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A Google Earth Engine tool to assess water budget and its individual components

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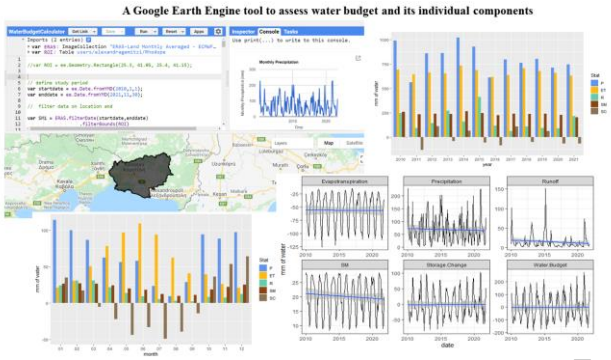
Graphical abstract



Abstract

In the present work a new freely available web-based tool is developed within Google Earth Engine (GEE) that aims to support water agencies, farmers and public services acquire information on the water budget components in the areas of their interest. The tool makes use of the high-resolution land component of the fifth generation of European ReAnalysis (ERA5), i.e. ERA5-Land, post processed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The application accesses the bands associated with the hydrologic variables from ERA5-Land, in order to estimate the water budget at the local, river basin and regional scales. Therefore, the time series of major water budget constituents i.e. precipitation, runoff, evapotranspiration, soil moisture and storage changes are computed at the monthly time step. Considering the use of freely available data sets and the convenient cloud functionalities offered by GEE, the developed application will offer a free supporting tool for farmers and decision makers to plan activities, infrastructures and measures in water resources management, emergency services and agricultural sectors.

Keywords: Water budget, remote sensing, ERA5 land, Google Earth Engine.

1. Introduction

Evaluation of water budget and its individual components is crucial for effective water resources management but also for planning activities in various sectors like agriculture and public services. Water budget is crucial for the knowledge of renewable water resources and is a pre-requirement for sustainable water resources management (Healy *et al.,* 2007). In that way precipitation and runoff are of particular interest for the assessment of flood risk in an area whereas soil moisture is useful for planning of agricultural activities but also highlights areas at high risk of fire. Previous research has shown that precipitation and runoff are strongly related to the occurrence of floods (Zhang *et al.,* 2018) and landslides (Chen *et al.,* 2020). On the other hand soil moisture is a crucial parameter for the agricultural sector as it quantifies the amount of water that is actually added and stored in the soil and is available for crop needs, but also expresses the drought conditions that affect crop production (Mozny *et al.,* 2012) which could also indicate alarming situation for wild-fire occurrence (Sungmin *et al.,* 2020). Evapotranspiration plays also a key role in the water availability for crops, whereas surface runoff is also important factor in mountainous terrains or in areas experiencing heavy rainfalls (Vallet *et al.,* 2013). For arid to semi-arid regions it has been shown that evapotranspiration is the prevailing water budget parameter, ranging well above the 50% of precipitation (Duque *et al.,* 2018; Falalakis and Gemitzi, 2020), controlling thus the amount of water the reaches ground surface and infiltrates into the soil. Overall, water budget estimation provides a means to allocate in a balanced way the water quantities for human needs and those necessary for ecosystem services. It also helps in acquiring information on how a human or naturally induced change in any of water budget components, is reflected in other components (Healy *et al.,* 2007).

It is therefore evident that knowledge of water budget and its allocation to various hydrologic parameters is of primary importance for human life and for various ecosystems functioning, although acquiring information for its spatial and temporal evolution is often restricted by lack of data of adequate coverage in time and space (Lakshmi, 2016), inherent uncertainties in all techniques that measure water budget components but also the dynamic nature of hydrological processes. Advances in hydrological science provide nowadays improved

measurement techniques and models for simulating water flow processes, whereas technological breakthroughs in remote sensing and improved interpretation of such data sets are powerful tools for the assistance of water resources managers to highlight the best operational option. Although there is a considerable progress in the knowledge of the hydrological systems, there is still a gap in communication of this knowledge to various stakeholders, including public services. Communication failure between end users and scientists results in the inefficiency of scientific research to be transformed into sustainable water resources management (Eden *et al.,* 2016).

The present work aims at providing a convenient and freely available tool for water managers and users to evaluate the various water budget components in a comprehensible way. For this reason, the ERA5-Land dataset has been adopted, to provide a user-friendly tool for the assessment of the evolution of water budget and the related hydrological variables over several decades at the local, regional or even larger scale. The advantages provided from a state-of-the-art data set such as ERA5-Land cannot be made easily available for the non-technically trained stakeholders. Our tool helps towards making such data sets accessible and comprehensible by all stakeholders, increasing thus their added value and their practical contribution to society.

2. Methods and materials

2.1. The ERA5-Land dataset

Components of the water budget, i.e. precipitation, runoff, soil moisture, evapotranspiration, are part of a total of 50 land variables of the ERA5-Land dataset. ERA5-Land constitutes a high resolution, i.e. 9 km, global reanalysis product of the land component of the ERA5, covering the period from January 1981 to the near present, with a latency of 2 to 3 months (Muñoz Sabater, 2019; Muñoz-Sabater *et al.*, 2021). ERA5-Land is a combination of model data with observations and aims to support climate change studies and various applications of water resources and land management, through the provision of a consistent data set that describes the water and energy cycles over land. ERA5-Land is provided at an hourly time step, but also monthly means are computed and are readily available. Evaluation of the ERA5-Land has been conducted using ground data, global model and satellite derived reference datasets and demonstrated its added value as far as the description of the hydrological cycle is concerned, supporting thus its applicability as a state-of-the-art dataset for a wide range of land applications (Muñoz-Sabater *et al.,*, 2021). In the present work we used ERA5-Land Monthly Averaged - ECMWF Climate Reanalysis data set to estimate time series of the water budget at various spatial scales.

2.2. The Google Earth engine platform

Google Earth Engine (GEE) (Gorelick *et al.,*, 2017) is a powerful platform offering many services to scientists, allowing processing of vast amount of remotely sensed data along with a variety of other scientific datasets e.g. climate and weather data, global land and ocean model datasets, demographic data, among others. Its main advantage is the easiness of accessibility of numerous datasets, and the cloud-based computations, relieving scientists of the tedious tasks of accessing, downloading and storing of those amounts of data. In that way, computationally demanding work flows, like global scale analyses, are now easily applicable through GEE. Additionally, users can upload their own data sets for use in their computations privately or shared with their colleagues all over the world. A recent study demonstrated the increasing interest of the scientific community in those challenging GEE opportunities to conduct research with minimum required resources (Kumar and Mutanga, 2018). Besides the numerous advantages of GEE, users should also keep in mind of several issues, like the non-commercial use of the free version along with limits in storage and processing resources in this version as well. Therefore, the possibility of a professional production application is not enabled within the free version, while the restricted programming language is also considered a disadvantage by many researchers (Navarro, 2017). Recent analysis (Kumar and Mutanga, 2018) has documented the challenging character of GEE developers' environment, which however still remains more accessible to the developed world, with far less applications and research studies originating from developing countries. Within our work we engaged the free version of the GEE to develop a tool that estimates water budget at various spatial scales utilizing the ERA5-Land data set. The developed tool is freely available for various end-users for non-commercial use, but also constitutes a prototype for a professional geospatial application, the can be used and expanded to commercial application.

3. Results and discussion

3.1. Application of the developed tool

To demonstrate the practical application of the developed tool we applied it at three different scales in the region of Thrace in NE Greece, i.e. at the local level for an area of ~ 90 km2, at the river basin level in Vosvozis River Basin with an area of ~ 350 km2, and at the regional level in Rhodope Regional District with an area of ~ 2500 km2, for the time period from 2010 to October 2021 (Figure 1). The study area has a diverse topography, with a mountainous terrain to the north and a flat plain area occupying the central and southern parts. From the hydrological point of view the area is a typical mountain front system recharge region (Gemitzi *et al.,* 2017; Falalakis and Gemitzi, 2020).

The following land variables are processed at the monthly time step: a) Precipitation (P) (mm) which represents the accumulated liquid and frozen water, including rain and snow, that falls to the Earth's surface, b) Runoff (R) (mm) which is the amount of water that drains away either as surface runoff or below the ground's surface as subsurface runoff, c) Evapotranspiration (ET) (mm) which represents the amount of water that evaporates from Earth's surface and the amount that is used for vegetation

transpiration processes. Since ET returns water to the atmosphere it has negative values, whereas positive ET corresponds to condensation, d) Soil Moisture (SM) (mm) which corresponds to the amount of water stored in top soil layer (0 to 7 cm), which is an essential parameter for the agricultural sector but also for fire brigade services, e) Storage Changes (SC) (mm) which represents changes in the amount of water stored in the top soil layers up to 289 cm deep.

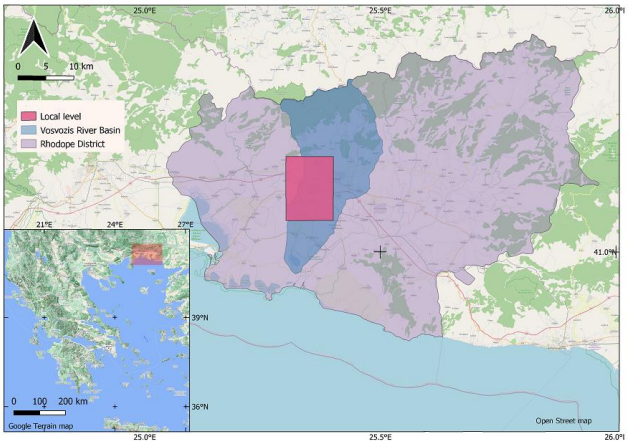


Figure 1. Location map of the application areas in NE Greece.

After extracting the above parameters, the water budget at the monthly time step is estimated by the following equation (Healy *et al.,* 2007):

$$P + Q_{in} = ET + SC + Q_{out} \quad (1)$$

where P is precipitation (in mm), Q_{in} and Q_{out} (mm) stand for the amount of water flowing into and out the examined area respectively, ET (mm) is the evapotranspiration and SC (mm) is change in storage in the soil layer up to 289 cm deep. Equation 1 can be customized according to each specific study scale and goals, e.g. precipitation can be the sum of rain, snow, fog, dew, and irrigation, while water flowing into and out of the area can be surface or subsurface flow, both natural or human induced (Healy *et al.,* 2007). In the present work Q_{in} and Q_{out} are approximated with Runoff described above. The water budget in the present work does not account for changes in groundwater storage, which is not estimated within the ERA5-Land data set.

3.2. Application at the regional level

Application of the GEE tool at the regional level is demonstrated at the Rhodope Regional District (Figure 1). Graphs of Figure 2 demonstrate the time series of the water budget components at the monthly time step. The estimated trends in all cases are not statistically significant (i.e. p>0.01) which is also evidenced by the substantial width of the 95% confidence interval zones. Therefore, there is no clear evidence towards an increasing or decreasing trend for the study area during the last decade. Overall, the water budget shown on Figure 2 seems to be balanced. However, it should be pointed out that deep groundwater storage is not included in the computations, and the results in terms of the storage component could be slightly different. However, the storage terms that are crucial for various sectors, i.e. soil moisture in the top 7 cm soil layer and storage changes in the top 289 cm of soil are estimated providing thus a useful output to stakeholders.

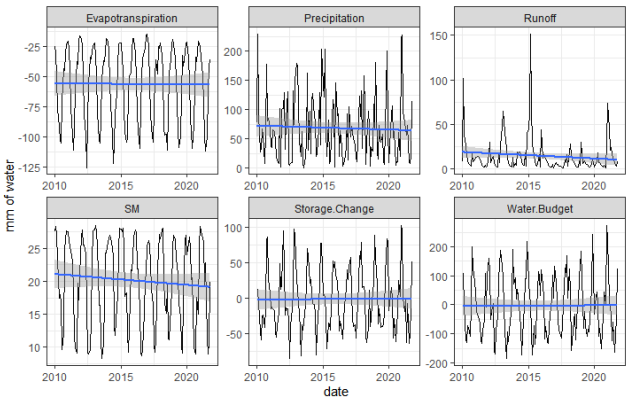


Figure 2. The monthly water budget and its constituents in Rhodope Regional District from 2010 to October 2021. Blue line corresponds to trend of the time series, whereas grey zones correspond to 95% confidence intervals.

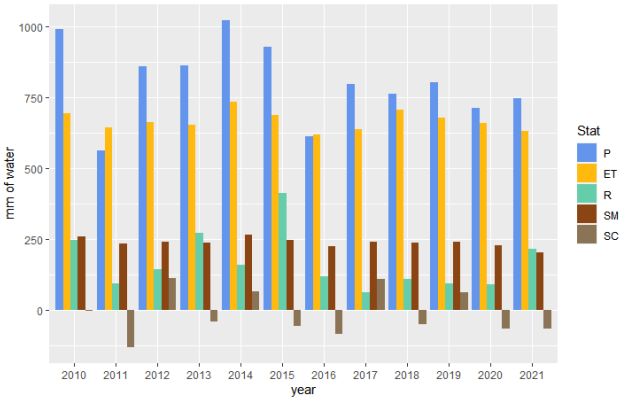


Figure 3. Annual water budget constituents, i.e. Precipitation (P), Evapotranspiration (ET), Runoff (R), Soil Moisture (SM) in the top 0 to 7cm soil layer, Storage Changes (SC) in the top 289 cm of the soil layer, from 2010 to October 2021 in Rhodope District.

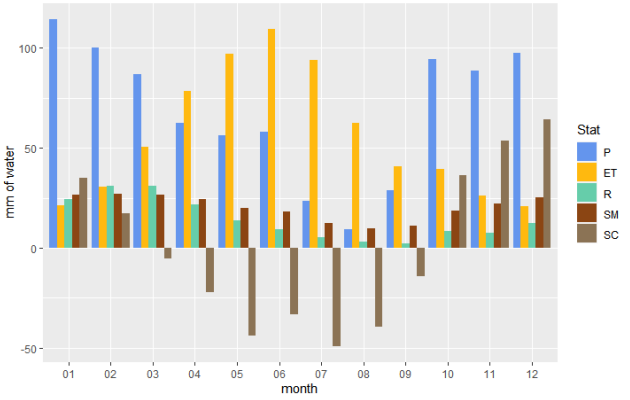


Figure 4. Mean monthly water budget constituents, i.e. Precipitation (P), Evapotranspiration (ET), Runoff (R), Soil Moisture (SM) in the top 0 to 7cm soil layer, Storage Changes (SC) in the top 289 cm of the soil layer, estimated from monthly values from 2010 to October 2021 in Rhodope District.

Figure 3 demonstrates the annual water budget components, which help in the identification of specific

years that showed either water deficit of surplus. In general, dry years are characterized by negative storage changes, with the driest of the decade being the 2011. Please note that 2021 is not a complete year, since the data for November and December 2021 were not available at the time of completion of the present work. Such results are especially useful for water authorities to assess the water availability in their areas of interest. Furthermore, public services like fire brigade, may take advantage of the information acquired, e.g. a prolonged period with negative storage changes is an alarming observation related to increased risk of wild fire occurrence.

Figure 4 shows the mean monthly values of the water budget components. The months with high evapotranspiration values and negative storage changes are the driest ones and those when irrigation should be applied, according to the plant requirements.

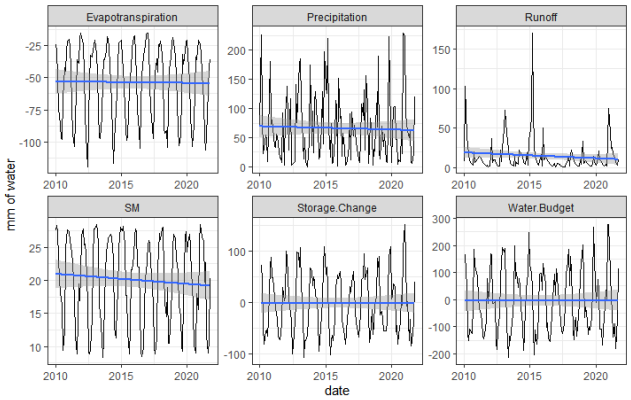


Figure 5. The monthly water budget and its constituents in Vosvozis River Basin from 2010 to October 2021. Blue line corresponds to trend of the time series, whereas grey zones correspond to 95% confidence intervals.

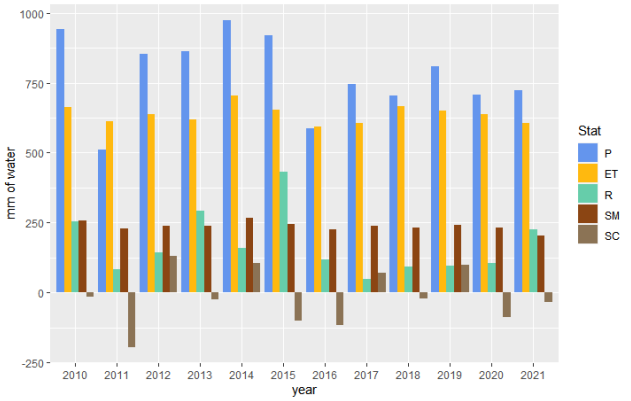


Figure 6. Annual water budget constituents, i.e. Precipitation (P), Evapotranspiration (ET), Runoff (R), Soil Moisture (SM) in the top 0 to 7cm soil layer, Storage Changes (SC) in the top 289 cm of the soil layer, from 2010 to October 2021 in Vosvozis River Basin.

3.3. Application at the river basin level

Application at the river basin level is demonstrated at Vosvozis River Basin. Time series graphs of the hydrological variables at the monthly time step, are shown on Figure 5. A consistent outcome to that in Rhodope Regional District is observed, which is expected considering that the specific river basin occupies a considerable part of the Rhodope District.

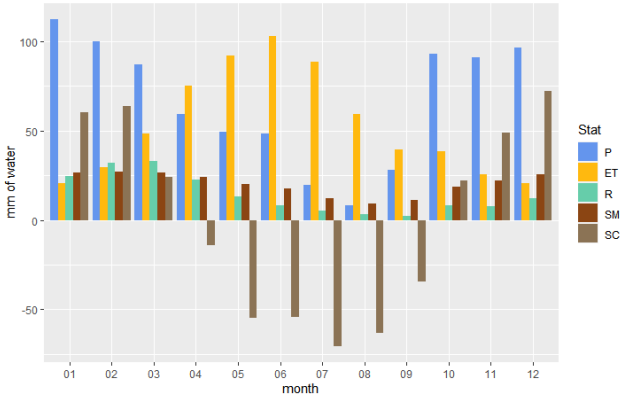


Figure 7. Mean monthly water budget constituents, i.e. Precipitation (P), Evapotranspiration (ET), Runoff (R), Soil Moisture (SM) in the top 0 to 7cm soil layer, Storage Changes (SC) in the top 289 cm of the soil layer, estimated from monthly values from 2010 to October 2021 in Vosvozis River Basin.

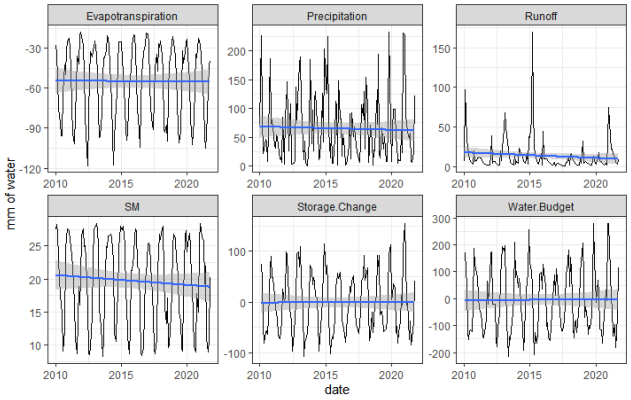


Figure 8. Local assessment of the monthly water budget and its constituents from 2010 to October 2021. Blue line corresponds to trend of the time series, whereas grey zones correspond to 95% confidence intervals.

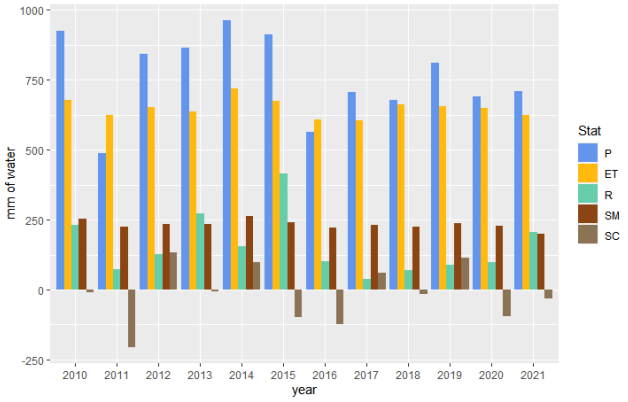


Figure 9. Annual water budget constituents at the local scale, i.e. Precipitation (P), Evapotranspiration (ET), Runoff (R), Soil Moisture (SM) in the top 0 to 7cm soil layer, Storage Changes (SC) in the top 289 cm of the soil layer, from 2010 to October 2021.

Figure 6 shows the annual water budget components from 2010 to 2021 (with 2021 comprising months from January to October) and Figure 7 demonstrates the monthly means of the same variables. The same outcome

as in the regional analysis of the previous section is observed in the case of Vosvozis River Basin, with the same dry and wet years and the same months indicating negative storage changes, although at a slightly different magnitude compared to Figures 3 and 4.

3.4. Application at the local level

The application at the local level is demonstrated at the area indicated in Figure 1. Figure 8 shows the time series plots of all water budget components. Figures 9 and 10 show the local level assessment of the annual (i.e. 2010 to 2021) and mean monthly water budget components.

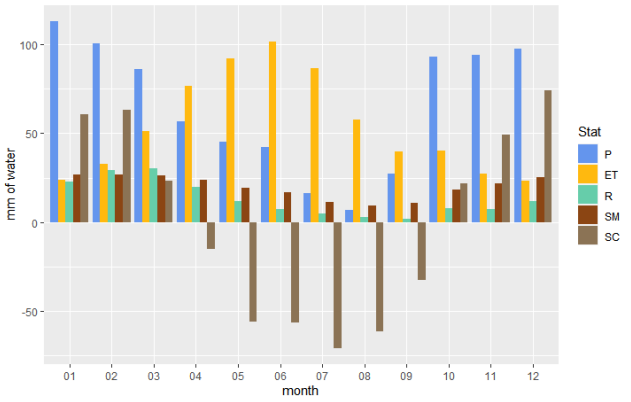


Figure 10. Mean monthly water budget constituents at the local level, i.e. Precipitation (P), Evapotranspiration (ET), Runoff (R), Soil Moisture (SM) in the top 0 to 7cm soil layer, Storage Changes (SC) in the top 289 cm of the soil layer, estimated from monthly values from 2010 to October 2021.

4. Discussion

Results obtained by the application of the GEE tool developed to extract the water budget and its components at the monthly and annual time scales and at regional to local spatial scales, indicate that ERA5-Land dataset can be easily transformed into a water budget representation that is comprehensible by various stakeholders. Therefore, all stakeholders such as farmers, water authorities, public services may take advantage of the freely available state-of-the-art dataset like ERA5-Land. The computed water budgets are consistent in all spatial scales and highlight the various components in a meaningful way. The extracted results in Rhodope area indicate that evapotranspiration is by far the largest water budget component, consuming more than 60% of precipitation and this is in agreement with results from previous research (Gemitzi *et al.,* 2017; Falalakis and Gemitzi, 2020). This is evident in all scales of analysis. Runoff and storage changes in the soil layers consume almost equal percentage of precipitation approximately ~ 20% each, while a portion of those quantities is expected to contribute to changes in groundwater storage, which is not evaluated in the present work. The driest years in the examined time period are the 2011 and 2016, and the wettest are the 2010 and 2014. Overall, the water budget demonstrates a balanced character at the decadal level.

The presented herein tool can be easily adapted to extract water budget from other publicly available data sets and to incorporate also groundwater storage changes when available. At its present version the code is running using the free GEE functionalities. It can be also easily transformed into a professional application using the subscription GEE advantages to overcome the memory and storage limitations. It provides the opportunity to acquire meaningful representation of the water budget and its components at various scales, enabling thus even the non-technically trained users to understand the evolution in time and space of land variables and transform thus the scientific advances in hydrology into meaningful policies in various sectors of human life such as agriculture, water management and other public services.

5. Conclusions

Previous research has shown that scientific progress cannot be effectively transformed into sustainable policies related to water resources management, if there is lack of basic knowledge of the related processes by various stakeholders. Recent advances in hydrology have resulted in state-of-the-art data sets that describe the land variables and the climate of the past at scales useful for practical applications. The non-technically trained stakeholders however encounter difficulties in acquiring information from those data sets and taking the full advantage of it. The present work uses the advanced functionalities offered by the freely available GEE platform in order to extract in a comprehensible way the water budget and its components at various spatial and temporal scales, making use of the recently released ERA5-Land data set. Results of its application at three different spatial scales in NE Greece, agree with those of previous research in the area, and highlight the usefulness and user-friendly character of the developed tool.

Acknowledgments

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Data availability

ERA5-Land bands were accessed from: https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY#bands.

The full ERA5-Land monthly averaged dataset (Muñoz-Sabater *et al.,* 2021) used in this paper is also available through the C3S Climate Data Store at https://doi.org/10.24381/cds.68d2bb30.

Google Earth Engine code can be found in: https://code.earthengine.google.com/1cf946effd5697bc563630d7a1906738.

The above code was generated using Copernicus Climate Change Service Information [2021].

No Conflict Statement

Authors declare no conflict of interest.

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