivided into mainly four different zones resulting from the four available weather stations for temperature (min/max), wind speed and relative humidity. In some cases the effect appeared as a composite of the above mentioned and the zones resulting from the nine rainfall gauges located in the basin (see fig. 3).

Figure 2. Segmentation of the catchment based on temperature stations (left) and precipitation gauges (right)

Leaf area index and evapotranspiration are SWAT components that, as yet, have received only scant attention [Arnold et al., 2008]. Daily predictions for ET and LAI were compared against average daily ET and LAI estimates derived through remote sensing. Please note that SWAT results were not necessarily compared to real values. The simulated and remotely sensed rates for evapotranspiration were mostly in the same range, even if in particular areas the model had over or underestimated the values. In general ET was very low during winter (0 to 1mm/d) as a result of low temperatures and restraint vegetation and elevated during spring with averages between 1.5 to 3mm/d. Maximum values were observed during summer reaching on average 5 to 7mm/d. On average SWAT performed relatively well in simulating evapotranspiration during cold periods, while it overpredicted the rates in springtime and underestimated the values in summer and autumn. In 2006 the overall comparison with remote sensing estimates showed a slightly better match than in 2005, although the zoning of the basin into areas with similar evapotranspiration rates occurred more drastically.

The segmentation effect of LAI estimates was less distinct (compare figure 4) but nevertheless noticeable and even enhanced during the year of extreme events (2005). The overall predictions however were not as good. In 2005 the model did not show any changes in LAI predictions from June until October, while the remote sensing images indicated a clear decrease. This phenomenon may be contributed to the precipitation rates, which were above the average this year. Optimal plant growth depends most on adequate water, nutrient supply and a favorable climate [Neitsch et al. 2001]. Higher water availability during summer could have improved the conditions under which biomass is produced and extended the growing season. If the time when a plant reaches maturity is postponed and the harvested date come later there will be no decrease in biomass and LAI. The sum of the average recorded precipitation for June, July, August and September in 2005 was 667mm, while the average sum of all ten years of records for the same period was only 348mm. In 2006 the model performed better in predicting LAI and moreover in simulating seasonal variability. The LAI varied between 0-1.5 in winter and spring, while in early summer it was between 1.5 and 2.5. Maximum values were observed during August (2.5 and 3.5).

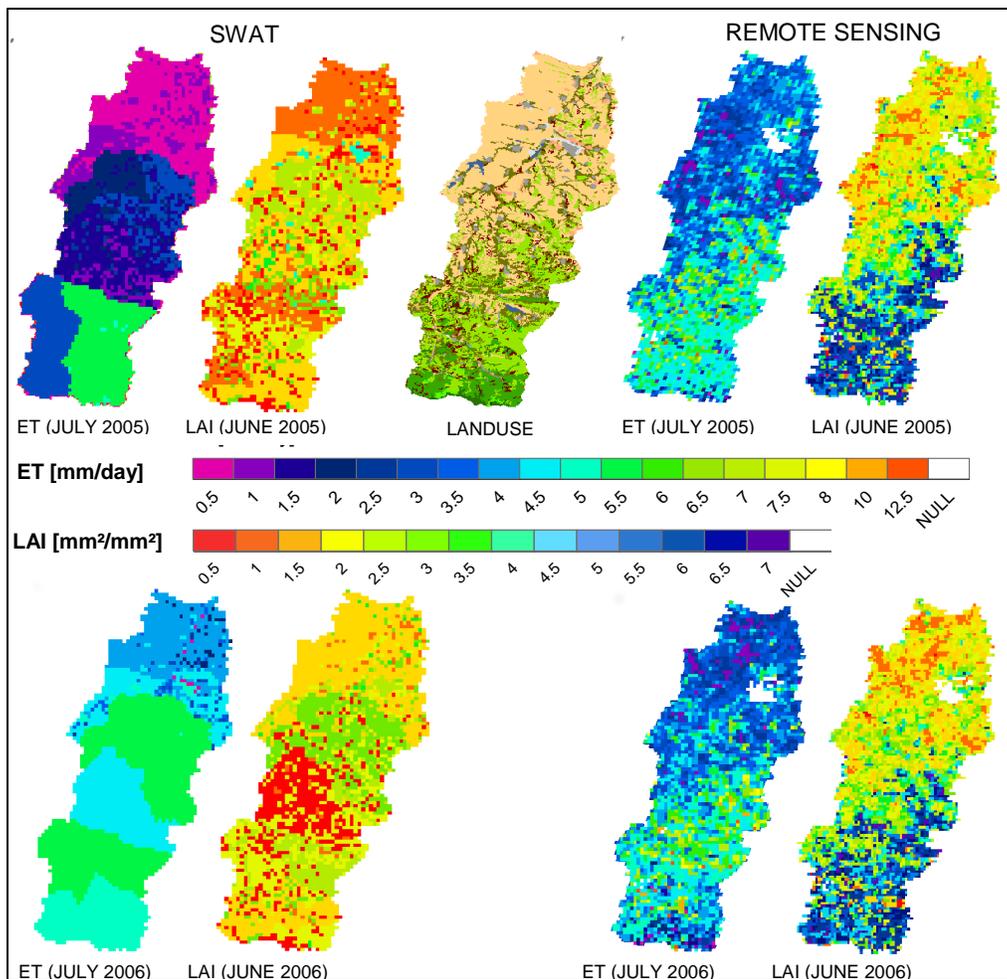


Figure 3. Comparison of simulated and remotely sensed ET and LAI with the landuse pattern of the catchment

Towards autumn the values had decrease to 1.5-2 and in December they reached again a minimum of 0-1. On the whole SWAT overpredicted the leaf area index by a relative value of 1.5. Remote sensing estimates strongly correlate with the landuse pattern of the study area, which itself is a RS product. Evapotranspiration and leaf area index predictions didn't indicate such pattern (see fig 3).

The leaf area index appears to be less dependent on climatic condition than ET, however only during periods with dense vegetation (i.e. growing season). In fact, as LAI is a function of plant heat units it is plausible that the landuse type has a greater influence on leaf area index during the growing season than in times when no crops are cultivated. For instance, during summer (June 2006) SWAT estimates values close to the ones obtained through remote sensing in the agricultural part of the watershed but it underpredicts the leaf area index in the forested area located in the South of the catchment This can be explained with the fact that the model doesn't assume a fully developed tree canopy, while the satellite image indicates the contrary. It should be recalled that 21% of the catchment area (mainly in the upper part) are covered with a deciduous broadleaf forest, which is known to fully develop its canopy during spring and summer and begin to lose leaves in autumn.

5 CONCLUSIONS AND RECOMMENDATIONS

Given the complexity of a hydrological system as well as the limited data availability the SWAT model performed reasonably well in predicting daily and average monthly discharges, however a need for improvement was identified for evapotranspiration and leaf area index simulation. In summary the following findings can be concluded:

- ET and LAI estimates were strongly correlated to climatic zones, while RS images showed a clear relationship with the land use pattern of the watershed
- Climate had a considerably greater impact on evapotranspiration and leaf area index simulation rather than different landuses or vegetation types
- The model performed better in simulating LAI and ET for a year with average climatic condition than for a year with increased total precipitation rates
- On average the evapotranspiration rates tend to be slightly underestimated, while leaf area indices were clearly overpredicted
- During summer (growing season) the model predicted reasonable LAI values for the agricultural areas but strongly underestimated the leaf area index for the forested areas
- The visual comparison of SWAT outputs with satellite images is a relatively simple yet effective way of evaluating the performance of the model towards specific parameters

Note that the results of this study are exclusively valid for the model of Vit Basin developed using the described methods and materials. Other watersheds, with different characteristics and greater data availability may give different results.

The effect of insufficient data, especially climatic information is enhanced by the approach used in SWAT to simulate weather conditions. Instead of assigning data from the station nearest to the centroid of a subbasin, it could be more practical to apply some basic interpolation method between the available stations including elevation.

The adjustment of specific parameters related to the assessed outputs was beyond the scope of this study. However a calibration towards the evaluated output is recommended for future undertakings with similar aims. The crop database could be revised by implementing information from local farmers and field measurements/observations.

The implementation of remote sensing images can also be used to calibrate hydrological models of watersheds with limited data. Besides evapotranspiration and leaf area index, products for soil moisture, snow cover and primary productivity (to name a few) are available and can be applied.

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