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Surface irradiance estimations on watercourses with remote sensing data

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ABSTRACT

The vegetation in the riparian zone of a watercourse influences the water state with multiple factors, first via direct substance discharge and secondly via shadow casting on the water surface. Shadowing directly regulates the solar radiant energy arriving at the water surface. Solar radiation input to aquatic environments is the most important abiotic factor for aquatic flora and fauna habitat development. Thus, to adequately assess the ecological state of water courses it is necessary to quantify the solar surface irradiance E (W/m^2) arriving on the water surface. When estimating the solar surface irradiance the complex coherence between incoming solar radiation, atmospheric influences, and spatial-temporal geometries need to be investigated. This work established a workflow to compute the solar surface irradiance for water bodies using different remote sensing data. The workflow was tested on regional level for a section of the river Freiberger Mulde, Saxony, for the year 2016. Product of the calculations is a map visualising the annual sum of the solar surface irradiance (kWh/m^2) arriving on the Freiberger Mulde water surface and the surrounding terrain. Based on these information bio-hydrological issues can be further examined.

Keywords: Surface Irradiance, Illumination, European Water Framework Directive, shadowing

1. INTRODUCTION AND MOTIVATION

The Sun is the center of our solar system and the Earth revolves epicentral around it. With a surface temperature of nearly 6000 K, a result of nuclear fusion of hydrogen to helium, the Sun emits an enormous amount of energy into space. This solar radiant energy partially reaches the top of Earth's atmosphere, enters the atmosphere and arrives at the Earth's surface, being essential to the metabolism of flora and fauna and is one key to the atmospheric dynamics. The photosynthetic activity of vegetation and solar radiant energy are closely linked. The available total solar radiation effects the potential of photosynthetic activity of aquatic or ground-based plants. Further, the vitality of the photoautotroph hydrophytes closely correlates with the ecological quality of water bodies.¹

In 2000 the European Water Framework Directive was established containing guidelines for sustainable and environmental friendly practices in regard to water.² This directive is realised on national level by the Water Resources Act in Germany.³ The edicts build the foundation for a monitoring and assessment programme on the ecological status and development of water courses in Germany. It is necessary to systematically observe and record the current and changing conditions of the national water environment as a basis for further assessment. Since the recorded, analysed and evaluated data supports the realisation of the law to maintain or improve the ecological state of water courses in Germany. As the state of aquatic and land vegetation is influencing the ecological status and balance of water courses, information on both quantitative and qualitative vegetation conditions are desirable.

It is possible to indirectly gain information about the potential growth of aquatic and land vegetation, when the amount of incoming solar radiation is known.^{4,5} The solar energy is one of the most important abiotic factors on aquatic plant growth and therefore the water quality. Thus, to further derive information on water ecological

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topics it is essential to know the illumination characteristics on a watercourse. With known illumination and non-illumination characteristics the intensity of the incoming solar radiation and irradiance E can be estimated.^{6,7}

The main goal of this work is to establish a workflow for solar surface irradiance calculations based on remote sensing data. The calculations incorporate necessary meteorological components like ozone, relative humidity, temperature and geometric relations between Sun and Earth to characterise illumination properties. To test the sufficiency of this workflow and the input data, the annual cumulative sum of solar surface irradiance $\sum E_e (W/m^2)$ for a section of the Freiburger Mulde, Saxony, Germany, for the year 2016 was calculated. This was accomplished in respect to the illumination and shading properties of the research area. At the top of the atmosphere (TOA) the average value of solar radiation is about $1361 W/m^2$. It differs depending on the location on Earth and the current elliptical orbit. In general the incoming solar radiation is most intense at the TOA and decreases in intensity on its way to the Earth surface due to optical properties of atmospheric constituents.⁸ Products and applications calculating the solar surface irradiance do exist, i.e. provided by the European Union or the DWD (German Meteorological Office). These commercial and free applications are commonly used to estimate the potential clear-sky, cloud free conditions, solar surface irradiance for photovoltaic modules, for energy production on a global or national scale. Regardless, barely one of the free or commercial applications consider the influence of clouds during their solar surface irradiance calculations nor provide a sufficient geometric resolution to estimate the incoming solar surface irradiance on rivers and small water bodies. Additionally, clouds depending on their optical thickness have a major impact on the incoming solar radiation while travelling to the Earth's surface.

Thus, the provided work established a workflow for the calculation of solar surface irradiance with respect to the influence of clouds based on satellite remote sensing data. The calculations are realised with the programming language R utilising application specific packages, like *insol*.^{9,10} To achieve this goal, the diverse meteorological and geometrical relationships of Sun and Earth constellation are to be considered.

The chosen area of interest to test the established workflow is a section of the river Freiburger Mulde in Saxony, located near the towns Döbeln and Westewitz. The region is called Klosterbuch. The river section was chosen due to the versatile influences of local topography and changing riverine vegetation. To incorporate a relatively broad spectrum of possible influences on solar radiation falling on a water surface. The characteristics of the riparian vegetation varies between high single standing deciduous trees to trees closely aligned alongside the river. Also small vegetation like bushes and in the south more permanent elements like a hill occur. Natural and artificial objects influence the shadow cast on the Freiburger Mulde and therefore the illumination.¹¹ Hence, to estimate the effect of shadowing of vegetation or topography on the solar surface irradiance, the chosen section is suitable.

2. METHODOLOGY

2.1 On the constellation of Earth and Sun

The Earth makes one entire rotation in 23.934 hours, one stellar day, and causes a change between day and night. The duration of day and night varies with the time of the year and is closely linked to the Earth's revolution around the Sun. In figure 1 (left) the change in day length is depicted for the research area.

Besides the diurnal illumination changes induced by the revolution of the Earth, annual illumination changes occur. One complete orbit of the Earth on its trajectory around the Sun has a period of approx. 365.256 days, which equals one sidereal year. The Sun seems to pursue a circular path on the celestial sphere during one sidereal year. This path is termed ecliptic. In respect to the ecliptic the Earth's equator is tilted. This axial tilt of $\sim 23.5^\circ$, termed obliquity ε of the ecliptic, is relatively stable.¹² In result the Sun seemingly changes its position, azimuth and elevation in the sky accordingly during the course of a year. In Figure 1 (right) this is depicted for the research area.

The annual and diurnal changes of the Sun directly relate to the illumination properties of the Earth's surface. In coherence with the illumination properties of a surface is the intensity of the arriving solar radiation.^{13,14} Concluding, induced by the annual and diurnal illumination changes the solar radiation accordingly changes during the course of a day respectively a year. Thus, to calculate the solar surface irradiance for a time period the temporal geometric and radiometric changes need to be considered.^{11,12,14}

Figure 1. Left: Annual regime of the day length change at the research area. Right: Analemmata for the centre of the research area (N51.13, E12.98; 8, 10, 12, 14, 16 o'clock local time)

The Figure 2 depicts the relationship between Sun elevation and incoming solar radiation on mid summer day for the research area. As seen with increasing elevation of the Sun the amount of the solar radiation increases.

Figure 2. Sun elevation and incoming solar radiation on mid summer day 2016 for the study area. (Sunrise: 06.00, Sunset: 22.43)

It is evident that shadowing occurs when an object is opaque. An opaque objects absorbs or reflect the light beam and casts a shadow on the opposite side of the light source. Resulting in a significant influence on the arriving solar radiation and therefore on the solar surface irradiance.^{8,13} Shading underlies temporal-geometric conditions and is directly effected by the position of the shadow casting object (cf. Figure 3) and surrounding topography.^{11,15} Further, the elevation of the Sun is another determining variable for the shadow cast, especially in length.

Figure 3. Diurnal variation of the course of the sun influencing the azimuth of shadows (left), diurnal and annual variation of the sun elevation influencing the length of the shadow (right).¹¹

To adequately detect the spatio-temporal progression of the shaded areas quarter-hourly calculation of the shadow casting is suggested.¹¹ The temporal and geometrical factors, the further diurnal annual changing position of the Sun are thereby sufficiently accounted for.

2.2 Considering atmospheric conditions

To calculate the solar surface irradiance E_e at the Earth's surface, energy transformation processes induced by the atmosphere need to be considered. The solar irradiance at the Earth's surface is decisively affected by the atmospheric transmission.^{6,13} The chemical and physical composition of Earth's atmosphere attenuates the incoming solar irradiance. These atmospheric influences affect the distribution and the amount of solar surface irradiance via scattering and absorption. Resulting in a further subdivision of solar surface irradiance into direct $E_{e,dir}$, diffuse $E_{e,diff}$ and reflected $E_{e,ref}$ proportion (cf. equation 1).

$$E_e = E_{e,dir} + E_{e,diff} + E_{e,ref} \quad (1)$$

Direct solar irradiance is used to describe solar radiation coming on a straight line from the Sun to the Earth's surface without accounting interaction with external influences. Thus, all radiation beams come from the direction of the Sun. This portion of E is especially high on clear-sky days. Meanwhile, diffuse solar irradiance $E_{e,diff}$ takes external effects induced by the optical depth of the atmosphere on the solar irradiation into account. $E_{e,diff}$ increases with increasing optical depth of the atmosphere.⁶ The transparency state of the atmosphere is determined by atmospheric aerosols and particles, i.e. water vapour and ozone. These elements influence and interact with the incoming solar radiation resulting in scattering effects. Very prominent here are clouds, especially low-clouds with a high optical depth.^{8,16} Scattering has a high influence on the solar irradiance and therefore on the solar surface irradiance arriving at the Earth surface. Reflection $E_{e,refl}$ of incoming solar radiation is a directed backscattering of the electromagnetic waves. The angle of reflection is analogous to incident angle of the solar beam. Reflection is commonly accompanied with an attenuation of energy, here the incoming solar radiation.¹⁶

To estimate the available incoming solar energy (solar surface irradiance E_e) the specific influences need to be incorporated in the solar surface irradiance calculations. Therefore, information on the chemical composition of the atmosphere and auxiliary data like surface height are required. The atmospheric variables with highest influence and topography induced impacts on solar radiation are the stratospheric ozone, the near-ground temperature, horizontal visibility, near-ground relative humidity, the surface albedo, cloud fractions as well as the surface height.^{9,17}

2.3 Data

Basically two super-ordinate categories in data acquisition can be distinguished, ground-based and remotely sensed. Especially satellite remote sensing data is successfully applied in atmospheric modelling.^{6,18,19} They can adequately provide information on the high variability of influencing factors on the total solar surface irradiance.^{20,21} A source for free remotely sensed data is Goddard Earth Science Data and Information Services Center (GES DISC).²²

An other administrative data providing service, especially for Germany, is the DWD (German Meteorological Office). The meteorological data provided by the DWD necessary for solar surface irradiance calculations are in majority ground-based measurements. The datasets are quality checked and partially free available as point or aggregated gridded product with different spatio-temporal resolutions. The closest station to the research area is approx. 13 km away (STATION ID131). Also the European Centre for Medium-Range Weather Forecasts (ECMWF) provide atmospheric reanalysis and forecast datasets. Their public datasets are free of charge. The ECMWF data was not utilised for the calculations. The datasets contain nearly the same information as GES DISC datasets. But the GES DISC provide a more suitable temporal resolution and for this work a better data handling and are all stored in the same file format, which can be easily converted to raster format. An equally spaced raster is needed to perform for instance the illumination calculations.⁹ Further, during the time of data research adequate aggregated and gridded data was not available for some time of 2016 via the ECMWF.

To derive atmospheric information for the year of 2016 the following remote sensing and ground based datasets were processed (cf. Figure 4), primarily acquired from the GES DISC.²²

The aberration MERRA-2 stands for Modern-Era Retrospective analysis for Research and Applications version 2. It the second project of NASA's atmospheric reanalysis program. The vast MERRA-2 archive stores

Figure 4. Input data and sources for the solar surface irradiance calculation for the study area. The datasets in the dotted boxes are ancillary sets

atmospheric datasets starting in 1980. Basis for the reanalysis are satellite platforms convey sensors specifically built for meteorological observations. In example MODIS (Moderate Resolution Imaging Spectroradiometer) or TES (Tropospheric Emission Spectrometer) both on board of NASA:EOS-Terra respectively Aura platforms. The majority of the cloud related data is contributed by CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation), on CloudSat, and CATS (Cloud-Aerosol Transport System) mounted on the ISS (International Space Station). For more extensive information on the data base or sensor specifications see Gass (2017).²³

OMI stands for Ozone Monitoring Instrument. The sensor is part of the EOS-Aura mission. It was built in collaboration of NIVR (Netherlands's Agency for Aerospace Programs) and the FMI (Finnish Meteorological Institute). The main contribution of OMI to the Aura mission is monitoring the Earth with hyper-spectral resolution to acquire information about key air quality components, i.e. ozone or nitrogen dioxide, and aerosol characteristics. Out of the provided hyper-spectral data specific derivatives are processed, like the OMOTO3 product.²⁴ The following Table 1 gives an overview about the used data.

Table 1. Meteorological and geometrical input dataset for the solar surface irradiance calculations

Parameter	Dataset	Resolution		Annotation	Datasource
		temporal	geometric		
Air surface temperature	M2TINXSLV	1 h	0.25 °	in K	MERRA-2 ²⁵
Relative Humidity	M2TINXSLV	1 h	0.25 °	in %	MERRA-2 ²⁵
Stratospheric ozone	OMTO3	1 d	0.25 °	in DU	OMI ²⁴
Aerosol optical thickness	inst3_2d_gas_Nx	3h	0.25 °	in m	MERRA-2 ²⁶
DSM—DSM	-	-	2m	-	GeoSN ²⁷
Clouds	tavg1_2d_rad_Nx	1 h	0.25 °	in %	MERRA-2 ²⁸
NDVI	MYD13A3	1 month	0.05 °	-	MODIS ²⁹

The first four rows of the table are the meteorological respectively atmospheric datasets required for the *insol* package by R to estimate the atmospheric model for the computations.^{9,10} The elevation dataset is necessary

for the height and location for i. a. illumination simulations. Cloud data and the NDVI are ancillary dataset to adjust the calculations. The present NA (not available) values in the datasets were substituted by interpolated values based on the values before the NA event and after.

The *relative humidity* was calculated based on the MERRA2 M2T1NXSLV dataset by setting the variables air surface temperature and surface dew point temperature in to functional relation.²⁵ The *weathermetrics* package in R was utilised to calculate the relative humidity.^{10,30}

The *Aerosol Optical Thickness* (AOT) τ , also termed Aerosol Optical Depth (AOD), is an important variable to calculate the horizontal visibility.¹⁹ In the following the term AOT is used for consistency. The horizontal visibility of the atmosphere is needed as an input for the solar surface irradiance calculations.⁹

The *visibility* is used to gain information on the optical attenuation of the atmosphere. There are multiple definitions and use of the term visibility in the literature. Visibility can be described via the equation 2 presented by Koschmieder (1924):³¹

$$V = \frac{1}{\sigma_h} \ln \left| \frac{C_0}{C_{thresh}} \right| \quad (2)$$

where σ_h is the horizontal extinction coefficient, C_{thresh} the threshold contrast, and C_0 the definite contrast of an object. Koschmieder (1924) suggested that in the majority of viewing conditions $C_0 = 0.02$ is true and introduced a theoretical ideally black object with the contrast of -1. With substitution of the related variables, the direct relation of V to σ_h comes apparent. The most basic relation between AOT and V can be based on the equation 2 by the substitution of σ_h with τ . Thus, it is assumed that the horizontal σ_h and vertical extinction σ_v coefficients are alike. Based on this theory the secondary assumption is made, with σ_h and σ_v equal, the nexus of horizontal visibility and horizontal extinction coefficient σ_h is also coincidentally true for horizontal visibility and the vertical extinction coefficient σ_v . The relations and validity of the above assumptions are extensively discussed in Hovart (1981) and Wilson (2015).^{32,33} Wilson (2015) concluded that with minor discrepancies the assumptions are valid. Thus, via the simple substitution of σ_h and utilising the suggested contrast values by Koschmieder the equation 3 can be applied for the calculation of V :³³

$$V = \frac{3.912}{\tau} \quad (3)$$

Further information on the coherences of aerosols on solar surface irradiance and visibility is detailed described in literature.^{32,34–36}

Riparian vegetation is influencing the water courses and their hydrological properties in multiple ways. In biotic manner via substance discharge or abiotic through altering the illumination properties. One major abiotic influence is shadow casting of the riparian vegetation, it reduces the local water temperature of the areas shaded.^{37,38} The energy of the incoming solar beam is either fully absorbed or intensely scattered. Vegetation with a dense foilage casts a broader shadow than flora with sparse or no foilage.³⁹ Heisler (1986) states that solar surface irradiance can be reduced up to 80 % on the shaded side of a mid-sized leave tree. Thus, depending on the vegetation cycle the influence of vegetation on solar surface irradiance differs, due to changing shading properties of the vegetation. To detect these changing illumination conditions on the water surface induced by the nearby vegetation phenology was the main objective implementing the NDVI (Normalized Vegetation Difference Index) dataset to the calculations. Following the natural course of seasonal vegetation cover changes, during the dormancy months less to no tree foilage and during the vegetation period more dense vegetation are apparent. The periods of seasonal transition in spring and autumn start with no to little foilage cover and gain density with progression of the season and vice versa.^{38,40}

Based on the NDVI it is possible to determine the greening and browning point of the vegetation season. The greening point determines the start of the vegetation season contrary the browning point in autumn. Here, both thresholds are used to discriminate the utilisation of either the DSM or the DTM. During the vegetation period the DSM was applied otherwise the DTM. The used MODIS NDVI product is scaled by factor 10000 to exclude float type data storage.

2.4 Workflow

To calculate the surface illumination and solar surface irradiance the software R and the library `insol` is utilised.^{9,10} The main influencing and attenuating atmospheric factors can be seen in Figure 5, showing the workflow.

Figure 5. Workflow of calculation cloud-sky solar surface irradiances (W/m^2)

Input data on solar radiation are combined to an atmospheric model. Based on the atmospheric model the physical impact, i.e. scattering, absorption, and reflection on the incoming and traversing solar radiation is estimated. The here considered main influencing factors on the incoming solar radiance are given in Table 2. The geometric relations are considered by computing the illumination properties of the research area to determine the changing shading characteristics (non-illumination) of the water surface. The `insol` library provided by R is calculating the solar surface irradiance W/m^2 under a clear-sky assumption. Clouds have a high influence on the incoming solar radiation. To account for the alteration of the solar irradiance by the optical depth of clouds auxiliary data on cloud coverage is implemented into the calculations. Thus, the results of the calculations are under cloud-sky conditions. In respect to the spatio-temporally variability of the Earth's illumination and the atmospheric influencing variables on solar surface irradiance, the calculations are carried out for one year at quarter-hour intervals.

Pre-Processing: The various meteorological and geometrical remote sensing input datasets need to be harmonised for adequate subsequent processing. During the pre-processing the data was re-projected to the geodetic reference system ETRS89 (European Terrestrial Reference System) and the coordinate system UTM 33N (Universal Transverse Mercator). The `insol` package only calculates on a Cartesian coordinate system. Additionally, the area of interest, was cropped out and resampled to the datasets with the highest geometric resolution (elevation models; 2×2 meter grid resolution).

Determining the influence of vegetation on the solar surface irradiance – Illumination properties of the research area: The riverine vegetation is closely linked to the illumination and non-illumination properties of the water surface. To gain information on the phenological stages respectively foliage of the riverine flora the MODIS NDVI product was utilised. Based on the MODIS NDVI dataset for 2016 for the study area a threshold θ was determined. This threshold distinguishes if dense vegetation is present or if the vegetation influences can be seen as negligible. Based on this information the corresponding elevation model was utilised to account for the illumination changes induced by riverine vegetation. DTM as basis for no significant vegetation influence and DSM for significant vegetation influence. The threshold of $\theta \geq 0.7$ was empirical determined after extensive analysis of the dataset and further used as a Boolean operator. If θ is TRUE than the DSM was processed. If θ is FALSE the DTM was basis for further calculations.

After determining the calculation basis via the NDVI, DSM or DTM for the shadow calculations the shading properties are calculated. The R function `doshade`, part of the `insol` package, is therefore utilised.^{9,10} The shading for the research area was calculated at quarter-hourly intervals for the entire year 2016. Simulating the illumination respectively non-illumination characteristics for the year. The output of the shadow calculations is a binary raster layer. The results of the shading calculations are afterwards used as a mask to exclude the shaded areas from the solar surface irradiance computations.

To calculate the solar surface irradiance the `insolation` function provided by R's `insol` package is executed. For each quarter-hour time step the parameters listed in Table 2 are the input variables for the `insolation`

Table 2. Atmospheric parameters influencing the incoming solar radiation with unit notation

Parameter	Unit
location	Northing and Easting
zenith angle	degree ($^{\circ}$)
stratospheric ozone	DU
surface height	m
near- ground temperature	K
visibility	m
near- ground relative humidity	%
surface albedo	%

function. Output of the function is a matrix containing the direct and diffuse irradiance for clear-sky conditions at the corresponding time step for a given location.⁹ The direct E_{dir} and diffuse E_{diff} solar surface irradiance are calculated under consideration of E_{refl} .

To further respect the energy attenuating influences of clouds in the calculations ancillary cloud information are implemented in the workflow as a next step. Overcast information, precise cloud fractions, are used as a weighting factor to adjust the direct and diffuse solar surface irradiance portions of the solar surface irradiance calculations. Therefore, the MERRA-2 `tavg1_2d_rad_Nx` dataset was utilised.²⁸ The weighting factor used to adjust the direct and diffuse solar surface irradiance portions is based on the findings by Wilcox (2012).⁴¹ Based on radiative effects of the clouds, being nearly fully absorbing to the direct portion of the solar surface irradiance the pixel fractions are considered by factor 1. Hence, the direct portion influenced via attenuation and absorption through clouds is adjusted accordingly. So if clouds are present to the given time step it is assumed that the direct portion of the incoming solar radiation is attenuated by scattering, absorption, or reflection. The direct energy of the incoming solar radiation is transformed to i.e. diffuse energy. Hence, if clouds occur the direct portion of solar surface irradiance decreases and the diffuse portion increases. Resulting in a cloud radiative properties adjusted matrix of the direct and diffuse solar surface irradiance portions. Additionally, the shadow mask is applied to the results of the direct cloud-sky solar surface irradiance calculations.

3. RESULTS

The quarter-hourly results of the solar surface irradiance computations, under assumption of cloud-sky (with overcast) conditions are presented in the following. During the computation the diffuse and direct part of the solar surface irradiance were processed separately (cf. Figure 6).

Figure 6. Yearly sum of solar surface irradiance (W/m^2). left: direct, right: diffuse

Figure 7 visualises the annual sum of the global solar surface irradiance in (kWh/m^2) of a Freiburger Mulde section south-east of the research centre in year 2016. For a perennial illuminated area of the Freiburger Mulde the average global solar surface irradiation is $124 (kWh/m^2)$ in June. For the same month an area temporary influenced by shading the energy arriving at the water surface is $96 (kWh/m^2)$. For the same two areas in December the amount of global solar surface irradiance is $41 (kWh/m^2)$ and with shade influence $32 (kWh/m^2)$.

In general, areas temporarily influenced by shading receive less global solar surface irradiance during the course of a year in comparison to the perennial illuminated water surface.

Figure 7. Annual sum (2016) of solar surface irradiance (W/m^2)

Figure 8 compares the results of the two surfaces with and without the influence of the shadow effect. It can be seen that there is a significant influence of the shading on the direct portion of the surface solar radiation. The results impressively show, how riparian vegetation can reduce the entry of energy (radiant power) into the waterbody.

Figure 8. Monthly solar surface irradiance under cloud-sky conditions. Left: not influenced by shadowing; Right: influenced by shadowing.

4. DISCUSSION

To interpret and estimate the accuracy of the calculated clear-sky and cloud-sky solar surface irradiance, the results were cross-checked with relevant literature.^{42, 43} Visualisations of solar radiation for Europe and Germany can be sourced from the European Commission or the DWD. Since the maps are provided by administrative sources they are assumed to be qualified to be used as a reference for comparison of the own calculations. The temporal resolution is monthly or annually for entire Germany or Central Europe. The solar radiation is depicted in total, so the diffuse and direct part are presented in combination. Unfortunately for the DWD maps no differentiation of the two portions forming the global surface radiation can be made. Further, the spatial resolution of the provided maps is on a national scale. Therefore it is not possible to adequately confirm the own results because of the missing details, especially for the watercourse. Anyhow, the DWD results allow a general categorisation of the own computed results. When comparing the annual sum of solar surface irradiance for the entire research area of 2016, both results are approximately in the same dimension. The annual sum of the own computations is $1032 \text{ kWh}/m^2$ and the annual sum published by the DWD is $1061 \text{ kWh}/m^2$ at the lower end.

An additional source providing information on both diffuse and direct solar surface irradiance is published by the European Commission. It is an online application for clear-sky and cloud-sky solar surface irradiance computation termed PVGIS (Photovoltaic Geographical Information System). The PVGIS calculations are based on information provided by the CMSAF (Climate Monitoring Satellite Application Facility).^{44, 45} To gain values for comparison on the cloud-sky solar surface irradiance the PVGIS tool was utilised. The months June and December 2016 were computed with the PVGIS tool plus the annual sum in kWh/m^2 for the year 2016. Both months show the most differences in geometry and generally in radiometry too.^{12, 42} It is visible, that the results of the own calculations are in general lower than the PVGIS. One reason for that could be the different atmospheric models applied for the computations. Further, the diverging underlying geometric and temporal resolutions of the datasets influence the accuracy of each computation. Especially, the high geometric resolution of the surface model, utilised in the own calculations, allows to discriminate the watercourse more explicit within the calculations. Due, to the high grid resolution of the surface models the illumination and therefore the solar radiation properties can be calculated more distinct in comparison to the PVGIS. Since no accurate ground-truth data for the year 2016 are available, no valid conclusions can be drawn upon the accuracy and reliability of the own calculated results. For the given case this means e.g. ground-based pyranometer measurements or light meter recordings. Light meter detect the illumination intensity and are available in different price categories and products. For recording illumination properties on the Freiburger Mulde section an inexpensive mobile device could meet the requirements.⁴⁶

Discussion on data

The todays operational satellite systems acquire and provide atmospheric and meteorological information. Multiple authors point out that the satellite remote sensing sensors and platforms primarily designed for climate research often operate on a global scale, temporally and geometrically.^{19, 47} The sensors are often optimised in detecting and monitoring small-scale to mid-scale phenomena and environments.⁴⁷ The section of the Freiburger Mulde is of regional scale. Therefore, the meteorological datasets available and utilised incorporate certain confinements in applicability on a regional scale. To asses the impact of the individual meteorological and geometrical input datasets on the solar surface irradiance calculations a sensitivity analysis can be carried out in the future. Based on this sensitivity analysis, it could be decided to substitute specific meteorological datasets for the enhancement of surface irradiance calculations.

Elevation Models: The DSM was utilized to include height information about the riverine vegetation. Based on these surface height information the shadow cast of the riparian vegetation was calculated. Thus, the length of the shadow is determined by the accuracy of height information derived from the DSM. Depending on the location and the Sun-Earth constellation inaccuracies in the DSM are more decisive. Both the temporal-geometric and the radiometric-geometric components of the illumination are influenced. During the months with low sun elevation the shadow length is longer than during the months with higher sun elevation.

Air Surface Temperature: The air surface temperature data provided by the MERRA-2 M2T1NXSLV dataset incorporate consistent information about temperature on an hourly basis on a global scale.²⁵ As mentioned the calculations have been carried out at 15 minutes intervals. The intermediate time steps between the hourly measurement were simply linearly interpolated, based on the known hourly information. Thus, any significant air surface temperature changes within in the hour are only approximately represented. An alternative to satellite remote sensing air surface temperature measurements for regional scale observations are ground-based climate stations. Administrative stations provide local measurements of meteorological variables of high quality and temporal consistency. The next administrative ground-based measuring station operated by the DWD is located approx. 13 km south of the research area. The station, ID 131, measures and logs variables like air surface temperature and relative humidity in 10 minute intervals. To transfer the air surface temperature station measurements to the 13 km distant research area the data needs to be further processed, for instance interpolated with information from other more distant DWD stations or extrapolated and gridded. Therefore, processing the DWD station (ID 131) would have brought a higher temporal resolution, in respect to the hourly MERRA 2 data, but not necessarily the needed higher geometric resolution.

Relative Humidity: The relative humidity for the research area was calculated on the surface dew-point and air surface temperature provided by MERRA-2 M2T1NXSLV. Thus, the same geometric and temporal limitations

apply. Further, the relative humidity was calculated with the aid of the air surface temperature and the surface dew-point temperature and not directly measured. This, means the limitations for the radiometers and the accompanied inaccuracies are transferred to the relative humidity dataset, which is not necessarily be true when measuring the relative humidity directly.

AOT: The visibility of the atmosphere is a very important factor in modelling the atmospheric radiative transfer properties. The AOT dataset was utilised to derive the horizontal visibility V for the computation of solar surface irradiance. Atmospheric aerosols are one constituent with the highest influence on solar radiation and are temporally and spatially highly variable.¹⁷ The M2TINXRAD dataset is mainly based on MODIS recordings. Chan (2009) estimated the accuracy of satellite AOT measurement by MODIS with ground-based recordings of AERONET and conclude a high correlation of both datasets.⁴⁸ Thus, the satellite remotely AOT dataset provides high agreement with ground-based measurement. Therefore, a global sufficient quality is assumed. For a regional scale a higher geometric resolution of the AOT dataset would help to distinguish the local variability of aerosols more adequate. The applied AOT dataset has a temporal resolution of three hours. This temporal differentiation is, especially during relatively instable atmospheric conditions, not detailed enough.^{8,49} Anyhow, the M2TINXRAD dataset was one of the only available sources for the fully consistent for the year 2016. Nevertheless, since direct V measurements for the research area were not available, to derive the meteorological optical range V AOT measurements were processed via the Koschmieder equation.³¹ Koschmieder's equation is valid to calculate V as long as the observed object is of ideal black color (the contrast threshold C_{thresh} is of 0.02 at a wavelength of 550 nm).^{31,32} The Koschmieder equation was devised under laboratory and ideal conditions. Also Baumer (2008) support the presumptions and substitutions made by Koschmieder, when devising the equation to calculate the visibility of the atmosphere.⁵⁰

NDVI: To simulate the influences of vegetation and non-vegetation periods, the NDVI respectively the greening and browning points were used to initiate the utilisation of either the DSM or DTM for the illumination calculations. Between the greening point and the browning point the DSM was used, during the rest of the year the DTM was implemented into the calculations. Thus, in the given case the NDVI is closely linked to the elevation models. The threshold value 0.7 to discriminate vegetation (greening point) and non-vegetation (browning point) period was set empirically after investigating the NDVI dataset and in respect to the natural course of the seasons. Here, a prior time series analysis of the NDVI product could provide more precise transition points. The greening and browning point only define the start of the corresponding period. For the greening point this means when the first leaves start to spring and vegetation is primarily sparse. In the course of the spring season the vegetation gains more density. Sparse vegetation has less impact, minor scattering and absorption influence, on solar radiation especially on the direct portion than dense vegetation.^{39,51} Thus, the point, respectively day, when the vegetation has become dense enough to influence the incoming solar radiation significantly needs to be determined. This could be accomplished via a NDVI dataset with higher temporal and geometric resolution and a ground-based reference dataset.

Clouds: To detect and record clouds three major techniques are used: First, satellite based via radar, second, satellite or aerial LiDAR, and third, satellite and ground-based radiometer.^{19,52} The MERRA-2 project and therefore the M2TINXRAD dataset are primarily based on the satellite mounted passive acquisition techniques, but are partly validated with other sources and acquisition techniques.²³ In the majority the accompanied deficits of passive acquisition is valid and could be one explanation for the larger amount of consecutive NA values in the high-cloud dataset, making that dataset insufficient in use for the solar surface irradiance computation. Due to the information gaps of the cloud datasets a global weighting factor was used to adjust the solar surface irradiance portions. With complete and level separable overcast information a level adjusted weighting factor can be applied. Further, the cloud type information are stored as cloud pixel fractions. This form of representation assumes no overlap of cloud types in a vertical profile nor in between the layers — low, mid, high. Theoretically, if high-clouds occur there is a high probability that mid- and low-clouds are also present. Meanwhile, when the satellite detects and categorises low-clouds the presence of mid- and high-clouds are highly unlikely, according to Kim (2008).⁵³ The potential masking of low-clouds by mid- and high-clouds can lead to incorrect categorisation of the individual clouds and their level, low, mid, high. Further, level overlapping clouds (*nimbus*) are not categorised and therefore are not accounted for, yet they have a big impact on the incoming solar radiation.⁵³ The cloud pixel fraction only gives information on how many percent of the entire pixel is covered with clouds.

The exact positional information of the cloud is thus not represented. With the current relative low geometric resolution of the cloud datasets this might be circumstantial, especially, at days of a highly unstable atmosphere. In general the cloud dynamic, genesis or dissolution is highly variable temporal and spatial. To improve the temporal and spatial resolution of the cloud information for the section of the Freiburger Mulde a ground-based dataset in combination with remotely sensed cloud data could be utilised.

Discussion on methods

The *insol* package with the on target *insolation* function is utilised to calculate the solar surface irradiance. The function takes meteorological and geometrical variables into account. The meteorological components are ozone, temperature, relative humidity, albedo, and visibility. The geometric variables are zenith angle and height. All input variables are time dependent, but the height is relatively stable over the time compared to the other input variables. The *insol* function itself is described in Bird (1981).⁵⁴ He introduced a simplified model to calculate the clear-sky direct and diffuse insolation (solar surface irradiance) on horizontal surfaces. On this model the *insol* function is based on. The solar surface irradiance calculations are carried out for a horizontal surface area. Originally the available energy for a surface is dependent on the inclination of the surface. In general, water courses are influenced by a higher slope near to the source. The inclination decreases with the distance from the source when considering one catchment area. In the given case, calculating the radiant flux arriving on the Freiburger Mulde, the computation in respect to a horizontal plane could be seen as true, since water surfaces are only slightly inclined with the direction of flow. Whether the slope can be neglected for all water courses needs to be determined in future.

Further, the *insolation* function assumes clear-sky conditions, meaning, no clouds are present in the atmosphere. Nevertheless, absorption induced by water vapour is the third most important influencing factor on solar radiation, after aerosol attenuation and molecular scattering.⁵⁴ Thus, the influences of overcast on solar radiation is not considered within the *insolation* function. Hence, after the bare clear-sky computations of the solar surface irradiance information on cloud cover were incorporated. This was done based on the assumption, that the clear-sky conditions are not given at all times during the course of a year. Especially, during the late autumn months and winter season overcast conditions are predominant.⁵⁵ A high influence on the solar radiation have clouds consisting of water droplets, due to their high optical depth linked to the radiative transfer.⁵⁴ Optically thick clouds absorb or scatter, whereby significant scattering and reflection occurs at the top of the cloud, influencing the incoming solar beam substantial. During complete overcast conditions the solar surface irradiance is primarily isotropic.⁵⁶ Thus, to approximate the cloud-sky conditions, meaning considering the influence of clouds on the incoming solar radiation, overcast information were used as a weighting factor to adjust the diffuse part and the direct part of the solar surface irradiance of the clear-sky computations. Especially, the direct part is attenuated by the aerosols building the clouds. If the direct solar radiation is not being fully absorbed by the cloud it is scattered. The direct solar radiation is transformed into diffuse energy. Thus, the direct part of the solar surface irradiance is decreasing and the diffuse part is increasing under cloud-sky conditions.^{33,55} So if overcast occurred the calculated clear-sky irradiance portions have been adjusted accordingly to the given cloud type based on the findings by Wilson et al. (2015).³³ In the given case due to the insufficient temporal continuity of the high-cloud dataset and the difficult determination of the mid-cloud, weighting factors for the total amount of cloud fractions have been used to weight the two variables. The most reliable information was given by the low-cloud datasets forming the main portion of the total amount of cloud fractions. Low-clouds fully absorb direct solar radiation. Thus, when overcast occurred during a time step the direct portion has been adjusted accordingly. Since energy can not be lost in a system, only transformed, it is assumed that the direct energy is scattered or reflected on top of the cloud and thus enters the diffuse energy state. With this assumption the high grade energy of the direct beam is transformed to diffuse low grade energy. Therefore, on days were clouds occur the direct radiant energy input on water surfaces decreases and the diffuse radiant energy increases.⁵⁶ Using a general weighting factor to categorise the absorption of the different cloud types is a simple and straightforward approach, which does not account for the complex wavelength depended cloud radiative transfer or additional inner cloud processes. The modelling of inner cloud radiative attenuation processes and radiative properties of clouds is very complex and time consuming.^{57,58} If cloud data with a higher temporal and geometrical resolution with ancillary information is at hand, the various wavelength depended cloud radiative transfer characteristics can be considered. Since these were not at hand the straightforward weighting approach was utilised.

5. SUMMARY & PERSPECTIVES

The main goal of the present work was to establish a workflow for solar surface irradiance calculations based on remote sensing data under consideration of the spatio-temporal illumination characteristics. The programming language R and the packages `insol` and `weathermetrics` were used for implementation.^{9,10,30} The calculations incorporate necessary meteorological components like ozone, relative humidity, temperature, as well as geometric dependencies of Sun and Earth for determining the illumination properties. Remote sensing data sources are provided by sensors like OMI (Ozone Monitoring Instrument), MODIS (Moderate-resolution Imaging Spectroradiometer), and the MERRA2 (Modern-Era Retrospective analysis for Research and Applications Version 2) project. The data is mainly sourced from the GES DISC (Goddard Earth Sciences Data and Information Services Center).²²

The analysis followed the presented workflow depicted in Figure 5. It includes at first the harmonisation of different remote sensing input data followed by the definition of the illumination and non-illumination characteristics for the study area. Then the clear-sky solar surface irradiance calculations are carried out and the ancillary cloud information are incorporated to adjust the direct and diffuse portions of the global solar surface irradiance. Then the annual cumulative sum of solar surface irradiance is derived. Due to the resource intensive calculations the HPC Bull cluster named Taurus was utilised, provided by the TU Dresden. The calculations have been executed on Taurus as an array job to compute each day of 2016 simultaneously. Due to the parallel processing the overall computation time was decreased significantly.

Based on the high geometric resolution of the surface models, 2×2 meters, utilised during the computation of the solar surface irradiance the radiant energy arriving on the water surface can be discriminated. Additionally, the illumination and shading characteristics on the Freiburger Mulde can be accounted for. Shading, i.e. induced by riparian vegetation, has a significant influence on the incoming solar radiation. Through absorption and scattering the direct solar radiation is altered strongly resulting in a decrease of radiant flux energy on shaded surfaces respectively water surfaces. Especially, the significant difference of temporarily shadow influenced water surfaces and perennial illuminated river sections. The annually available energy input into water courses determines the flora and fauna habitat developments essential.^{59,60} For adequate interpretation of the watercourse the geometric resolution of solar surface irradiance maps provided by administrative organisations like the DWD or the European Commission (PVGIS) are not detailed enough.

The annual averaged cumulated sum in consideration of overcast is $> 900 \text{ kWh/m}^{-2}$ (illuminated all year). Meanwhile, areas influenced by shadow casting objects, i.e. trees or hills, are $< 500 \text{ kWh/m}^{-2}$. If illumination is limited, the distribution of aquatic flora and fauna is limited, too. Further, the presence of aquatic flora is in close correlation with the ecological state of water bodies.^{59,60} In conclusion, to monitor, assess and maintain a good ecological status of water bodies and the environment, it is necessary to quantify the distribution of incoming solar surface irradiance on the water surface and therefore the energy input into aquatic systems. Based on the quantification of the energy entry into water courses, qualitative and quantitative information i.e. on plant growth, fauna development, and water quality can be assessed. With these assessments the edicts of Germany and the frameworks of the European Union can be met. Furthermore it can be used to maintain high water quality or build a foundation to take action to improve the quality of aquatic systems.

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