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CONNECTION BETWEEN INLAND EXCESS WATER DEVELOPMENT AND MOTORWAYS

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Abstract: It has been known for a long time that linear infrastructures (railways, roads, embankments) significantly influence surface and subsurface horizontal water movements. Clear evidence can be observed at places where oxbows and abandoned meanders are crossed by roads, while the effect can hardly be shown at lowlands free from linear water drainage forms. This research seeks to answer the question of whether the motorways opened in the last 10 years around Szeged, SE Hungary (M5, M43), have any role in the appearance of extended patterns of inland excess water along certain sections of the motorways. The infiltration conditions of two selected sample sites were determined by soil and geodetic studies and it was also possible to determine the elevation of the groundwater level. The analysis of results underlines the significant effect of linear infrastructures. Inland excess water patterns along the studied highway sections are caused by the motorway M43.

Keywords: inland excess water, motorway, groundwater movement, anthropogenic effects, soil compaction

1. INTRODUCTION

The natural drainage networks and hydrological systems are seriously influenced by roads, embankments, ditches, and channels in several catchments with high population density. These anthropogenic effects can be obvious in hilly areas (Carluer & De Marsily, 2004; Buchanan et al., 2013) but are hardly recognized on flat plains without any significant linear channels, especially in dry periods. On the other hand, when the weather turns rainy in a year, the surface and subsurface water can cause serious problems such as runoff and inland excess water (Szatmári & van Leeuwen, 2013). This has happened in the last decades in Hungary.

After the period free from inland excess water of the 1990s and since the turn of the millennium, the extension of inland excess water has again covered more than 200000–300000 hectares in Hungary in periods when the precipitation has been higher (1999, 2000, 2006, 2010) (Szlávik, 2007). The inundations have affected several areas in southeast Hungary where no inland excess water had been documented or these areas had been indicated as being lowest-risk areas on the maps of inland excess water risk and inundation frequency (Bozán et al., 2008; Kozák, 2008; Körösparti et al., 2009; Pásztor et al., 2009). The hydrometeorological conditions of the previous autumn and winter periods, the high groundwater level, and the permanent soil frost may be natural reasons for the inland excess waters of the previous decade (Barta, 2013), while anthropogenic effects can also have a significant role (Hamza & Anderson, 2005; Pálfai, 2007; Szlávik, 2007; Ndiaye et al., 2007). Among these factors, the role of linear infrastructures can be highlighted, and their negative effects on runoffs can be seen on satellite images and aerial photos (Fig. 1).

In the second part of the referenced period, several linear infrastructures were built around Szeged (SE Hungary). The Kiskunfélegyháza–Szeged section of the M5 motorway was opened in December 2005 and the section of the M43 motorway to the northeast of Szeged was opened in 2010 (Fig. 2). In one section of the sample area (MOL Rt., Algyő Mining Field) detailed groundwater level measurement and modelling were carried out from 2002 to 2005 (Mucsi et al., 2004; Geiger & Mucsi, 2005).

Figure 1. The effect of the manmade dam can be identified in places marked with arrows on the RapidEye satellite image of 24 March 2011 (RGB 543 false coloured, resolution 5 × 5 m). Projection: HD72/EOV (km)

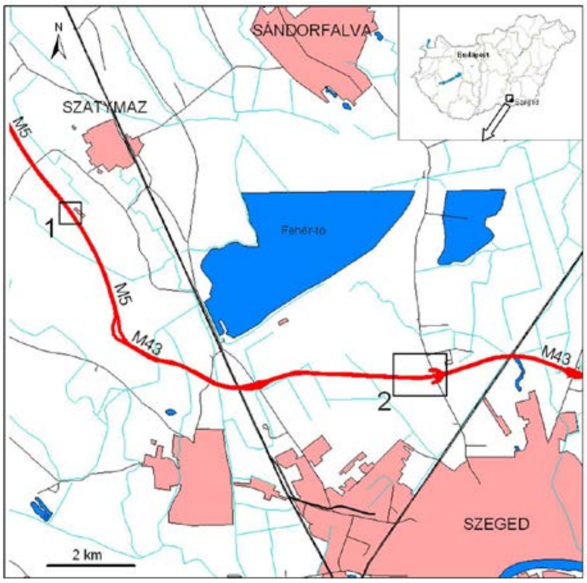

Figure 2. The two motorway sections studied near Szeged

In the spring of 2006, inland excess water was observed around Szatymaz on both sides of the M5 motorway in areas where in the past it had never occurred. This extreme phenomenon was also observed in orchards and unfortunately a significant part of the peach plantation died. Owners and experts raised the idea that the motorway that opened in December 2005 may be a barrier to the surface and subsurface water flows.

In spring 2010, a similar phenomenon occurred on the northern side of the newly opened M43 motorway, which resulted in strong reactions in the media. According to estimations, more than 200 hectares were inundated to the north of the Sándorfalva junction of the M43 motorway on both sides of the embankment, but especially on the northern side. Farmers working in this area blamed the motorway for the inland excess water. It is a matter of fact that the drainage system of the prospective motorway had not been established and it was hard to decide whether the pipe culverts further away could fulfil their function.

The objective of this study was to decide whether the impact of the motorway on the groundwater movement, the appearance of inland excess water, and the surface water movement could be proved in the two areas. In order to characterize the infiltration conditions, a detailed soil analysis was carried out on both sides of the motorways and the inland excess water spots as well as the elevation of the groundwater level were determined by geodetic measurements. For the M5 motorway, our results probably support the hypothesis suggested by the field experiences that the motorway is a significant hydrological barrier to the surface and subsurface water movement from north to south; for the M43 motorway, they unequivocally support it.

2. CHARACTERIZATION OF THE SAMPLE AREAS

2.1. Szatymaz, M5 motorway

In the area situated northwest of Szeged (46°19.8’N, 20°1.7’E, Fig. 2) the motorway runs at the border of the Dorozsma-Majsa Sand-Ridge and the South Tisza Valley (Dövényi, 2010). It is characteristic that the northwestern–southeastern longitudinal depressions at the eastern boundary of the Duna-Tisza Sand Back are crossed by the motorway in the NNW–SSE direction at about 20–25°. Due to this direction, the motorway can be a barrier mainly to the southeastern water flows typical of the Dorozsma-Majsa Sand Back, while in certain places, that is, sections channelling down from the intermediate sand ridges to the depressions, it can dam back the groundwater flowing locally in the southwestern direction.

Our study has been carried out in a similar section, where due to the flat depression situated south-southwest of the motorway, water movement is likely to happen from northeast to southwest. The depression is 84–87 m above sea level, while the north-northwest side is 87–88 m above sea level. Small-scale land management (peach, alfalfa, wheat) is taking place within a dense network of farms (so-called *tanya*) on the sandy soil on both sides of the motorway.

2.2. Sándorfalva Junction, M43

Close to the junction of the M43 motorway (46°17.7'N, 20°7.8'E, Fig. 2) between Szeged and Sándorfalva (Fig. 3), the road runs in the South Tisza Valley landscape (Dövényi, 2010).. The area is situated at the edge of a flood plain with small relative relief, 78–80 m above sea level. The largest area of the flood plain is built up of 15–20 m thick Holocene sediments that change from silt to clay and silty clay and then down to coarser and coarser fluvial sediments, from which the studied area of infusion loess rises (Dövényi, 2010). In the area, a southeastern local water flow direction can be assumed, based on the flatter depression situated south-southeast from it. Later this was proved by the digital elevation model (DEM) developed for the area (Fig. 5). The south-southeast area is 78–79 m, while the sample area is 79–81 m above sea level, which means that there is a difference of 1–3 m in altitude. Large-scale arable farming (wheat, corn) takes place along the motorway.

3. METHODS

3.1. Preparation and use of DEM

In the sample area of Szatymaz, which has higher relief intensity, the slope and runoff directions could be determined even from a 1:10.000 scale topographic map due to the sharp differences in relief. The runoff directions along the M43 before the construction of the motorway could only be determined on the basis of the high resolution digital elevation model of the wider environment (area of 4 × 3 km). The contour lines of the 1:10.000 scale topographic maps were digitized, then the horizontal coordinates were assigned to all cut-off points, and finally a regular grid of 6641 points was extracted. The *thin plate spine algorithm* of the *radial base function* method was chosen in *Surfer* software among the best smooth but undistorted interpolation methods (Kovács & Szanyi, 2005) and its result was converted in *ArcGIS*, preserving the 10 m resolution in raster format (in total, 12000 points). The depressions were uploaded with the *Fill* tool and then the runoff directions were determined by the *Flow Direction*. The *Flow Accumulation* function could assign the catchment area to all pixels (pixel number) and thus the runoff network could be displayed.

Figure 3. Inland excess water conditions just after the opening of the M43 (7 May 2010, left) and one year later (31 March 2011, right)

3.2. Soil analysis

The soils were sampled at both sides of the motorway. Analysis of the soil samples collected from all horizons of the soil profiles was carried out in order to determine the following characteristics of the surrounding soils: the plasticity index according to Arany (according to Hungarian Standard 08-0205:1978), pH, carbonate and salt content (according to Hungarian Standard 08-0206/2:1978), organic matter content (according to Hungarian Standard 21470/52:1983), the basic hydrophysical properties of the characteristic horizons of the soil profiles (porosity, field capacity, bulk density), and the saturated hydraulic conductivity (according to Hungarian Standard 08-0205:1978).

3.3. Geodetic measurements and their processing

After 2006, no inland excess water appeared for at least two years in the Szatymaz area, and thus our measurements were carried out in spring 2008 when the groundwater level was high but there was no inland excess water. Water levels from the surface and ground surface elevation were measured with a Leica Sprinter digital level at a total of 8 points (7 boreholes and 1 dug well) on the two sides of the motorway. These helped to calculate the water levels above sea level, and then the directions of groundwater flow were found by determining the dip direction of the planes fitted on the resulting points separately at both sides. The joint groundwater surface was interpolated based on the above mentioned eight points using the program *Surfer8*.
On 6 May 2010, 15-15 boreholes were made on both the northern and the southern side of the studied section of M43 and standing water levels were measured in all the holes with centimetre-level accuracy. In order to determine the precise ground surface elevation of the boreholes and the groundwater and inland excess water levels, detailed RTK measurement and levelling were carried out not only at the 30 boreholes but also on the contours of the open inland excess water spots. The interpolation from the measured data was carried out using *ERDAS* and *Surfer8* software. Among the several interpolation methods chosen on a theoretical basis, two methods have brought acceptable results: *kriging* and the *thin plate spline* algorithm of the *radial base function* method applied during the establishment of the digital elevation model.

4. RESULTS

4.1. Szatymaz, M5

During the measurements, the groundwater level was 140–170 cm below the *Arenosols* of the area and the soil analysis clearly showed that, until the groundwater level, there was no layer with lower hydraulic conductivity that could cause vertical backwater or could be a barrier to the lateral water flow in the deeper layers. Nevertheless the approximation with planes of the groundwater level showed an approximately 70° difference in the flow directions between the two sides of the motorway. Moreover, on the northeastern side, the direction is parallel to the motorway (Fig. 4). Several interpolation methods were applied for the approximation of the groundwater level with a curved surface (see Barta & Szatmári, 2010); however due to the limited number of measurement points, the results contained large errors.

Figure 4. Result of the approximation of the groundwater level with planes. Legend: 1 – groundwater flow direction. Projection: HD72/EOV.

Therefore, the effect of the motorway could not be fully proved here but the modifying effect is supported by the fact that the flow direction of the northeastern side is exactly in line with the motorway (in the case of each method) and a nearly 90° difference can be observed in the groundwater direction at the two sides of the motorway. This cannot be considered to be clear evidence; it only further strengthens the possibility of this anthropogenic effect (Barta & Szatmári, 2010).

4.2. Sándorfalva Junction, M43

In conformity with the preliminary expectations and based on the DEM, the surface runoff of the studied 4 × 3 km area had a southeast direction (Fig. 5). In this context, it is worth observing the drainage system of the area, which suits the natural runoff conditions well, as can be seen on the western and northeastern side of the area. Unfortunately, there is no drainage system in the sample area itself, and thus when the motorway was constructed the establishment of a drainage system would have been essential for the collection of the water runoffs from the motorway and other areas. Our results draw attention to another problem: the establishment of the overpass at the Csongrád road cannot exclude the possibility that the water flow from west to east is blocked in the southern forefront of the overpass, and thus the risk of inland excess water may increase at the southern part of the motorway. We will refer to this problem in the evaluation of the groundwater levels.

According to the field and laboratory soil analysis, *Chernozems* on loess with loamy texture were found on both sides of the motorway, and these are the best quality farmlands around Szeged. The soil organic matter content of the 50–60-cm-wide A-horizon is more than 2%. Below this, the organic matter of the B-horizon is only 1% and after longer or shorter transition the loess is reached at 80–100 cm. Its texture is sandy loam in this area. A carbonate content of 2–9% was measured in the A-horizon, which increases above 11–13% from the B-horizon in all places. The salt content of the humus soil horizon is low but a salt content of 0.08–0.11% was measured below 1 m, which indicates the hydromorphological effect. Due to the advanced physical degradation resulting from the several-decades-long large-scale cultivation, the hydrological properties are worse than usual in *Chernozems*. According to our measurements, the highest values of the saturated hydraulic conductivity in the ploughed horizons were 0.3–0.4 mm/h but there were also values with a smaller order of magnitude, while the hydraulic conductivity of the plough pan was 0.01 mm/h at all measurement points (Kun et al., 2012). Although, according to the measured data, even the plough pan cannot be considered impermeable, temporary inland excess water may appear in areas with significant catchments as a result of higher precipitation. However, these lower values are beneficial for the formation of inland excess water and thus it is important to enable gravitational runoff of the surface water.

The groundwater levels in the boreholes change from 15 to 135 cm, and the deepest groundwater levels are under the highest relief in the north as well as in areas east of the southeastern Sándorfalva road. This second finding was unexpected because this is the lowest part of the examined area. The groundwater levels in the boreholes were 78.1–79.3 m above sea level. In addition to the 30 boreholes, the elevation of the water level of some observed inland excess water patterns was determined.

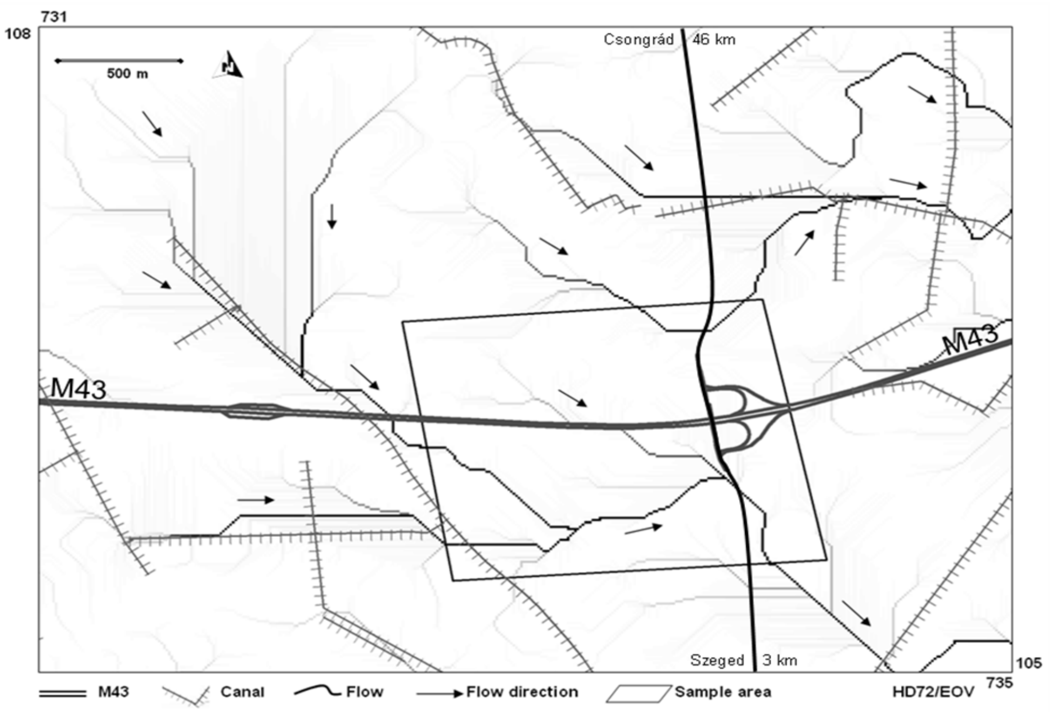

Figure 5. Sample area north of Szeged and its surroundings with the natural runoff directions

The most significant inland excess water occurrences are in long patterns from west to east, directly next to the embankment on the northern side of the motorway. Taking into consideration the 22–23 mm precipitation as a result of the thunderstorm on the afternoon of 6 May 2010, water levels were measured again on 7 May, and thus separate groundwater level maps could be prepared for the two consecutive days. The following can be highlighted from the analysis of the unprocessed data:

1. The average groundwater level in the 15 boreholes on the northern side of the motorway was 50 cm higher than that on the southern side of the motorway on both days.

2. The highest water levels were measured at the borehole row situated directly next to the motorway on both sides and the groundwater level was lower when moving away from the motorway to the north or to the south.

3. Water levels rose by 25–40 cm on average in the boreholes and in the inland excess water patterns by the second day; moreover new inland excess water spots appeared on the southern side of the motorway. Here the inland excess water patterns were situated minimum 25 cm lower than the northern ones on the previous day.

4. The absolute water levels (in metres above sea level) in the three boreholes of the southeastern area over the road leading towards Csongrád lagged behind by at least 30 cm compared to the water levels measured in the closest boreholes of the southwestern quarters on both days. Moreover, even on the second day, no inland excess water appeared here. This verifies the earlier hypothesis that the *water movement from west to east is obstructed in the area affected by the new overpass*.

The contour map of the groundwater level of the studied area was designed for both days. The character and possible conclusions that could be drawn from the maps of the two days were similar, so only the situation of 6 May is analysed in detail. In addition to the water levels measured in the boreholes, the data of the inland excess water was also included in the interpolation. Moreover, in order to decrease the interpolation errors, the largest northern inland excess water pattern was framed by points with an altitude of 79.33 m above sea level. The results were loaded with significant extrapolation errors as no measurement was done in the northeastern quadrant of the quadrants framed by the two linear infrastructures. The sample area had to be restricted and the areas on the eastern side of the Csongrád road were excluded from the study. The difference between the applied interpolation methods was less than 5 cm in the studied area. The surface resulting from the kriging method was chosen for further analysis (Fig. 6).

One of the main characteristics of the developed surface is the “excess water hill” rising over the neighbouring groundwater level, which cannot exist permanently due to low water conductivity. The significantly larger gradient of the southern side is obvious, but it is possible that this could be only the result of the groundwater level sloping southwards. However, it is significantly different from the southeastern slope of the surface (Marton, 2009). In order to find the answer, another groundwater level map hade to be made by excluding the northern inland excess water pattern and its surrounding boreholes (also on the southern side of the motorway). The original and “undisturbed” groundwater level before the precipitation in April–May was determined by removing the “excess water hill” (Fig. 7).

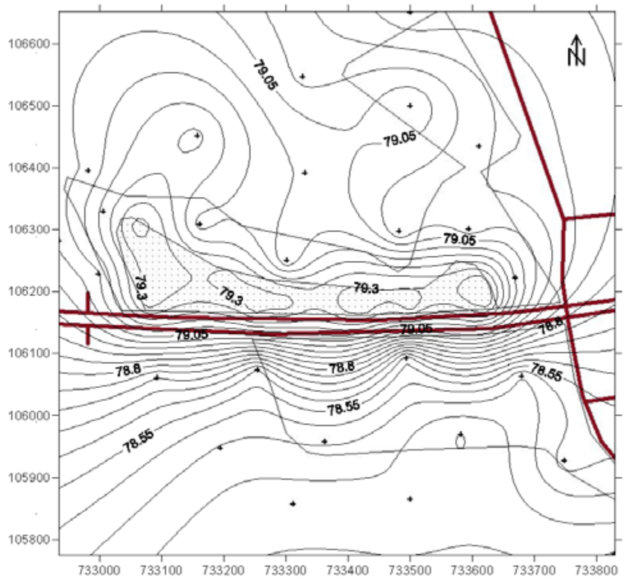

Figure 6. Water level in metres a.s.l. on both sides of the M43 on 6 May 2010. Dotted and surrounding areas show inland excess water pattern. Crosses show the boreholes. Projection: HD72/EOV.

Even when removing the inland excess water hill, the interpolated groundwater surface was found to be 10–15 cm higher than that indicated by the actual data. This is considered the most important evidence for the damming effect of the motorway.

5. DISCUSSION

Although, as mentioned earlier, in the Szatymaz area our former study was not able to show the requested effect, based on the results along the M43, the following clear and quantitative evidence can be listed in addition to the damming role of the motorway:

1. Based on the measurements on the second day (7 May 2010), the 25-cm difference in altitude

above sea level of the inland excess water levels on the northern and southern sides of the motorway *clearly shows that the gravity-controlled surface runoff is blocked by the embankment of the motorway*. Based on the runoff directions shown by the relief model, the water surplus arriving from the northwestern direction should have left the area by gravity in the southeastern direction.

2. The effect of the overpass construction can be demonstrated – only in a short section – in the water levels measured on the western and eastern sides of the Csongrád road, although this impact is less significant than the soil compaction resulting from the embankment construction of the motorway.

3. Considering the maximum 5-cm deviation of the groundwater level resulting from the various interpolations, the difference map obtained by interpolation after removing the "excess water hill" resulted from the inland excess water pattern, and based on the 10–15 cm water level differences of the cross-sections, it can be stated that the motorway acts as a barrier to the surface water flow and is responsible for the limited underground connection between the northern and southern groundwater bodies.

There is definitely a hydrological connectivity between the two sides of M43 below the foundation of the motorway that is composed of compacted loessy sediments. This connection is basically controlled by differences in hydraulic pressures and the Darcy law, but, as can be seen in Fig. 8, this can significantly slow down the equalization of the water levels of the southern and northern sides.

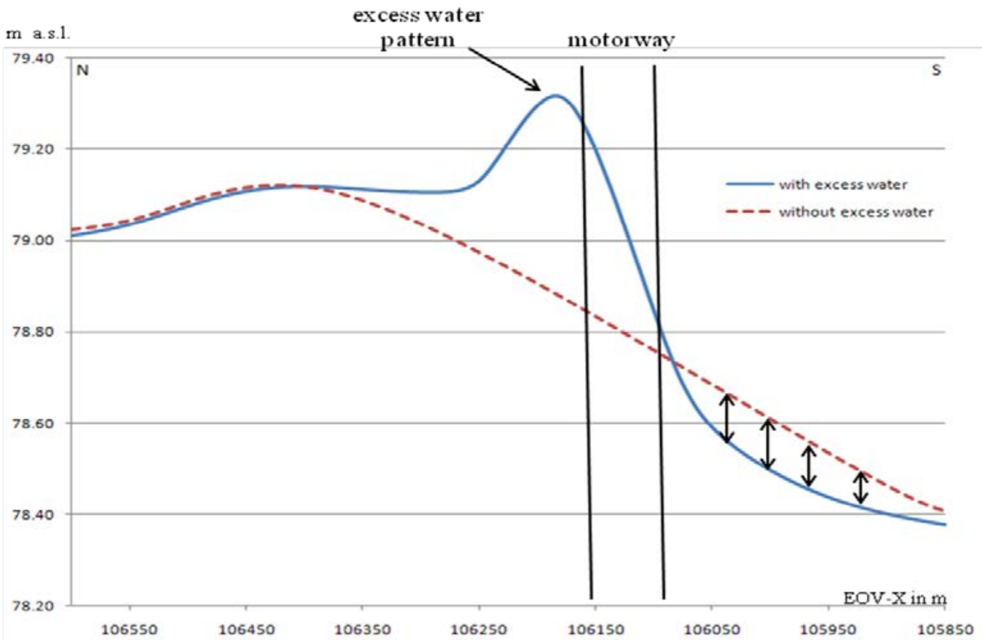

Figure 7. North–south profile of groundwater level with and without inland excess water on 6 May 2010 across the M43 motorway

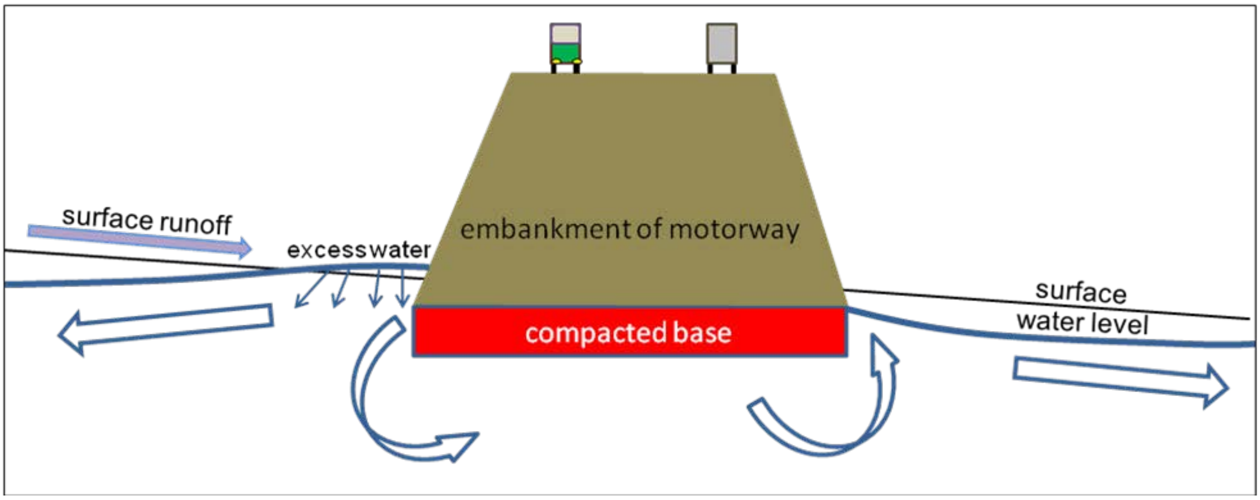

Figure 8. Role of motorway in modifying the surface and underground water flow

6. SUMMARY

This study tried to answer how recently opened motorways among linear infrastructures influence surface and subsurface water regimes, and consequently what role they play in the development of inland excess waters and the expansion of inland excess water patterns. After examining the Szatymaz section of the M5 motorway in 2008, a 1-km^2 sample area was designated along the M43, north of Szeged, where significant agricultural losses were recorded in 2010. Based on the topographic model of the area, this study focused on understanding the natural runoff patterns, determining and analysing the soil conditions that have a role in soil formation, and developing the groundwater topography on both sides of the west–east motorway based on geodetic measurements.

The results support our initial hypothesis that the embankment of the motorway entirely blocks the surface water flows while significantly obstructing the subsurface water interaction, which leads to great differences in the groundwater levels on the northern and southern side of the motorway as well as to the establishment of large inland excess water patterns on the northern side. Our studies could demonstrate the impact of the overpass over the road connecting Szeged and Csongrád on the groundwater flow on the southern side.

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