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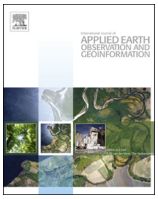

A GIS-based framework for quantifying potential shadow casts on lakes applied to a Danish lake experimental facility

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ABSTRACT

We present a Python-based framework for analyzing and quantifying potential shadow casts on lake and reservoir surfaces from the surrounding terrain features. The framework is based on remote sensing data and in this case a detailed Danish nationwide digital elevation model (DEM), which renders not only the physical surface of the terrain, i.e. the topography, but also the elevation of, for instance, buildings and vegetation. We developed a methodological framework encompassing existing computational routines embedded in the open source QGIS platform as well as existing computational packages available for Python, which collectively enable calculation of shadow casts from all elements surrounding a lake or a reservoir surface. Our framework is demonstrated through application to a Danish lake experimental facility but may be used for lakes or reservoirs world-wide to evaluate if shadow casts need to be considered and accounted for in modelling studies by correction of e.g. radiation inputs.

1. Introduction

Mathematical models are crucial instruments to help understanding the behaviors and dynamics of aquatic ecosystems (Jørgensen and Bendoricchio, 2001). Models also serve an important role as virtual laboratories for scientists and managers to assess adaptive measures to mitigate the effects of changes in climate and land use on lakes and reservoirs (see application examples in, for instance, Nielsen et al., 2014; Trolle et al., 2015). The current suite of published models vary significantly in complexity and focus (Mooij et al., 2010), both in terms of conceptual process completeness and in the way they resolve the physical domain, varying from spatially homogenous (0D) over vertically or horizontally structured (1D) to full 3D models (Janssen et al., 2015). Moreover, some models incorporate both hydrodynamics and ecosystem processes, while others have stronger emphasis on ecosystem components than hydrodynamics and vice versa (Hu et al., 2016). Nevertheless, depending on the type and complexity of a given model application, it is essential to build simulations using representative external driving data such as meteorological variables, and inflow and outflow of water and nutrients. Amongst the external drivers, solar radiation constitutes a key variable. It provides the energy that drives the thermal structure of the system and thereby affects water temperature, thermocline depth and mixing, which are all significant factors regulating various biotic processes and biogeochemical interactions. Solar input and mixing depth strongly influence the photosynthetically active radiation (PAR) to photosynthesis of algae and aquatic vegetation (Wetzel, 2001).

Briefly described, incoming solar radiation is a function of location and time (i.e. latitude, day of the year and time of the day) and of the corresponding weather-conditional cloud cover (Dubayah, 1994; Iqbal, 1983). Ideally, radiation inputs in model applications can be retrieved from local metrological stations that are representative of the local lake or reservoir and its characteristics. Such data is, however, often not sufficiently representative or are constrained (e.g. temporally or in the availability of measured parameters), and modellers therefore often need to incorporate alternatives to local measurements in their model setups. Typically this could include using meteorological stations situated some distance from the site, national grid-interpolated datasets or reanalyzed model datasets (e.g. the American Climate Forecast System Reanalysis product (CFSR, www.ncdc.noaa.gov) or the European reanalysis products (www.ecmwf.int)). The downside of using non-local climate station data or national/global climate data, at somewhat coarse grid scales, is the potential lack of accuracy in rendering the local lake or reservoir conditions. As to solar radiation, the characteristics of the terrain (e.g. mountains and obstacles such as vegetation) adjacent to a shoreline may influence lake/reservoir conditions by shadow casting, which is obviously not accounted for in the non-local-specific data. Within the domain of watershed modelling,

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such influences from complex terrain characteristics on several hydrometeorological and hydro-ecological processes have been articulated (Liu et al., 2012). Terrain-induced shadow casting may, for instance, produce differences in the distribution of terrestrial vegetation on reverse-facing slopes (Dubayah, 1994) or impact snow melt distributions in mountainous regions (Marsh et al., 2012), with direct influences on the hydrological dynamics in streams. Spatial heterogeneity in the interception of solar radiation and its impact on, for example, snow melt (Helbig et al., 2010) has therefore been incorporated into the modelling of watershed hydrology (Aguilar et al., 2010; Zhang et al., 2015).

Within the community of lake and reservoir modelling, remote sensing based data are increasingly incorporated into modelling workflows (e.g. Allan et al., 2016; Van Den Hoek et al., 2015). However, to the best of our knowledge, effects of terrain-feature-induced shadow casts, quantified using digital elevation models (DEM) and the derived solar radiation pattern, have not yet been accounted for in lake and reservoir modelling. While shadow casts from lakeshore terrain features may be ignored for lakes or reservoirs with substantial pelagic areas, they may potentially influence higher proportions of the surfaces of smaller lakes or reservoirs. Shadow casts may influence the littoral domain of the system by constraining primary production and the growth of submerged vegetation in sub-areas and, not least, impact the thermal dynamics. To which extent shadow casts (if present) introduce acknowledgeable model biases or are relevant to consider for a given lake or reservoir depends on the purpose of the model exercise. Thus, a first step in articulating potential interference and modelling relevance is to quantify the possible shadow casting effects on a given lake or reservoir. In this study, we applied a detailed DEM available on a nationwide scale for Denmark. The DEM renders the physical surface of the surrounding terrain, including the topography and elevation of, for example, buildings and vegetation, enabling calculations of shadow casts from all features surrounding a lake or reservoir surface. Our study presents a methodological framework encompassing existing computational routines embedded in the open source QGIS platform as well as existing computational packages available for the Python programming language. The framework was developed with special attention to ease, and was used to conduct a shadow casting analysis for a Danish lake experimental facility. With this paper, we aim to release and communicate the framework per se to the modelling community, allowing modellers to adopt the methodology for further exploration of the importance of shadow casts on lake and reservoir systems and the relevance of, for instance, correcting radiation inputs to aquatic models.

2. Installation, dependencies, structure and required inputs

The framework is written in Python 2.7 and is available through www.wet.au.dk. With QGIS installed on the computer, the framework utilizes the standard Python library modules that come with the installation of QGIS, and as the framework depends on the PyEphem package (http://rhodesmill.org/pyephem/) only one additional module needs to be installed to enable astronomical calculations in Python. The current framework version is developed and structured to be executed through the dedicated Python console of QGIS, where program initializations of spatial layers are done by reference to the layer names within the QGIS Layers Panel and outputs are written to a folder specified by the user within the framework prior to usage.

To calculate the shadow casts induced by terrain features, the user needs to prepare a DEM rendering the physical surface of the terrain (including elements such as elevation of buildings and vegetation). To maximize calculation efforts, a mask polygon should be prepared, encompassing the targeted site (i.e. lake or reservoir) with adequate buffer distance to the lake or reservoir shoreline to encapsulate adequately the surrounding shadow casting features (see examples of required GIS layers in Fig. 1-II).

For each day between the user-specified start and ending date, the framework (Fig. 1-III) computes the time of sunrise (SR) and sunset (SS) through the PyEphem package and then assigns SR and SS to the nearest hour backwards and forwards, respectively (i.e. SRsnap and SSsnap). With 10 min intervals between SRsnap and SSsnap, the framework activates the QGIS GRASS integrated r.sun (Hofierka and Ri, 2002) and r.sunmask.datetime (https://grass.osgeo.org/grass70/manuals/r.sunmask.html) routine (also applied in Liu et al. (2012), which generates a geo-tif file that shows the extent of shadowing for a predefined area (i.e. the mask), while accounting for shadow casting effects from the surrounding terrain's elevation including terrain obstacles. The reason for identifying SRsnap and SSsnap is to cover sunrise and sunset while avoiding nighttime calculations. For post-analysis, each 10-min computed geo-tif file is named by the framework with the representative date and time.

The requirements to process the geo-tif output vary from site to site. However, to initialize Python based building blocks for post-analysis, the framework includes a routine to process each shadow cast geo-tif file with a zonal-statistical-approach. Prior to performing the post-analysis, the user must prepare a polygon (.shp) outlining the zones for which the 10 min shadow cast should be quantified. These zones may, for example, render the bathymetrical characteristics of the lake or reservoir. As output, a. txt file is created for each day (encompassing all the 10 min geo-tif files for a given day), each line representing a shadow cast cell with information on within which zonal id it is located, the name of the geo-tif file analyzed, the area fraction within the zone, and whether the cell is computed as shadow or sun for the given time (Fig. 1-III). From here, the post-analysis text files may be processed and plotted as necessary.

3. Trial application of the framework

The framework was developed as a side product of an ongoing study applying an aquatic ecosystem model (the GOTM-FABM-PCLake (Bruggeman and Bolding, 2014; Hu et al., 2016)) to the Danish situated (56.245 °N; 9.530 °E, Fig. 1-I-a) lake experimental facility Lemming, hosted by Aarhus University. The facility consists of twenty-four cylindrical outdoor fully mixed flow-through mesocosms (diameter: 1.9 m, water depth: 1 m) where three temperature scenarios are combined with two nutrient levels in four replicates (Liboriussen et al., 2005, 2011). The facility is located in surroundings with shading terrain features (Fig. 1-I-b,c); hence, the possible need for quantitative shadow cast calculations.

The framework was tested for the lake experimental facility using a high resolution DEM available as an open access product from the Danish Data Agency (www.sdfe.dk). The DEM (Fig. 1-II) is LiDAR based (recorded from 2014 to 2015 and compiled nationwide) and represents the physical surface, including elevation of buildings and vegetation in meters above average sea level (Danish Vertical Reference – DVR90). The cell size is 0.4 m with a horizontal and vertical accuracy of 0.15 and 0.05 m, respectively. The DEM was flattened at the lake experimental site (to 33.3 DVR) to avoid internal shadow casts, and the mask for calculation (Fig. 1-II) covered an area of 45,000 m^2. The framework was applied to one year's cycle of shadow casts producing approximately 1600 and 3400 geo-tif files for January and June, respectively. Interim framework outputs from the lake experimental facility are exemplified by snapshots of the shadow casts throughout the entire day of January 1 (Fig. 2). For that specific day, the maximum angle of the sun reached approx. 11° given the location. The DEM features pose shadow casts with varying magnitude and extent throughout the day and across the experimental facility.

In the trial application, the physical extent of each of the 24 mesocosms was used to quantify the potential differences in the extent of shadow cast. Based on the post-analysis, the accumulated zonal area exposed to radiation throughout the day was computed as a percentage relative to an unshaded maximum exposure from sunrise to sunset (Fig. 3-a). Moreover, variations during the day, exemplified for two zones, were extracted from the post-analysis, deriving the zonal area