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Evaluation of Impact of Land Use in Adjacent Areas Causing Damage to Dirt Roads Using GIS Tools – Case Study

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1. Introduction

The existing road network is subjected to considerable pressure and can fail due to lack of bearing capacity, overloading and surface erosion (Ngezahayo et al. 2019). This is particularly evident in the case of dirt roads, which may be seriously damaged as a result of rills and gullies formation (Fig. 1). Analysis of threats of potential damage to unpaved roads needs to include the impact of adjacent areas (Arnáez et al. 2004, Zhang et al. 2019). Relief, land use and maintenance operations performed on roads affect their life cycle. This is not only of economic importance in relation to costs incurred on their repairs and rehabilitation, but also due to traffic restrictions.

Fig. 1. Erosion of investigated road

Roads may absorb surface run-off, thus resulting in a denser hydrographic network (Jones et al. 2000). In that case they accelerate rainwater inflow to watercourses, while at the same time increasing the amount of contaminants washed from the land and road surface. In view of the linear character of roads their role in the modification of surface run-off may be multi-faceted. Roads alter the natural relief, leading to changes in the natural directions of rainwater flow (Benda et al. 2019, Jones et al. 2000). Rural unpaved roads are the most vulnerable to erosion due to the lack of vegetation protection and other protective measures. Thus, during rainstorms, unpaved roads become natural water collection areas and experience the most serious erosion (Yang et al. 2019). This is particularly important in foothill and mountainous areas (Gołąb 2015, Varol et al. 2019).

Topography is an important determinant of surface runoff forming. The extraction of drainage networks from digital elevation models is required for hydrological processes simulations and erosion modelling (Buchanan et al. 2014). A widely used method for extracting drainage networks use calculation of the flow accumulation matrix (O'Callaghan & Mark 1984, Zhou et al. 2019). Effect of soil moisture variability on the runoff can be analysed using topographic wetness index (TWI) (Minet et al. 2010, Raduła et al. 2018).

In order to conduct a comprehensive analysis it is necessary to consider spatial variability of the environment applying GIS techniques and tools (Radecki-Pawlik et al. 2016). Particularly, conducting an effective land planning requires a good understanding of road-induced erosion and sediment production process. River monitoring, sediment determination methods and road erosion models are widely used to estimate the road-induced erosion (Varol et al. 2019). Another indispensable element is availability of high quality data describing analysed areas (Chu et al. 2010, Hancock 2005, Thomas et al. 2016, Vaze et al. 2010). Large areas may be investigated based on LiDAR data (Buchanan et al. 2014, Mohamedou et al. 2019). In turn, satellite images may be used to investigate the land use structure.

2. Methods and description of the study object

The aim of this study was to determine the impact of adjacent areas on the condition of dirt roads and their potential role causing damage to these roads. The investigated area is located in the Komorniki commune, Poznań county (52°19'18" N, 16°48'31" E). Dirt roads a and b are two of the access roads to concrete road c leading to a housing estate (Fig. 2).

In 2014 and 2015, when roads were being constructed in that housing estate, it was the main access road. This led to frequent operations of surface levelling in that two roads. The part of the analysed area located above road a was 15.7 ha in area, at a mean slope of 4.4%. According to Chachaj (1996) northern part of investigated area is composed of sands and gravels of crevice accumulation. Southern part is built from glacial sands on tills. In the Lithological Map of Poland whole area is described as fluvioglacial gravelly sand (Chachaj & Dobosz 2007).

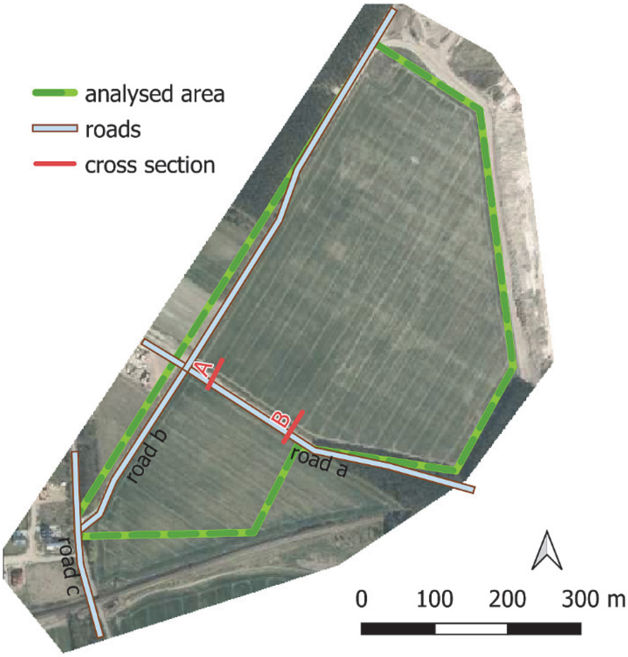

Fig. 2. Analysed area

Spatial analyses were performed using a point cloud generated by LiDAR scanning, provided by the Geodesy and Cartographic Documentation Centre. Raw laser scanning data was processed and the other works related to the generation of the Digital Elevation Model (DEM) and further geomorphological analyses were performed applying such software as SAGA 7.1.1 (Conrad et al. 2015) and QGIS 3.2.

LiDAR data in the form of LAS files contain XYZ coordinates of points and their classes. For the analysed area the mean point density is 6 per 1 m^2, while the mean elevation error is max. 0.2 m. The surface analysis was conducted on points classified in accordance to the LAS format as lying on the ground (classification code 2). Additionally, the points which ordinates were very highly divergent from the mean ordinate of the area (i.e. 21 points with ordinates exceeding 500 m a.s.l. in relation to those within the 80-110 m. a.s.l. range), were manually removed from such a constructed set. The next stage consisted in the construction of a model of the area in the form of a regular GRID, in which point interpolation was applied based on Cubic Spline Approximation. The grid mesh size was assumed as 0.1 m.

Flow accumulation matrix was calculated using flow tracing algorithm with Rho8 method (Costa-Cabral & Burges 1994). The risk of surface run-off may be evaluated based on the Topographic Wetness Index (TWI), which is a quantitative measure describing the impact of topography on hydrological processes. It indicates areas which tend to accumulate water and may potentially promote surface run-off (Beven et al. 1984, Hjerdt et al. 2004, Hornberger et al. 1985, Quinn et al. 1995). This is determined by the dependence between the size of the area involved in surface run-off and the land slope value. The concept for TWI was developed by (Beven & Kirkby 1979) and the index is calculated from the formula:

$$TWI = \ln \frac{a}{\tan \beta} \tag{1}$$

where:
a – local upslope area draining a certain point per unit contour length,
β – local slope (slope of the cell).

Weather data was collected from the Institute of Meteorology and Water Management National Research Institute for the station in Poznań, located approx. 15 km from the investigated area. The analysed case occurred after heavy rain which took place on 22 and 23 February 2017. The accumulated rainfall over an 16 hour period reached 19.7 mm, and was equal 86% of multiyear mean for February. Mean daily air temperatures for this days were 5.6°C, and were almost 6°C higher than multi-year mean for February. There were also no snow cover.

3. Results and discussion

One of the main factors affecting the condition of dirt roads is related to the inflow of water from adjacent areas (Fig. 3). In order to include the effect of this factor it is required to conduct a detailed analysis of relief for these areas. Existing run-off routes may significantly influence the amount of water and the location, through which water may reach the road. The arrangement of surface run-off routes is affected not only by the relief itself, but also tillage operations causing soil compaction at sites of agricultural machinery working passages and the formation of passage routes (Laflen & Flanagan 2013, Montgomery 2007). This may be revealed applying shading on the digital elevation model (Fig. 4). The arrangement of such furrows following the slope and the related run-off routing may considerably accelerate the formation of surface run-off, as well as enhance its intensity, causing a marked increase in the surface erosion risk (Bakker et al. 2008, da Rocha Junior et al. 2016, De et al. 2008, Zemke et al. 2019). This is particularly evident in a magnified fragment of the map, in which we can see relief depressions formed by passages of agricultural machines (Fig. 4). Wheel tracks allowed for a preferential flow and created a runoff line in the wheel tracks where the soil was compacted (Morvan et al. 2014, Zumr et al. 2015). Arnáez et al. (2012) found that farming operations carried out with tractors generated wheel tracks approximately 50 cm wide and 5-7 cm deep..

Fig. 3. Roads a and b

It can also be seen that at a small distance from the field end a run-off line, running parallel to the road, is formed due to repeated passages of agricultural machines over the same tracks. In Fig. 4 we can also see irregularities resulting from the location of the object at the overlapping of two LiDAR flights. Incorporation of such formed depressions into the numerical elevation model makes it possible to establish routes of surface run-off and its gradual accumulation (Fig. 5). The darker colour denotes the routing of increasing amounts of water. As can be seen, the above-mentioned passage tracks located in the upper part of the analysed area, above road a, considerably facilitate surface run-off towards that road. At the same time, within the distance of approx. 15 m from the road we may observe an independent surface run-off route, draining water towards the intersection with road b (Fig. 5). This is also evident at the cross-sections of road b (Fig. 6 and 7).

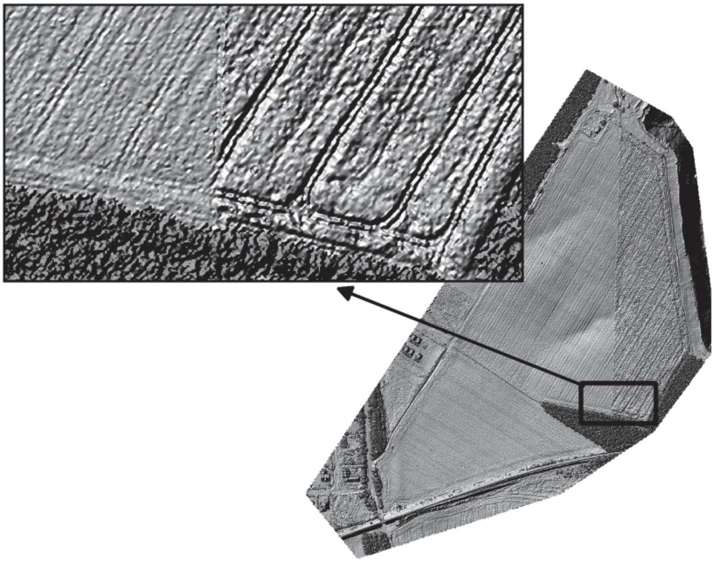

Fig. 4. Shadowing of terrain model

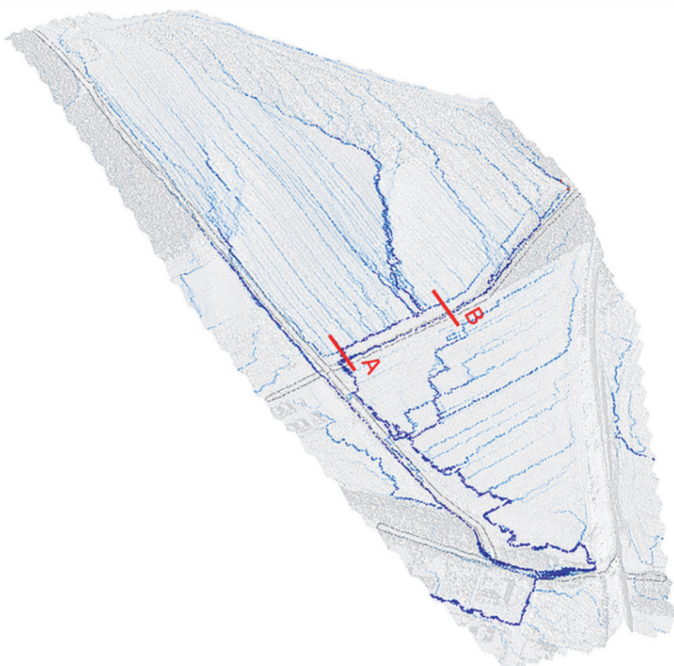

Fig. 5. Flow paths and accumulation of lateral flows (A i B – cross sections)

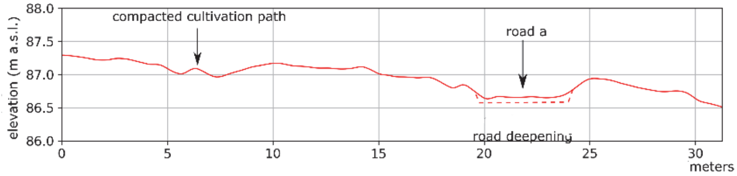

Fig. 6. Cross section A

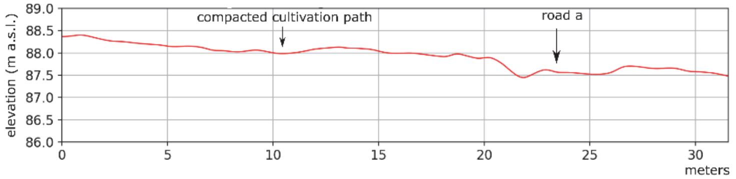

Fig. 7. Cross section B

As can be seen in Fig. 8 run-off from the area located above road a does not flow onto it directly, but reaches it at a certain distance from road b. Initially water is accumulated in a depression of road a (Fig. 9) and next it flows into a field located below. Before year 2015 such an arrangement – apart from a temporary flooding of the hollow – caused no road damage.

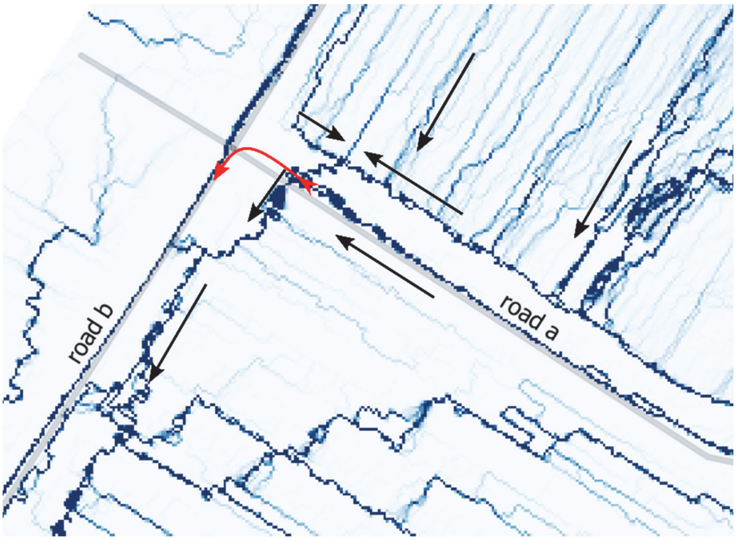

Fig. 8. Directions of water flow (red arrow show water flow after road deepening)

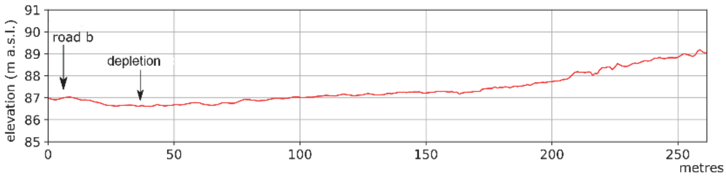

Fig. 9. Profile of road a

Starting from 2015 road a was periodically levelled, which resulted in its deepening by approx. 10 cm (Fig. 6). This led to a change in the direction of water flow, as shown in Fig. 9. A single rainfall, which occurred on 22 and 23 February 2017, caused overflow of the water flowing onto road a in the direction of road b (Fig. 3). The rainfall amounted to slightly below 20 mm within 16 hours. This precipitation washed out road b at a road section of approx. 80 m starting from the intersection of road a, and in the road section of approx. 30 m from the intersection with road C (Fig. 1). The width of the gully ranged from 0.8 to 1.4 m and its depth amounted to as much as 0.55 m. It needs to be stressed here that such considerable damage resulted from the coincidence of several adverse factors, such as a lack of dense vegetation cover, which promoted formation of surface run-off and an increased volume of inflowing water. Another factor was connected with tillage operations following the slope in the land relief what can increase runoff and finally total amount of water flowing to the road (Takken et al. 2001)

The risk of surface run-off may be evaluated based on the Topographic Wetness Index (TWI), which is a quantitative measure describing the impact of topography on hydrological processes. The TWI was chosen because of its well-known high predictive power for small catchments in relatively wet conditions (Minet et al. 2010). The value of TWI reflects the spatial distribution of soil moisture content and the saturation degree of ground surface. High TWI values are ascribed to sites potentially accumulating slope water. The highest values of this index are recorded at a large recharge area and a small slope angle (Radecki-Pawlik et al. 2016). In the study area the highest TWI values are recorded in the area situated above road a (Fig. 10). In turn, low TWI values indicating a lesser water saturation degree may be observed in the area below road a and in a narrow belt of the area between the road and the machinery passage tracks. Such marked differences result mainly from the direction of performed tillage operations. Both areas are characterised by similar soil conditions and land slopes. In turn, in the upper part of the area tillage operations are performed following the land slope, thus promoting surface run-off. In the lower part of the catchment, tillage operations are performed perpendicular to the line of slope, which hinders the formation of run-off (Fig. 10).

It needs to be stressed here that the quality of calculated TWI increases with an increase in the DEM resolution in the modelling process (Buchanan et al. 2014), which at larger areas requires computer equipment of considerable computation capacity (Sørensen et al. 2006).

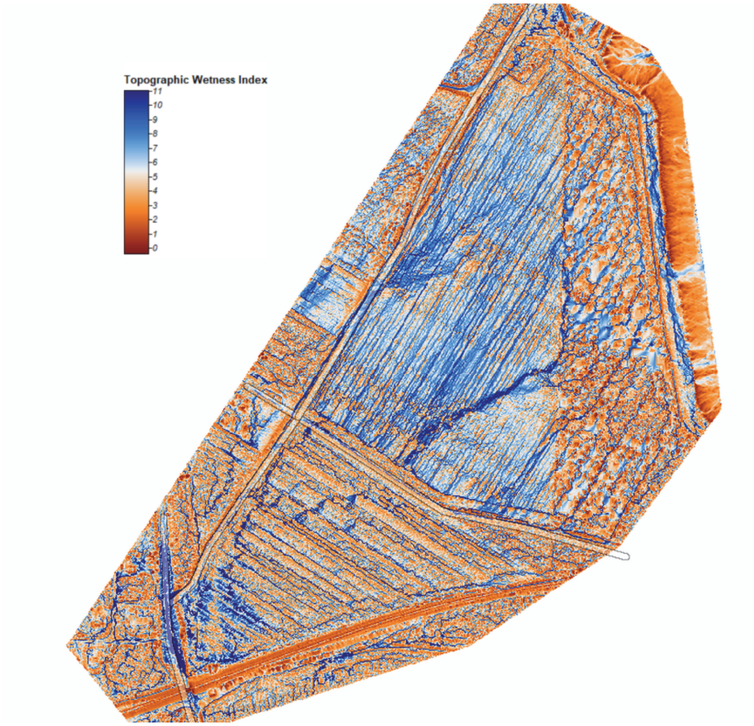

Fig. 10. Spatial distribution of TWI values

4. Conclusions

The study results indicate the necessity to include the impact of relief in areas adjacent to dirt road on their stability and life cycle. When planning road maintenance and rehabilitation operations we need to take into consideration the impact of these operations not only on roads directly subjected to these measures, but also on roads linked to them. The destructive impact of surface run-off is manifested particularly in periods of poorly developed vegetation cover, e.g. in early spring. GIS tools, providing a spatial assessment of the potential distribution of adverse factors, considerably facilitate the analysis of threats related to water inflow onto roads from adjacent areas.

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Abstract

Surface run-off from areas adjacent to dirt roads may cause considerable damage to these roads. The degree of damage is determined from the amount of flowing water, run-off intensity as well as sites, in which run-off reaches the roads. These parameters result from soil conditions, as well as natural relief and the land form modified by tillage operations. Another parameter influencing the formation and the degree of erosion is connected with maintenance operations regularly repeated in the life cycle of these roads, such as e.g. surface levelling or use of paving materials. The analysis involved GIS tools, which made it possible to consider the impact of spatial variability in the surroundings of such roads on the incidence of adverse factors. The application of LiDAR data made it possible to indicate the formation of surface run-off routes and the resulting threats of damage to dirt roads.

Keywords:
unpaved road, TWI index, DEM, road erosion, surface run-off

Wpływ użytkowania terenów przyległych na erozję dróg gruntowych – analiza przypadku

Streszczenie

Spływy powierzchniowe z terenów przyległych do dróg gruntowych mogą wywoływać znaczne uszkodzenia tych dróg. Stopień uszkodzeń wynika z ilości spływającej wody, intensywności spływu oraz miejsc, w których spływy docierają do dróg. Parametry te wynikają z warunków glebowych oraz naturalnego i wynikającego ze stosowanych zabiegów uprawowych ukształtowania powierzchni terenu. Kolejnym parametrem wpływającym na powstawanie i stopień erozji są cykliczne zabiegi konserwacyjne stosowane w procesie utrzymania tych dróg, jak np. wyrównywanie powierzchni czy stosowanie materiałów utwardzających. W analizie zagadnienia zastosowano narzędzia GIS pozwalające na uwzględnienie wpływu przestrzennej zmienności otoczenia takich dróg na występowanie czynników szkodliwych. Wykorzystanie danych LIDAR pozwoliło na wskazanie ścieżek formowania się spływów powierzchniowych i wynikających z nich zagrożeń uszkodzeniami dróg gruntowych.

Słowa kluczowe:
drogi gruntowe, wskaźnik TWI, NMT, erozja dróg, spływ powierzchniowy