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Simulation of vegetation and relief induced shadows on rivers with remote sensing data

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ABSTRACT

Rivers are the lifelines of our environment. For this reason they are always in the focus of environmental studies. For the assessment of the ecological status of rivers the member states of the European Union have developed different monitoring programs and approaches. The shadowing of a river affects the temperature of the water and also the energy balance of the water body. Therefore changes in temperature also influence the biological and chemical status of rivers and lakes. The main objective of this study is the simulation of the shadowing of a section of the river Freiburger Mulde for a full year. This ensures that effects of different sun positions over the year (azimuth, elevation) and also local topography conditions in the close environment of the river section are taken into account. For all analyses a digital surface model and a digital elevation model with a geometric resolution of 2 m is available. The result of this simulation is a raster layer which represents the theoretical annual hours of shadowing of the river section. The results indicate a decrease of illumination of partly more than 80 %. In future this information can be expanded by means of further affecting factors such as the consideration of the phenological status of deciduous trees in the riparian zone.

Keywords: shadowing, simulation, river assessment, European Water Framework Directive

1. INTRODUCTION AND MOTIVATION

The European Water Framework Directive is an important tool for sustainable and environmentally compatible use of water. On the one hand, the Directive defines common environmental objectives within the European Union, on the other hand it obliges the Member States to show that all their waters have a good ecological status and that water quality is not deteriorating.¹ The Water Framework Directive is implemented at national level. In Germany, this is done with the Water Resources Act.² The success of such policies and laws can only be ascertained with the aid of a comprehensive monitoring program. In this context, a large number of studies have shown the value of remote sensing data in the context of such a monitoring program.

These include, for example, studies on the erosion³ or analyses on the biological quality of water bodies, for example, on chlorophyll concentrations⁴ or on algae growth.⁵ A review of the challenges, current and possible future developments in the use of remote sensing data in the context of the analysis of water bodies is provided by Palmer et al. (2015).⁶ The data sources used in this context range from satellite images and aerial photographs to data from Unmanned Aerial Systems (UAS). In addition, administrative geodata are also available whose quality can have an immediate impact on the evaluation of the rivers.⁷ Referred to hydromorphological parameters, it was possible to show how further scientific data were used to analyse the sinuosity of rivers⁸ or to determine information about river width variations.⁹

Analyses of erosion or channel migration information about the riverbank line are also very important.^{10–13} A detailed overview of analyses of riverbed morphology using remote sensing data is given by Lane et al. (2010).¹⁴ For large rivers satellite images are useful to extract riverbank lines.^{13,15,16} A higher geometric resolution is needed for small and medium rivers.^{17,18}

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In Germany for small and medium rivers a mapping procedure has been developed by the German Working Group on water issues of the Federal States and the Federal Government represented by the Federal Environment Ministry (LAWA). This procedure can be divided into two methods, the on-site-method and an overview method, where the use of remote sensing data is strongly recommended.^{19,20}

Nevertheless, it is possible to use remote sensing data for the analysis of single parameters originally assigned to the on-site method. This includes, for example, parameters such as channel patterns⁸ or the bank structure. Part of that bank structure, for example, is the riverine vegetation as well as the closely related parameter of shadowing induced by that vegetation. However, this parameter is often described using a simple categorical scale with the classes sunny, partially shadowed and shadowed.²¹

It shows that the shading of the waters has a great influence on the suitability as a habitat for different species. Because the warmer the water, the less is the oxygen saturation in the water.^{22,23} Under these considerations it seems to be quite useful to perform a more accurate analysis of river shadowing.²⁴ Such information can form the basis for appropriate action programs.

The aim of this study is to carry out simulations of shadowing by vegetation and relief for a whole year and a well-chosen river section. For this purpose only data should be involved in the analysis, which are provided by the local authorities. The aim is to take into account geometric constellations in the system of sun, vegetation and the earth's surface and also to integrate local topographical conditions into the analysis. The potential illumination is in the focus of this research.

2. STUDY AREA AND DATA

The study area is a small section of the Freiburger Mulde and has a length of about 2 km. This river section is located some kilometers north of the town of Döbeln between the villages of Westewitz and Klosterbuch (cf. Figure 1). The Freiburger Mulde is a low mountains river that rises in the ore mountain and merges with the Zwickauer Mulde after 124 km. For the next 147 km the river is called Vereinigte Mulde and flows near the town Dessau into the river Elbe. This river section is chosen due to different characteristics of riverine vegetation. Single trees, small group of trees, but also tree rows shape the landscape and are able to cast shadows on the waterbody. In addition there is an increase in the river width from approximately 20 m up to 70 m on a length of only about 1.5 km.

Figure 1. Digital orthophoto of the study area (Saxon State Spatial Data and Land Survey Corporation (GeoSN))

The most important data source for the present investigations is a digital surface model (DSM), which was provided by the Saxon State Spatial Data and Land Survey Corporation (GeoSN; cf. Figure 2 right). In the corresponding digital elevation model (DEM) the vegetation, buildings and other objects on the earth's surface

are filtered. The DEM generally serves to determine the shadows as it would appear without the presence of vegetation or other objects (cf. Figure 2 left).

Figure 2. left: Digital Elevation Model (DEM, left); Digital Surface Model (DSM, right)

In addition, river bank lines were extracted from digital orthophotos in an earlier study by Karrasch and Hunger (2016). These lines represent the true river bank lines taking into account the influence of overhanging vegetation on the visible bank line. It is thus possible to distinguish the original water body of the river from the environment.⁹

In order to ensure that all the shadows that could fall onto the surface of the river at a certain time, the real study area for shadow calculations had to be extended beyond the extent of the figures above (cf. Figure 2). For this reason the actual calculations were made for a total area of 5 x 5 km. The shown study area is in the center of that area.

3. METHODOLOGY

Basically, the calculation of shading is based on a simple principle. Shadowing occurs when there is temporarily or permanently an object between the source of radiation and the surface of projection which does not have complete transparency for the corresponding radiation type. The situation becomes more complex when all three components are temporally and spatially variable. The system of the sun as the source of radiation and the earth's surface as the surface of projection is highly dynamic. In order to be able to make statements about shadows on the earth's surface, in addition to a specific location (latitude, longitude), further geometric properties of the system of sun, object and earth must be taken into account. Figure 3 shows schematically the basic geometrical relationships of the apparent course of the sun around an object, for example a tree. It becomes clear that both diurnal effects play a role, as well as annual variations in the apparent course of the sun.

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)

Based on the geometric conditions, two different components of shadowing or irradiation can be determined. On the one hand, this is a temporal-geometrical component and, on the other hand, a radiometric-geometrical

component. The former essentially deals with the question of the direction of the light and whether a surface is in principle shadowed or not. The latter, on the other hand, also takes into account radiometric aspects of casting shadows with the intensity of radiation.

All methods explained in chapter 3 are performed using the software R statistics and the very useful library *insol*.

3.1 Temporal-Geometric aspects of Illumination

Due to the fact that the axis of rotation of the earth is not perpendicular to the ecliptic, daylight variations result and influence the availability of light by the sun. For the study area, it can be seen that differences of more than 8 hours occur between the summer solstice (>16 hours) and the winter solstice (< 8 hours; cf. figure 4).

Figure 4. Variations of daylength in the study area

In addition to this basic availability of light, there are two temporally variable directional dependencies. Figure 5 shows the course of the sun in the sky at midsummer (21.06.2017) and midwinter (21.12.2017). This shows that both the azimuth and the elevation must play an important role considering the cast of shadows and, in particular, its variability in the course of the day.

Figure 5. Course of the sun in the sky at midsummer (21.06.2017, left) and midwinter (21.12.2017, right)

However, it is clear that the directional dependency in the azimuth is also not constant. Because of the elliptical earth orbit and the already mentioned inclination of the earth's axis to the ecliptic, the azimuth of the sun varies for a given solar time in the course of the year. The dimension of this effect depends on the location (latitude, longitude), but also on the daytime. Figure 6 shows the sun positions (azimuth, elevation) in the study area for different local times (8, 10, 12, 14, 16 o'clock). It is visible, that the variability of the azimuth in the course of the year in the morning and evening hours is significantly ($> 30^\circ$) higher than at noon (6° - 7°). The figure also shows that the sun doesn't rise above the horizon (0° elevation) at 8 or 16 o'clock in the winter months.

Figure 6. Analemmata for 8, 10, 12, 14, 16 o'clock local time in the study area

Based on the presented conditions, there is the necessity of an annual simulation of the sun positions and thus the illumination or shadowing of the earth's surface. It becomes clear that from the geometrical reasons it is not possible to determine shadow simulations from a shortened time series. Therefore, it is necessary to know the direction vector to the sun (sunvector) for every time and place. By means of a digital surface model or a digital elevation model, it is then possible to determine whether this location- and time-specific vector intersects the DSM or DEM or not. In the case of an intersection, it can be assumed that the particular element on the surface is shaded at that specific point in time.

Figure 7 shows the results of such a shadow analysis for the days of the summer solstice and the winter solstice in the year 2017 in the study area at the Freiburger Mulde at noon.

Figure 7. Shadowing of the study area at summer solstice (left) and winter solstice (right) at noon

Figure 7 clearly shows the differences in the lengths of the cast shadows caused by the riverine vegetation. If this calculation is repeated for the entire year, it is possible to determine the shadowing of the earth's surface, according to a well-chosen interval of discretisation. Differences in illumination allow conclusions regarding the intensity of shadowing. However, they do not allow any conclusions how the geometrical conditions affect the intensity of the illumination.

3.2 Radiometric-Geometric aspects of Illumination

The qualitative estimation of the illumination of a surface will only be possible if radiometric aspects are taken into account, which also depends on the geometric constellation resulting from the system of sun, object and earth's surface. Accordingly, it can be assumed that the angle between the normal vector $\vec{n}$ of the surface and the sun vector is related to the illumination intensity of the surface. The flatter the source of radiation illuminates the surface (elevation of the sun), the greater is that angle, and the smaller is the solid angle Ω and thus the intensity of illumination.

Figure 8 shows schematically the illumination of two surfaces inclined differently to the source of radiation. The intensity of illumination falling on the surface element ($|\overrightarrow{SV_1}|$, $|\overrightarrow{SV_2}|$) corresponds to the projection of the normal vector of the surface ($\vec{n}$) onto the vector to the actual sun position. Since this approach occurs in the unit circle, the length of the projected normal vector can be understood as the fraction that the surface receives in comparison to the same surface if it is inclined directly to the sun. In this case, the unit vector in the direction of the source of radiation (sun) is identical to the normal vector of the surface.

Figure 8. Schematic representation of radiometric aspects of illumination

The considerations in Chapter 3.1 (geometrical-temporal component) expect that a surface is always fully illuminated regardless of its orientation (slope, aspect), if there is no object between the radiation source and the surface element. Considering radiometrical-geometric conditions the projected normal vectors ($|\overrightarrow{SV_1}|$, $|\overrightarrow{SV_2}|$) can be used as weighting factors. For example, if the sun illuminates a horizontal plane for one hour with a constant elevation of 30° , the length of the projected normal vector of the surface is 0.5. Then the real illumination is actually only 30 minutes in comparison to the same surface if the sun is in zenith.

Figure 9 shows the results of an analysis for the two already known times of the summer solstice and winter solstice at 12 o'clock. It is clear that due to the high elevation of the sun ($> 60^\circ$), the illumination of the study area is significantly higher than at the same time on 21.12.2017 (elevation $< 20^\circ$).

Figure 9. Illumination of the study area on summer solstice (left) and winter solstice (right) at noon considering the local topographic conditions

With this method, cumulative solar hours can also be determined for a whole year (2017), which are almost independent of the topography (taking into account the normal vector of the surface) and the elevation of the sun (taking into account the unit vector to the sun).

At this point it is important to mention that the analysis is based exclusively on direct solar radiation. Diffuse fractions of radiation caused by atmospheric scattering (Rayleigh scattering, Mie scattering, non-selective scattering) are not considered.²⁵

3.3 Temporal resolution of the annual simulation

The need to simulate the illumination of the earth's surface over the whole year has already been explained. Closely linked to the accuracy of the simulation results raises the question of the temporal resolution of these simulations. It can be assumed that with an increasing interval of discretisation between the discretely performed illumination analyses, the accuracy of the cumulated hours of sunshine decreases for both cases, with and without consideration of the topography (see chapter 3.2). For this reason, detailed analyses of the illumination for different temporal resolutions were carried out for the months of June and December. These analyses are performed at intervals of 5, 10, 15, 30, 45 and 60 minutes. To assess the accuracy, the simulation with an interval of 5 minutes was selected as the reference. The differences of the different simulations with the reference result allow conclusions about the deterioration of the simulation accuracy with increasing interval of discretisation. The goal is to find an interval that satisfies the requirements of the accuracy of the simulation.

4. RESULTS

4.1 Determination of a valid simulation interval

The choice of the temporal discretisation of the simulation affects the accuracy of the determination of shaded and illuminated surfaces. For example, Figure 10 shows the results in June and December for 5 and 60 minutes intervals.

Figure 10. Cumulated hours of sunshine; top left: 5 minutes simulation for June; top right: 60 minutes simulation for June; 5 minutes simulation for December; top right: 60 minutes simulation for December

The visual comparison shows differences, which are difficult to quantify. But it is quite visible that the higher the interval, the more fan-shaped artefacts exist, especially in the case of isolated standing objects (solitary trees), or even in the case of the tree rows along the river bank. Considering the topography of the study area it becomes clear, that the real illumination of the surface is significantly decreased due to the low elevation of the sun especially in December. The same applies in June (cf. Figure 11).

However, it is also clear that the described fan-shaped artefacts occur especially for discretisation intervals of 30 minutes and more. A statistical comparison shows that the errors increase with increasing interval size (cf.

Figure 11. Cumulated hours of sunshine considering the local topography; top left: 5 minutes simulation for June; top right: 60 minutes simulation for June; 5 minutes simulation for December; top right: 60 minutes simulation for December

Figure 12 bottom left). The consideration of the topography reduces this error significantly, but also produces a shift of the error into the positive range (cf. Figure 12 bottom right). This means that the illumination is overestimated with an increasing interval, which means that the shadowing is underestimated. These results are also confirmed for calculations for June, although the shift is less than in the winter month (cf. Figure 12 top).

Figure 12. Statistical analysis of the simulation intervals; top left: June; top right: June considering the local topography; bottom left: December; bottom right: considering the local topography

The results of this sensitivity analysis show that a simulation interval of 15 minutes does not lead to an appreciable worsening. For June, deviations from 2:15 hours of sunshine are expected, and 30 minutes, taking into account the topography (IQR).

In December it is 1:15 hour or respectively 8 minutes illumination. These differences can also be visualized (cf. Figure 13). The results show that the deviations for a simulation interval of 15 minutes are clearly below the results for 60 minutes. Especially considering the local topography and the elevation of the sun the deviations decrease to only a few minutes per month.

Figure 13. Comparison of 60 minutes and 15 minutes simulation (white areas exceed the limits of the legend); top left: Difference between 60 minutes simulation and reference; top right: Difference between 60 minutes simulation and reference considering local topography; bottom left: Difference between 15 minutes simulation and reference; bottom right: Difference between 15 minutes simulation and reference considering local topography

4.2 Simulation of the year 2017

Based on these findings and considering the geometric-temporal and geometric-radiometric aspects presented, the simulation of the entire calendar year 2017 was carried out. Figure 14 shows the results of these analyses for the selected river section at the Freiburger Mulde.

Figure 14. Final results of shadow calculation; left: without consideration of the local topography; right: with consideration of the local topography

It is clear that the cumulated hours of illumination in the course of the year are very different. Specifically, the areas where riverine vegetation is available, the illumination is less than 2000 hours a year (Figure 14, left). In contrast to single trees on the river bank, tree rows significantly increase the effect of shading. As already mentioned, the inclusion of the local topography reduces the real illumination significantly. However, the effect of vegetation as one of the most important reasons for shadows on water bodies remains.

4.3 Impact of vegetation and relief on shadowing

In order to determine the proportion of vegetation on the shadowing, differences between the simulations were calculated using the digital surface model and the elevation model (DSM-DEM). Since the latter does not contain any vegetation, it can be assumed that this difference represents the portion of the illumination time which is induced by the vegetation. Figure 15 shows the result of that analysis.

It's quite clear that large differences between the illuminations with and without the consideration of the local topography can be determined based on the calculation with the digital surface model and the digital elevation model (DSM-DEM). Especially in the case of tree rows, differences of 4000 hours of sunshine are induced which

Figure 15. Difference between illumination of the digital surface model and digital elevation model; left: without consideration of the local topography (2017, 15 minutes simulation); right: with consideration of the local topography

are caused by the vegetation as the objects that cast the shadow (cf. Figure 15, left). Considering the topography, these differences are smaller. Nevertheless it can be seen that values of up to 2000 hours are also reached here (cf. Figure 15, right). In a few parts of the study area, however, it is also found that the calculated differences are positive. This includes, in particular, the agricultural areas in the close environment of the river. This indicates that structures such as grain are also shown in the digital surface model. Their exposure to the sun allows more illumination than the underlying surface, which was depicted in the digital elevation model. In regard to the relative differences in the illumination (with topography; cf. Figure 16) it can be stated that the cumulated time of illumination can decrease more than 80 %.

Figure 16. Relative differences of illumination considering the local topography in the study area Freiburger Mulde (left) and for a subsection (right)

5. DISCUSSION AND SUMMARY

The presented results show the influence of riverine vegetation but also the relief in the close environment of the chosen river section on its illumination or shadowing. It was demonstrated how the interval of discretisation of an annual simulation can have an influence on the results of determining shadows. Nevertheless, it must be noted that the current modeling of the illumination does not yet include any information about the phenological status of the riverine vegetation. In the particular selected section of the Freiburger Mulde it must be assumed that the trees do not have foliage cover during the winter months. The permeability of the trees to sunlight is much higher than the modeling with the digital surface model can be expected. Insofar the illumination of the water body is underestimated while the shadowing is overestimated. For the annual balance, however, this effect plays a smaller role than, for example, in the summer months because the intensity of the sun is also slightly lower during the winter months (cf. Figure 5). The inclusion of the phenological state of the vegetation can be realized, for example, by additional remote sensing data. The evaluation of NDVI time series allows the estimation of the time when the permeability to light is decreasing. For such considerations, for example, MODIS-NDVI time-series data²⁶ or the MODIS Land surface phenology data²⁷ are suitable. Although these data have a relatively low geometrical resolution of only 250 m, the temporal resolution of about 2 weeks should allow a determination of this important time in spring. It is not so much a question of determining the time for individual plants or trees, but rather the determination of a point in time for a larger coherent study area. If such a point in time is known, the results of the shadow analysis can be used with the aid of the DEM instead of the DSM. Therefore a joined evaluation of DEM and DSM is always recommended.

An overestimation of the shading also depends on the characteristic of the selected data base. The digital surface model used in this study is a 2.5D dataset. This leads to the assumption that a complete shadowing occurs even in the area of the defoliated trunk, similar to the crowns of the tree (cf. figure 17).

Figure 17. Schematic representation of DSM-Shadows in comparison with real crown shadows

It is possible to consider this effect, if detailed information about tree species are available. There are a number of studies dealing with the determination of tree species based on the analysis of remote sensing data.^{28–30} Since this effect also occurs in the summer and during this time the highest values of illumination are present, depending on the type of vegetation, it can have a great influence on the cumulated annual hours of illumination.

In connection with the used digital surface model, its quality must also be discussed. The geometrical resolution of only 2 meters is especially important for analysis of shadows of single trees. In the case of a tree row on the river bank, such errors can only occur at the edges of that tree row. The height accuracy, which is given with 20 cm (2σ), has an effect on the shadow lengths. The resulting error increases with the decrease of the elevation of the sun. However, since the radiation intensity also decreases in this case, the influence of this error is probably negligible. Exact quantitative statements regarding these effects can only be made after further intensive simulations.

The presented results are based on a simulation in which the vector to the sun is temporally variable in the course of the day and year. In addition to its temporal variability, however, this vector has also a spatial variability. This circumstance must be taken into account for large areas of investigation by using temporally variable sun vectors for each raster element of the digital surface model. In the presented case this effect is negligible due to the limited extent of the study area of less than 1.5 km.

So far, the results have only been discussed in connection with the system of sun, shadow casting object and earth surface. Depending on the atmospheric conditions, however, actual radiation can be between 1000 watts on very sunny days and only 50 watts on very cloudy days. Therefore, further analyses will also include parameters such as relative humidity, air temperature, visibility and permeability of the atmosphere as well as the ozone concentration. With their help, it will be possible to determine direct and diffuse irradiation on the earth's surface to improve the results of the illumination and analyses of shadowing.

But also in the presented form the results can already help to evaluate the quality of the river sections. As already described, the shading is a parameter which is integrated into the evaluation system according to the

European Water Framework Directive. The influence of the shadowing on certain species in the water body and thus also on the biological component of the water quality is given. Monitoring the shading conditions, not only on rivers, but explicitly also on lakes, can help to support appropriate action programs.

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