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Impact of highway construction on land surface energy balance and local climate derived from LANDSAT satellite data

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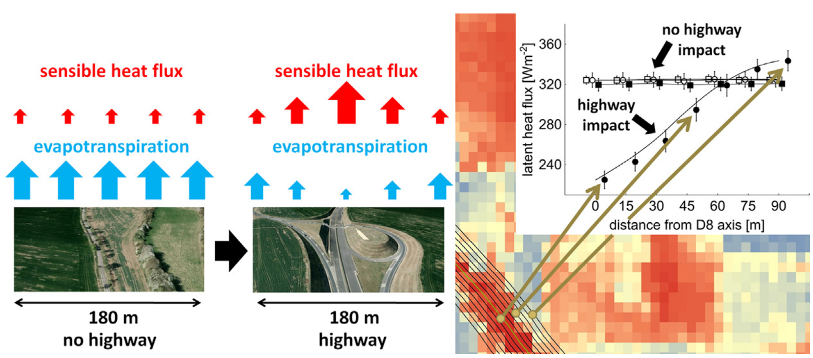
HIGHLIGHTS

- Land surface energy balance calculated using satellite images and ground measures
- Highway construction affects local climate up to a 90 m distance from a highway axis
- In highway surroundings an increase of surface temperature could reach up to 7 °C
- A decrease in the amount of evaporated water could reach as much as 44 m^3 for each km

GRAPHICAL ABSTRACT



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ABSTRACT

Extensive construction of highways has a major impact on the landscape and its structure. They can also influence local climate and heat fluxes in the surrounding area. After the removal of vegetation due to highway construction, the amount of solar radiation energy used for plant evapotranspiration (latent heat flux) decreases, bringing about an increase in landscape surface temperature, changing the local climate and increasing surface run-off. In this study, we evaluated the impact of the D8 highway construction (Central Bohemia, Czech Republic) on the distribution of solar radiation energy into the various heat fluxes (latent, sensible and ground heat flux) and related surface functional parameters (surface temperature and surface wetness). The aim was to describe the severity of the impact and the distance from the actual highway in which it can be observed. LANDSAT multispectral satellite images and field meteorological measurements were used to calculate surface functional parameters and heat balance before and during the highway construction. Construction of a four-lane highway can influence the heat balance of the landscape surface as far as 90 m in the perpendicular direction from the highway axis, i.e. up to 75 m perpendicular from its edge. During a summer day, the decrease in evapotranspired water can reach up to 43.7 m^3 per highway kilometre. This means a reduced cooling effect, expressed as the decrease in latent heat flux, by an average of 29.7 MWh per day per highway kilometre and its surroundings. The loss of the cooling ability of the land surface by evaporation can lead to a rise in surface temperature by as much as 7 °C. Thus, the results indicate the impact of extensive line constructions on the local climate.
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1. Introduction

Evaporation of water through plants by evapotranspiration is associated with the transformation of a high level of solar energy (Penman, 1948). In normal air pressure and at a temperature of 15 °C, the latent heat of evaporation in water amounts to 2466 kJ kg^{-1} (Procházka et al., 1998), i.e. around 0.68 kWh l^{-1}. Therefore, vegetation plays an important role in solar energy transformation by consuming a large proportion of incident solar radiation for water evaporation in the process of evapotranspiration (Monteith, 1975; Gates, 1980; Monteith and Unsworth, 1990 and Jones, 1992). Increased vegetation cover leads to a lower solar energy flux into the sensible heat flux thereby reducing the warming of the surface and the adjacent atmosphere layer (Pokorný, 2001).

Furthermore, the importance of vegetation cover lies in its ability to transform solar energy and thereby influence climatic conditions of the territory. Dense vegetation cover, with a high ability to evaporate water, can stabilize the air temperature regime (Brom and Pokorný, 2009; Brom et al., 2012; Hesslerová et al., 2013 and Pokorný, 2001) as well as other climatic characteristics, e.g. air humidity and wind speed (Huryna et al., 2014). A high amount of evaporated water can change the circulation of water in the atmosphere both horizontally and vertically (Gordon et al., 2003, 2005; Scheffer et al., 2005; Pielke et al., 2011 and Makarieva and Gorshkov, 2010), which can lead to changes in the amount of horizontal and vertical precipitation and thus changes in the hydrologic regime of the landscape (e.g. Hayden, 1998; Stohlgren et al., 1998; Foley, 2005; Gordon et al., 2005; Scheffer et al., 2005; Makarieva et al., 2006; Makarieva and Gorshkov, 2007, 2010; McPherson, 2007; Pielke et al., 2007; Jackson et al., 2008 and Malhi et al., 2008). In this context, vegetation cover increases the retention capacity of the landscape for water (De Roo et al., 2001; Brutsaert, 2005 and Procházka et al., 2009). A secondary effect of high evaporation from vegetation cover is the higher formation of convective clouds (Gambill and Mecikalski, 2011) and radiation fog (von Glasow and Bott, 1999 and Potužníková and Sedlák, 2004), which can result in a change to the radiation balance of the surface. The above-mentioned impact of vegetation on climatic conditions has been observed on all levels of spatial scales. At the microclimatic scale, the role of tree shading is emphasized (Wang et al., 2016 and Shiflett et al., 2017) as well as land cover and vegetation structure or the size and spatial configuration of vegetation patches (Yan et al., 2014; Xu et al., 2017 and Zhou et al., 2017). Moreover, evapotranspiration can have a large effect on surface cooling (Kjelgren and Montague, 1998; Armson et al., 2012 and Rahman et al., 2015). At the mesoscale landscape structure and vegetation have been shown to have a strong effect on climate (Pielke and Avissar, 1990), air circulation (Mahfouf et al., 1987 and McPherson, 2007) and rainfall (Makarieva et al., 2009 and Medvigy et al., 2011). Similar effects of vegetation on climate conditions have been observed also on macroclimatic and continental or global scales (Kalnay and Cai, 2003 and Makarieva and Gorshkov, 2010).

The removal of vegetation cover reduces the cooling effect of evapotranspiration (Hesslerová and Pokorný, 2010; Brom et al., 2012 and Hesslerová et al., 2012).

The impact of vegetation removal on the local climate is comprehensively covered in the literature when it comes to built-up urban areas (Oke, 1995; Weng, 2001; Arnfield, 2003 and Ramamurthy and Sangobanwo, 2016). However, the effect of highways has been ignored even though they are extensive constructions requiring the removal of large areas of vegetation. Moreover, highway construction brings about the development of more built-up areas. These are usually industrial estates or extremely large storehouses, service roads and other paved surfaces with almost no place for any vegetation. Since the size and structure of vegetation patches play an important role in solar energy dissipation or the intensity of the cooling effect (Jiao et al., 2017), we presume a large effect of vegetation removal on local energy fluxes and climate conditions caused by highways and additional building construction. Moreover, most past studies focused usually on just the impact of changes in vegetation cover on air or surface temperature, whereas detailed descriptions of energy flux changes as a driving force is missing. Our aim was to fill this lack of knowledge. Our hypothesis was that construction of highways is associated with significant changes in the heat flux of the land surface which influences the temperature of the local environment, air circulation and the climate of the wider surroundings.

The aim of this work was to describe the impact of construction of a highway and related nearby built-up areas on the local climate and heat balance of the surface of the surrounding landscape. In other words, to describe the way in which solar energy, incident on the landscape surface, is distributed in the individual heat fluxes in the studied site before and during a highway construction. Another aim of this work was to determine the amount of energy that would shift from the latent heat flux into sensible heat flux due to highway construction and to identify the perpendicular distance from the actual highway in which such an effect could be observed. This would quantify the impact of a highway construction on the wider surroundings.

2. Materials and methods

2.1. The study sites

The study sites were two sections of a four-lane highway (the "D8"), located in the central part of the Czech Republic, central Europe (Fig. 1), which were constructed in the 1990s (see details in ŘSD, 2006) and covered by multispectral satellite images used for the purposes of this study. The final tarmac surface of the highway has a mean width of 26.5 m, after the completion of the construction. The evaluated section no. 1, stretching along 9600 m, was built between 1990 and 1993 and the unfinished state was captured in a satellite image acquired on 7th August 1991. Section no. 2, stretching along 8900 m, was constructed between 1993 and 1996 and the unfinished state can was captured in a satellite image acquired on 1st July 1995. Both sections are situated in a plain with an average altitude of 228 m above sea level. The land cover of the surrounding areas is composed of a patchwork of agricultural land with fields and meadows, and partly forests and smaller villages. The long-term average annual air temperature is 10 °C (17 °C in summer) and long-term average annual precipitation is 500 mm (200 mm in summer) (Tolasz, 2007).

2.2. Data description

LANDSAT 5 TM (Copyright ESA, distributed by the Eurimage) multispectral satellite images were used to calculate surface heat balance parameters (latent, sensible and ground heat flux) and landscape functional parameters (the amount of vegetation, surface wetness and surface temperature). The data were used to create satellite maps where each pixel displays a value of an observed characteristic in a given location. The satellite images were selected to capture the study sites on cloudless days in the peak vegetation season (July, August) in the years preceding the construction of the observed highway sections and during their construction (Table 1). All of the images were taken at around 9:30 UTC + 1 (11:30 local time). The satellite data were rectified into the S-JTSK (EPSG: 2065) cartography projection using polynomial raster transformation (Schowengerdt, 2007) in the ORTHO ENGINE module of PCI – GEOMATICA 9.1. Radiometric corrections were made using device constants of the satellite sensor (Chander et al., 2009). Solar radiation geometry corrections and atmospheric corrections were implemented for the optical bands of the satellite images using the COST procedure (Chavez, 1996). Radiometric and atmospheric corrections were made using ATMOSC in the Clark Labs – IDRISI TAIGA. Atmospheric corrections were implemented for the thermal bands of the satellite images using the single-channel algorithm for

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