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Polynomial Regression Model for River Erosion Prediction in Transport Infrastructure Development

Cosmin PĂUNESCU*[a], Laura COMĂNESCU[a], Dobre ROBERT[a], Ionuț SĂVULESCU[a], Alexandru GIUREA[a]

[a]*University of Bucharest, Faculty of Georgaphy, Bd. Nicolae Bălcescu 1, 010041, Bucharest, România*
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A B S T R A C T

Sustainable implementation of highway projects requires a multi-criteria analysis of the terrain and all of its components that have a direct influence on road design, construction and operation. At a strategic level, one of the most challenging factors in highway corridor studies are rivers and especially river erosion prediction. The result of this inquiry involving GIS and statistical techniques for river erosion prediction helps in choosing the optimal road route, in order to meet the real-world connectivity requirements in a sustainable manner, with low environmental impact. This paper aims to create a tool for river erosion prediction based on polynomial regression that can be used in transport infrastructure development at a strategic level.

Keywords:Transport infrastructure development, river erosion prediction, GIS, Romania

1.Introduction

Sustainable transport has become an important goal in transport planning and research in recent decades, especially with the development of Geographic Information System (GIS) techniques and methods (Rybarczyk& Wu 2010).

In order to develop a transport infrastructure unity across all member states of the European Union, as well as of the neighbouring countries, the TEN-T Trans-European Transport Network was established, with two levels: TEN-T Core and TEN-T Comprehensive. The ultimate goal is to connect all regions of the European Union in a unitary, balanced, economically and environmentally sustainable manner.

In order to align to the European criteria, the Romanian Government has adopted the General Transport Master Plan of Romania, a strategic document which establishes and prioritizes transport infrastructure projects in Romania in the period from 2014 to 2030 and correlates them with the available funding sources (Bolos et al. 2016).

The adaptation of transport infrastructure to the needs and requirements of connectivity represents a priority at national, regional and European level and is based on several defining steps in regard to sustainable socio-economic development and environmental impact (Dobre&Păunescu 2020).

River erosion is a complex phenomenon as a result of a multitude of factors that affect the balance of an ecosystem (E. A. Varouchakis et. al, 2016). Considering the fact that erosion affects the morphology of rivers and local habitats, an attempt was made to create a statistical tool based on GIS to predict the erosion produced by rivers in order to identify critical areas that can cause damages to transport infrastructure, at the earliest stages of implementation, such as planning.

River erosion is a common phenomenon, but predicting and locating it is difficult (E. A. Varouchakis et. al, 2016). The proposed method was applied on an area of 710 km2 and 230 km of rivers and the validation was carried out in several areas where rivers may affect a future infrastructure investment for Brașov – Bacău highway.

* *Corresponding author.* Tel.: +40758473327
E-mail address: george-cosmin.paunescu@unibuc.ro

2.Data and methods

Study area is located between the municipalities of Brașov and Bacău (figure 1), where it is proposed to be implemented a transcarpathian highway that will connect Brașov with Bacău. The Brașov - Bacău highway project is part of the TEN-T Comprehensive network and is included in the General Master Plan for Transport of Romania.

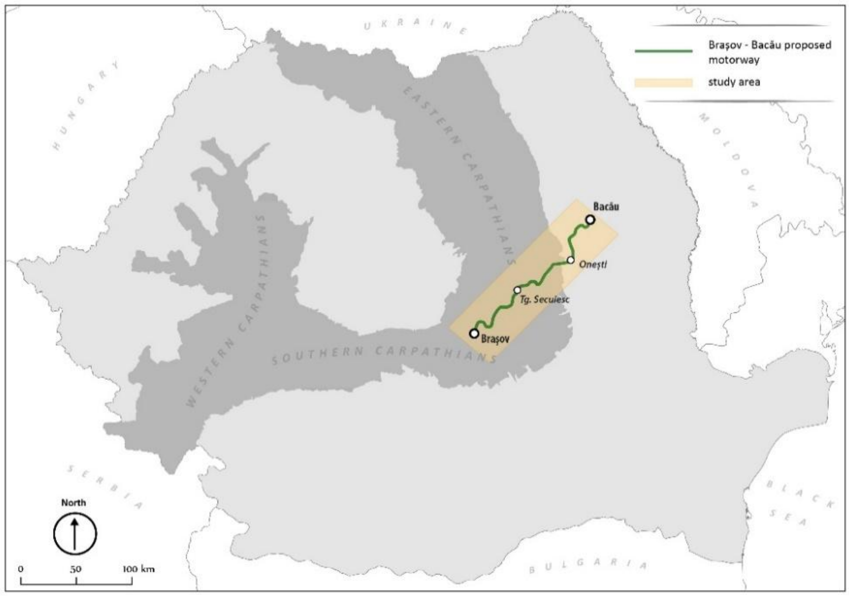

Figure 1. Study area

This type of analysis is proposed to be used at a strategic level to identify problematic areas in terms of river erosion that may produce additional costs during the design, construction and operation of a highspeed road network.

Methodology proposes to identify areas prone to river erosion or accumulation processes is based on GIS and statistical techniques. A digital terrain model was created at a spatial resolution of 5 meters using contours extracted from the Topographical Map of Romania (scale 1:25000). Also, ortophotoplans from 2005 and 2017 from Land Registry Office of Romania were used and 2020 ortophotoplan generated by authors with UAV technology. The next step was to extract rivers from ortophotoplans, that was later used to validate the methodology. Proposed methodology was applied for 2017 river data, that was divided into segments of 20 meters long and for each the average altitude was extracted from the digital terrain model.

For 19 rivers within the study area, a table database was prepared with the average altitude for each segment of 20 meters. For each table file related to each river, the polynomial regression was calculated, the goal being to identify the equilibrium profile of each river or the ideal trend line. Second degree polynomial regression was calculated using CurveExpert Pro. Polynomial regression was chosen because it is a statistical modeling tool that determines a pattern of relationship between the independent variable x (river length/number of river segments) and the dependent variable y (mean elevation). For each segment of 20 m of a river, the polynomial regression was calculated and the difference between the average altitude extracted from the digital terrain model and the data resulting from the application of the regression was realized (table 1).

Table 1 - Example of table database for some segments of Oituz River.

River	Segment length (m)	Mean altitude (m)	Polynomial regression (m)	Difference (m)
R. Oituz	20	688.68	691.88	-3.20
R. Oituz	20	688.45	691.54	-3.09
R. Oituz	20	688.43	691.20	-2.77
R. Oituz	20	688.18	690.87	-2.69
R. Oituz	20	687.75	690.53	-2.78
R. Oituz	20	687.55	690.19	-2.64
R. Oituz	20	687.17	689.85	-2.69
R. Oituz	20	687.75	689.52	-1.77

Depending on the trend line, the longitudinal profile of a river can be divided in 3 large types of sectors: the overlap of the longitudinal profile with the trend line (in this case, no clear erosion or accumulation trend can be identified – in this sectors, river has reached its ideal equilibrium profile); sectors where the difference between the longitudinal profile of the river and the trend line is negative (in this case a general tendency of the river of erosion is identified) and sectors where the difference between the longitudinal profile of the river and the trend line is positive (in this case a general tendency of the accumulation river is identified).

For each individual hydrographic network, regarding the average altitude extracted from the digital land model and the polynomial regression that represents the ideal flow profile of the river, we created a series of graphic (figure 2) and cartographic materials (figure 3).

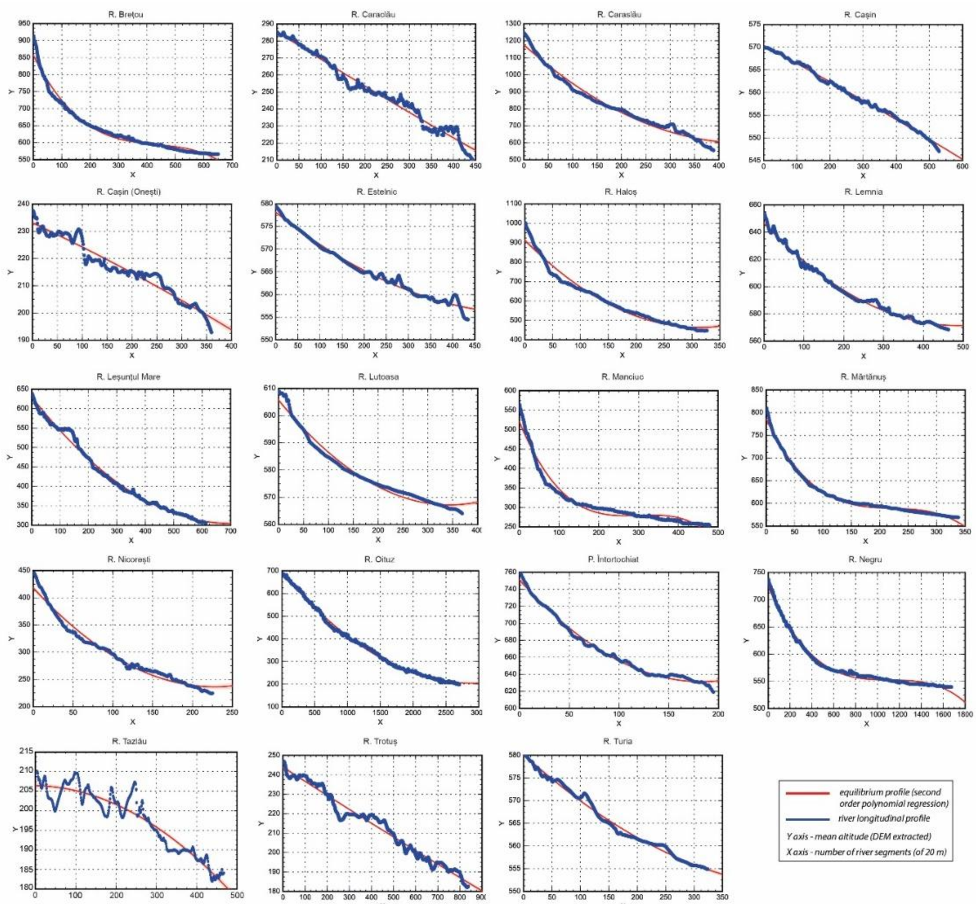

Figure 2. River network analysis using polynomial regression

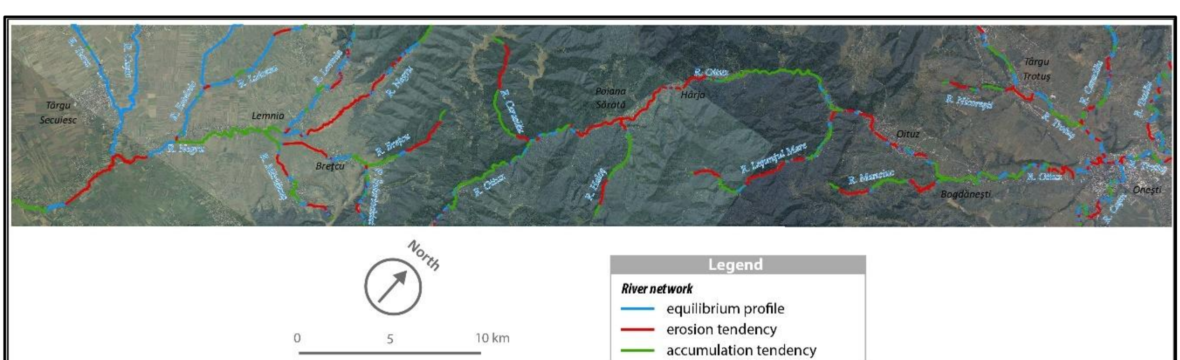

Figure 3. River network analysis using polynomial regression

3.Results

Results and data validation were focused on three main rivers for which field validation was also carried out: Oituz, PârâulÎntortochiat (confluence with Brețcu river) and Leșunțul Mare (confluence with Oituz river). These sectors were chosen because that areas can be used in order to develop road highspeed infrastructure.

3.1 Oituz River

For the largest river in terms of length in the study area, Oituz River, the equilibrium profile based on polynomial regression (figure 4) emphasize three types of river sectors:

- Sectors where the longitudinal profile of the river overlaps with the equilibrium profile – these being considered as sectors where the river has reached an equilibrium profile. In this situation, the general trend of erosion is not a clear one, being considered areas where the river has reached a balanced profile.
- Sectors where the difference between the longitudinal profile of the river and the trend line is negative – these being considered as sectors where the river shows a strong erosion tendency characterized generally by straightening of the courses.
- Sectors where the difference between the longitudinal profile of the river and the trend line is positive – these being considered sectors where the river shows a strong tendency for accumulation, generally characterized by meanders.

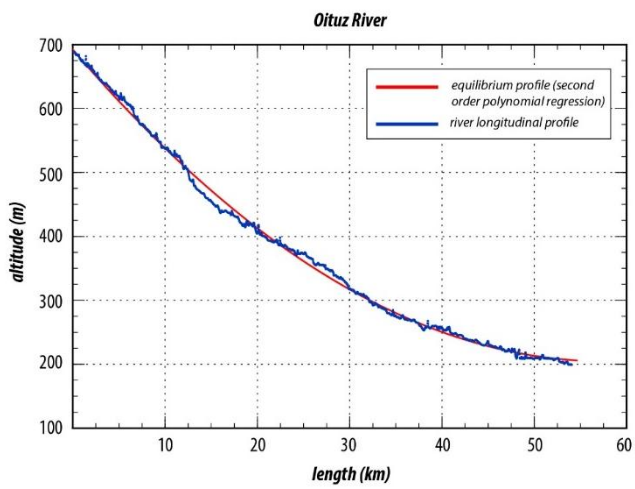

Figure 4. Polynomial regression analysis for Oituz river

In order to test the methodology, the 2017 river that was used in this analysis was compared with 2005 river and overlapped on 2020 UAV and GPS calibrated ortophotoplan (figure 5).

Figure 5. Oituz river – erosion tendency

The result of the analysis is validated in this sector of the R. Oituz (located in the east of the Oituz town). The cartographic support is represented by the 2020 orthophotoplan obtained after mapping the area with UAV systems. The river shows a tendency of erosion, characterized by the straightening of the course, a fact that can also be observed following the comparison of the thalweg from 2005 with that of 2017, respectively 2020. In this sector we avoided drawing a highway alignment, given the fact that the result analysis indicates an intense dynamic of the Oituz River. In a further multi-criteria analysis, higher costs and risks of this kind of areas led to other sustainable areas identifying process.

3.2PârâulÎntortochiat

PârâulÎntortochiat (figure 6) was chosen for data validation because of its confluence with Brețcu river which represents a potential area that can be taken into consideration for highway corridor proposal, mainly because there are no slopes in the area that can cause difficulties during construction and operation of Brașov – Bacău highway.

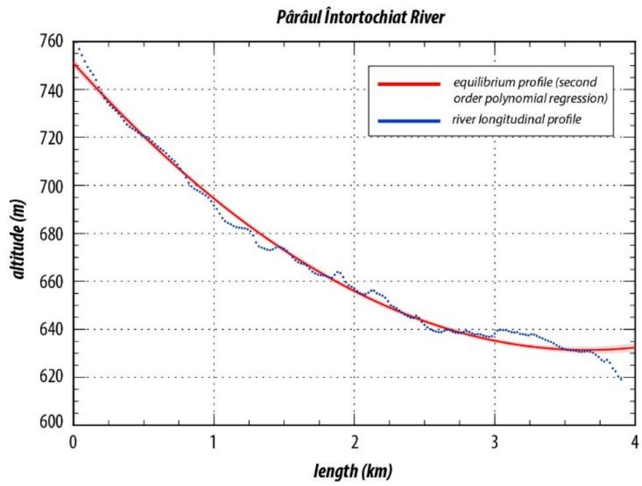

Figure 6. Polynomial regression analysis for PârâulÎntortochiat river

In the confluence area (km 3 to 4), erosion dynamics is intense, considering the altitudinal gradient of the longitudinal profile and interdependence with R. Brețcu's course changes. R. Brețcu shows in the area of confluence with PrâulIntortochiat an accumulation tendency that created a series of sinuous sectors, which in turn affected the flow of PârâulIntortochiat, giving it a strong erosion tendency in the confluence area. All these factors contribute to a constant movement of the confluence point and constant changes for PârâulIntortochiat's talweg (figure 7).

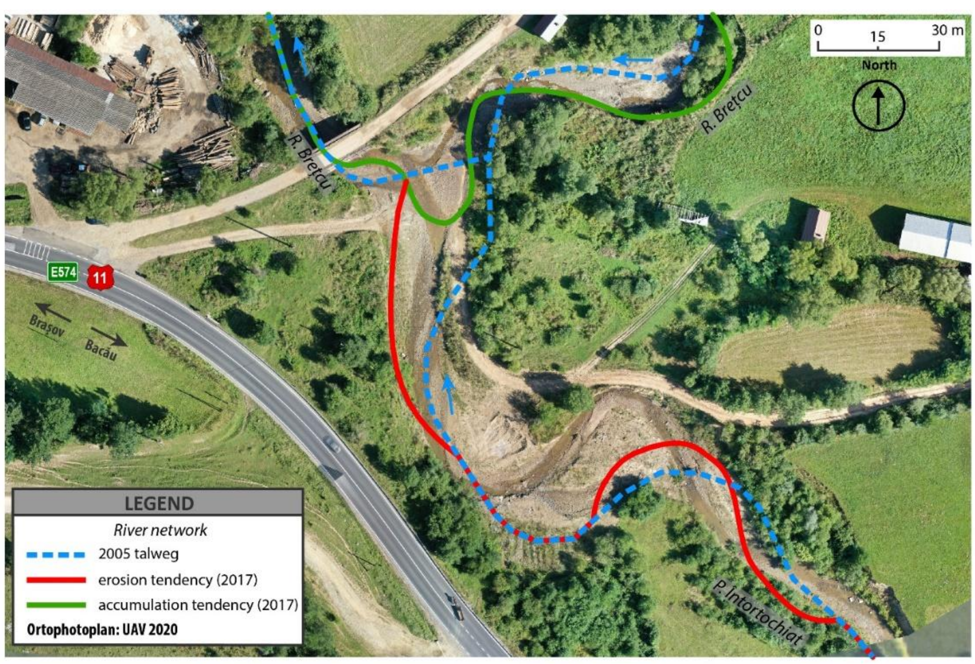

Figure 7. PârâulÎntortochiat river – erosion and accumulation tendency

The cartographic support is represented by the 2020 orthophotoplan obtained after mapping the area with UAV systems. The river shows a tendency of erosion, characterized by the straightening of the course, a fact that can also be observed following the comparison of the thalweg from 2005 with that of 2017, respectively 2020. In this sector we avoided drawing a highway alignment, given the fact that the result analysis indicates an intense dynamic of the two rivers. Also, taking into consideration that anthropic hydrographic interventions in confluence areas can negatively impact the cost-benefit ratio, we identified other areas for drafting a highway alignment in this area.

3.3 Leşunțul Mare river

Leşunțul Mare river (figure 8) in the confluence area with Oituz River was chosen for data validation mainly because due to other geomorphologic and anthropic constrains. Also, it is the only area that can be used for drafting a highway alignment in a sustainable manner due to other geomorphological constrains.

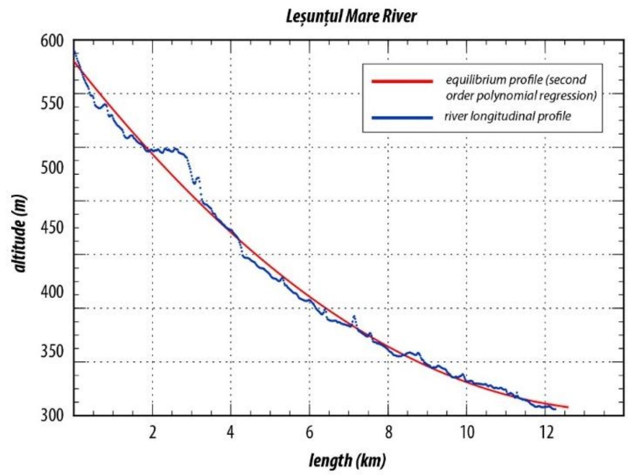

Figure 8. Polynomial regression analysis for Leşunțul Mare river

The tendency of erosion and course straightening is obvious, this being easily identified following the comparison of the river bed in 2005, 2017 and 2020. This was also determined by the fact that R. Oituz in the area of confluence Leşunțul Mare was identified with a strong erosive character on its banks following accumulations of sedimentary material. It can be seen on the 2020 orthophotoplan that the accumulation tendency of R. Oituz caused a very high pressure on the left bank, endangered the stability of some houses, as well as the national road DN11, a fact for which the course was channelled and a concrete retaining wall was implemented by local authorities (figure 9). This proves once again that the results of the proposed analysis can identify, in early stages, river erosion potential that can cause material damage, including damages of transport infrastructure.

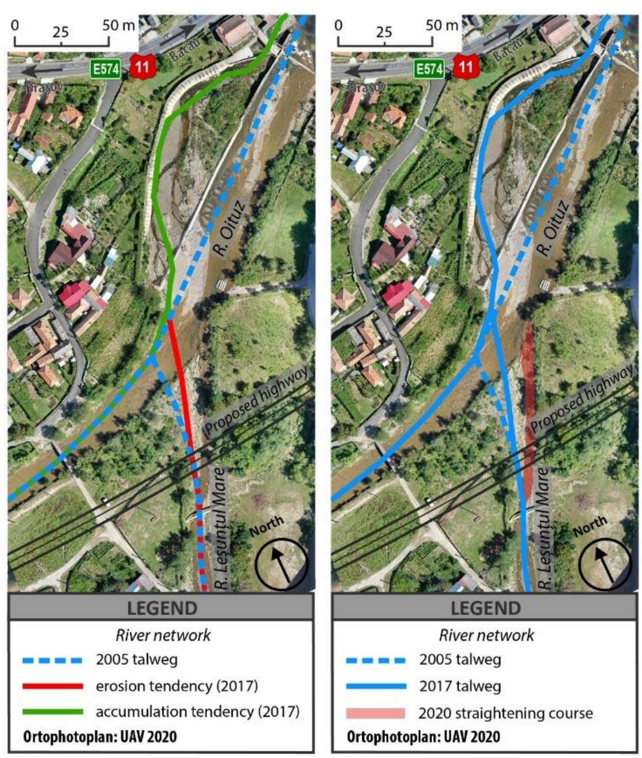

Figure 9. Leşunțul Mare river – erosion and accumulation tendency

Even though in the case of the analysis presented previously, for the confluence area of the Brețcu River with PârâulIntortochiat and the Oituz River (in the east of the Oituz town) we were able to identify other stable areas in order to propose an alignment of the Braşov -Bacău highway, in the confluence area of the Leşunțul Mare with the Oituz, we could not identify another favourable area due to the multitude of restrictive elements.

Thus, in this area, the Leșunțul Mare shows a strong erosion tendency in the confluence sector, which is also corroborated with the accumulated material (alluvial cone) in the confluence area that creates a constant movement of the point of contact between the two rivers. Furthermore, the area identified with the accumulative character of the R. Oituz, downstream of the confluence, is characterized by a strong sedimentation that, over time, determined the creation of a branch that produced a strong erosion of the concave bank. This led the local authorities to channelize the river in this sector and strengthen the left bank. Considering the fact that this area could not be avoided, we proposed a 50 m embankment sector for the highway and the extension of the regularization works and the development of the right bank, prone to erosion.

4.Discussions and conclusions

Proposed methodology represents an analysis model which can provide geographically substantiated quantitative solutions for highway planning. This new approach, as a part of a multi-criteria analysis, has proven to be a solid study for early stages of road infrastructure development. Polynomial regression has proven to be a powerful tool in order to establish the ideal longitudinal profile of a river, or its equilibrium profile. Based on that ideal profile, research team could rapidly identify, for a large study area, prediction for erosion or accumulation river sectors that can potentially influence a road infrastructure project (from planning up to the implementation). Also, due to identification of erosion or accumulation river sectors, even at an infrastructure planning level, research team could estimate environmental and financial impact of using certain areas that are prone to erosion, using a sensitivity analysis. Currently, research team is working in order to further develop this methodology with other validation criteria, such as lithology properties, especially rock hardness. This methodology as a part of multi-criteria analysis and sensitivity analysis can be used at a governmental or regional decision-making level because it provides objective information on which scientifically substantiated choices can be made.

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