Improving flood risk map accuracy using high-density LiDAR data and the HEC-RAS river analysis system: A case study from north-eastern Romania

Cristian C. Stoleriu | Andrei Urzica | Alin Mihu-Pintilie

1Department of Geography, Faculty of Geography and Geology, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
2Department of Science Research, Institute for Interdisciplinary Research, Alexandru Ioan Cuza University of Iasi, Iaşi, Romania

Abstract
North-eastern Romania is frequently affected by storms that produce annual floods with catastrophic effects upon agriculture areas. The implementation of the 2007/60/ EC Directive, which aims, among other things, to assess and manage flood risk, is currently being carried out by means of rough hydrological risk maps. Additionally, the limits of the potentially floodable areas generated on digital elevation models with 30 points/m resolution (SRTM) do not correspond to the current topographic reality. Three tests (T1, T2, and T3) for modelling the floodplains and the comparative assessment of potential damages in the case of 30 localities in the study area (Bașeșu River basin) were carried out in this study. The results indicate that official data (T1) underestimate potential damage in the case of hydrological events with a recurrence interval probability of 1% (100-year). The T2 [1%] (100-year) results also highlight the role of hydro-technical works in mitigating floods. In T3, the hydrological risk areas were generated with an accuracy of 0.5 m, evaluating the probable damage in cases of events with probabilities of 3% (33.3-year), 1% (100-year), and 0.1% (1,000-year) recurrence intervals. The accuracy of the official hydrological hazard maps (T1) was improved using high-density LiDAR data and HEC-RAS software (T3).

KEYWORDS
flood risk zone, GIS, HEC-RAS, LiDAR, plateau-plain transition, vulnerability assessment

1 INTRODUCTION
Floods are the most common natural hazards on Earth and cause most of the material and human losses (Brinke, Knoop, Muiiwijk, & Ligtvoet, 2017; Kelman, Gaillard, & Mercer, 2015; Whitfield, 2012). In Europe, the literature indicates a significant increase in risk phenomena associated with the maximum discharge due to climate change (Alfieri et al., 2014; Bloschl et al., 2017; Hall et al., 2014, 2015; Kundzewicz, Pinskwar, & Brakenridge, 2013; Schneider, Laize, Acreman, & Flörke, 2013). The plateau-plain transition zone of Romania faces this periodic phenomenon, especially at the end of winter, as a result of the sudden melting of snow, as well as during the hot season (spring–summer) due to torrential rainfall (Romanescu et al., 2018a). Most of the time, natural factors that lead to floods are increased by anthropogenic activities with a negative impact on the environment. Among these, uncontrolled deforestation favours

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the reduction in the interception, retention and infiltration of water, while emphasising soil erosion on slopes (Romanescu, Hapciuc, Minea, & Iosub, 2018b). Additionally, the increase in the impact of floods on human communities is due to the location of dwellings in the floodplain area, the construction of embankments that border the rivers over which transport routes overlap, the reduction in active seepage through inefficient hydro-technical works, and so forth. The most violent hydrological events of this kind occur mainly in northern and eastern Romania (Mihu-Pintilie, 2018; Romanescu, Cimpianu, Mihu-Pintilie, & Stoleriu, 2017).

At the regional level, the Moldavian Plain often faces floods as a consequence of its overlapping of two large hydrographic basins, the Siret River (mountain–plateau transition zone) (Romanescu, 2009; Romanescu, Hapciuc, et al., 2018b; Romanescu, Mihu-Pintilie, et al., 2018a; Romanescu & Nistor, 2011) and the Prut River (plateau-plain transition zone) (Romanescu & Stoleriu, 2013a, 2013b; Romanescu, Stoleriu, & Romanescu, 2011; Romanescu, Zaharia, & Stoleriu, 2012). The first recorded flood event in this area dates back to 1895, when several rivers flooded and caused significant damage (Romanescu et al., 2011). With the implementation of a permanent monitoring system for the hydrological regime, the information related to the risk phenomena associated with the maximum discharge increased. Over the past three decades, the most devastating floods occurred in 1991, 2008, and 2010, affecting the Siret, Jijia, and Prut Rivers and causing significant material damage as well as the loss of 22 lives (Romanescu et al., 2017; Romanescu, Mihu-Pintilie, et al., 2018a; Romanescu & Stoleriu, 2017).

Currently, the development and implementation of a flood disaster management plan, as well as the development of hydrological risk maps for informing the population, have become more than a necessity. At the national level, most studies were conducted under programmes coordinated by the National Administration “Romanian Waters” and the National Institute of Hydrology and Water Management (Romania); their results can be viewed through WebGIS platforms (ANAR, 2014). The generation of these datasets was part of the small-scale implementation of the 2007/60/EC Directive, which aims to manage flood risk (Connor & Hiroki, 2005; de Moel, van Alphen, & Aerts, 2009; Demeritt, Nobert, Clark, & Pappenberger, 2013; Müller, 2013; Parker & Fordham, 1996). At the local level, the County Scheme of Defence Against Flooding (CSDAF) is another programme for flood defence plans. However, the risk maps and the limits of the potentially floodable areas generated by digital elevation models (DEMs with 30 point/m resolution) (SRTM) do not have high accuracy and do not reflect the topographic reality. The degrees of generalisation of the predictive models either underestimate hydrological risk assessment or exaggerate flood extent without incorporating the role of storage areas in flood mitigation.

In this context, the main objective of this study is to improve the accuracy of the flood risk maps using high-density LiDAR data and various hydraulic modelling methods in GIS-dedicated software (HEC-RAS—Hydrological Engineering-River Analysis System). In the literature, modelling of floods with different recurrence intervals has been successfully applied for multiple scenarios (Ghanbarpour, Salimi, & Hipel, 2013; Jonkman, Vrijling, & Vrouwenvelder, 2008; Kaoje, 2016; Kappes, Papatheoma-Köhle, & Keiler, 2012; Kourgialas & Karatzas, 2011; Kourgialas, Karatzas, & Nikolaidis, 2012; Li & Heap, 2013; Merwade, Cook, & Coonrod, 2008; Nandala, 2009; Nandala & Ratnayake, 2011; Patel & Gundaliya, 2016). In the territory of Romania, the small-scale modelling of floods using GIS techniques has been a point of interest for several researchers (Arghiu, Ozunu, Samara, & Rosian, 2014; Costache, Pravalie, Mitof, & Popescu, 2015; Salit, Zaharia, & Beltrando, 2013; Zaharia, Costache, Pravalie, & Minea, 2015), but for the Moldavian Plain, there are relatively few studies, and they only have a regional character (Enea, Urzica, & Breaban, 2018; Romanescu et al., 2017; Romanescu, Hapciuc, et al., 2018b; SMIS-CSNR 17945, 2013). The present experiment is based on three tests of modelling the flood extent areas and the comparative assessment of the potential damages applied to the floodplain of the Baseu River (NE of the Moldavian Plain). The results obtained contribute to the small-scale assessment of the flood risk in the plateau-plain transition zone of Romania.

2 | STUDY AREA

2.1 | Hydro-geomorphological framework

The hydrographic basin of the Baseu River is located in north-eastern Romania. The total area is 967 km², which represents 4.1% of the area of the Moldavian Plateau. From a morphological point of view, 90% of the analysed territory overlaps with the Moldavian Plain and 10% with the Suceava Plateau represented by the Iaînești Hills. The general morphostructure of the basin is of the monoclinic type with relief shapes of the cuesta type. The altitude varies between 54 m (Baseu floodplain) and 318 m (Pădurea Cristinești hill). The dominant altitude class is between 150 and 200 m (>30%). The asymmetry of the Baseului valley requires an uneven development of the hydrographical basin; the left slope accounts for 80% of the territory of the analysed area. The shape ratio is 0.27 and is a consequence of the dendritic development of the potential drainage network (Figure 1).

Local geological conditions are characterised by the presence of recent alluvial floodplains accumulated over a succession of sandy clay deposits, 200–300 m thick, and thin
layers (2–3 m thick) of limestone and sandstone of Volhinian and Basarabian age (lower and medium Sarmatian deposits). The lithological factors induce a relief energy ranging from 0.02 m/km² in the basin floodplain near the confluence with the Prut River to 141 m/km² in the hilly area north-west of the study area. The average declivity is 4.61°. The dominant slope class is between 0° and 3° (40% of the total area) and corresponds to the floodplain, inter-fluvial, and structural plateau sectors. The maximum value is between 30° and 35° and corresponds to the landslides and gravitational processes, as well as to the active river banks consumed by erosion.

The Bașeu River springs from a relative altitude of 260 m, is 92.6 km long and is one of the most important tributaries of the Prut River (after the Jijia River). The total length of the hydrographic network is 1,101.9 km, with an average density of 1.13 km/km² (maximum density is 5.1 km/km²). Climate conditions control 60% of the water flow rate, often overtaken in transition seasons and in periods with maximum rainfall. At the level of the analysed territory, the average air temperature values are between 7.7 and 9.6°C. The annual average precipitation is between 450 and 624 mm, with peak values occurring in the high basin areas. The groundwater contributes between 30 and 40% of the average annual flow. Between 1966 and 2016, the multi-annual average flow rate at Stefanesti station (south of the basin) was 1.6 m³/s, with fluctuations between 0.1 m³/s (2016) and 6.9 m³/s (1969). The historical flow was recorded in July 1969 and was 330 m³/s. Negative hydrological events associated with the maximum discharge occurred in 1973 (100 m³/s), 1979 (83.1 m³/s), 1988 (73 m³/s), 1996 (65.2 m³/s), 2005 (124 m³/s), and 2010 (77.3 m³/s). An important role in modelling floods and their manifestation is accounting for storage areas. On the course of the Bașeu River are 9 storage areas placed on the upper and the middle river course and used either for irrigation or for fish farming. The storage areas, in addition to the economic and industrial role, also have a protective role for the settlements located in the lower part of the lakes.

2.2 | Habitation in the Bașeu River basin

There are 70 human settlements within the hydrographic basin of the Bașeu River, most of which are concentrated along the valleys. Of the total number of settlements, 67 are rural settlements, and only 3 are urban settlements: Darabani, Săveni, and Ștefănești. According to the latest national census in 2011, the total population was 79,000 inhabitants, and the density was 817 ppl/km². Of these, only 30 human settlements are located in the sector of the Bașeu River floodplain, and only these will be analysed from the perspective of the vulnerability to the hydrological hazards associated with the maximum discharge. The total area of these localities is 37.55 km², with a population of 36,914 inhabitants and an average density of 840 ppl/km² (Table 1).

Regarding the flood manifestations on the territory of the studied settlements within the Bașeu hydrographic basin, the most important event took place in 1969 amid abundant precipitation generated by the intense activity of the Azoric anticyclone on the territory of Romania (Figure 2a). The duration of the flood was 125 hr, and the maximum recorded flow was 330 m³ (flow rate: 1.6 m³/s) (Figure 2b). To this event, one can also add the historical flood that occurred in the common floodplain of the Bașeu and Prut Rivers in 2008, which affected the territories of Stanca (S26), Stefanesti (S27), Baduți (S28), Bobulești (S29), and Romanesti (S30) (Figure 2c). Being a profoundly rural area
dependent on subsistence farming, the most significant damage was recorded in this sector. Additionally, these events must also be related to the fact that the studied region is one of the least developed economies in the EU, making the impact of natural hazards a major one on the resilience of the population.

### TABLE 1 Settlements code and habitation features within Bașeau River basin

| Code | Settlement | Surface (km²) | Population (no.ppl) | Population density (ppl/km²) |
|------|------------|---------------|---------------------|----------------------------|
| S1   | Alba       | 3.58          | 1,406               | 393                        |
| S2   | Bașeù      | 1.08          | 539                 | 499                        |
| S3   | Hudești    | 2.75          | 1,100               | 400                        |
| S4   | Havânna    | 4.18          | 2,823               | 675                        |
| S5   | Gârbeni    | 0.64          | 420                 | 656                        |
| S6   | Tătărași   | 1.14          | 797                 | 699                        |
| S7   | Balințî    | 0.67          | 396                 | 591                        |
| S8   | Niculea    | 0.13          | 41                  | 315                        |
| S9   | Negreni    | 1.09          | 909                 | 834                        |
| S10  | tuibieni   | 2.14          | 1,727               | 807                        |
| S11  | Chișcăreni | 0.61          | 495                 | 811                        |
| S12  | Sat Nou    | 0.28          | 124                 | 443                        |
| S13  | Petricani  | 0.97          | 645                 | 665                        |
| S14  | Sâveni     | 2.29          | 8,145               | 3,557                      |
| S15  | Vălăinești | 1.56          | 1,596               | 1,023                      |
| S16  | Bozieni    | 0.34          | 255                 | 750                        |
| S17  | Sărbi      | 1.04          | 1,064               | 1,023                      |
| S18  | Miron C.   | 0.83          | 472                 | 569                        |
| S19  | Slobozia   | 0.18          | 86                  | 478                        |
| S20  | Hâinești   | 1.28          | 1,127               | 880                        |
| S21  | Moara J.   | 0.22          | 89                  | 405                        |
| S22  | Mihălaşenți| 1.07          | 743                 | 694                        |
| S23  | Negrești   | 0.32          | 300                 | 938                        |
| S24  | Păun       | 0.41          | 289                 | 705                        |
| S25  | Năstase    | 0.31          | 183                 | 590                        |
| S26  | Stânga     | 1.05          | 812                 | 773                        |
| S27  | Ștefănești | 2.42          | 6,630               | 2,740                      |
| S28  | Bădiuți    | 1.08          | 985                 | 912                        |
| S29  | Bobulești  | 2.06          | 1,322               | 642                        |
| S30  | Românești  | 1.83          | 1,394               | 762                        |

3 | DATABASE AND METHODS

The experiment is based on three flood modelling tests with 3% (33-year), 1% (100-year), and 0.1% (1,000-year) recurrence intervals: (a) Test 1 (T1) used the 1% (100-year) flood extent generated by the CSDAF based on DEMs with 30 point/m resolution—SRTM; (b) Test 2 (T2) used the 1% (100-year) flood extent generated by high-density LiDAR data (1 point/m resolution) and HEC-RAS, but without taking into account the role of hydro-technical works in flood hazard modelling; and (c) Test 3 (T3) used the 0.1% (1,000-year), 1% (100-year), and 3% (33.33-year) recurrence intervals where hydro-technical works have been incorporated into the hydraulic model. To highlight differences between SRTM (T1) and LiDAR (T2 and T3), only the 1% (100-year) recurrence interval for each test was used.
Additionally, (b) a flood vulnerability assessment for the 30 settlements in the study area was conducted using T3 with 0.1% (1,000-year), 1% (100-year), and 3% (33.33-year) recurrence intervals.

3.1 Climate and hydrological data

The climatic data series covers a time frame of 50 years (1966–2016) of monitoring the air temperature and daily rainfall at 12 pluviometric stations, 3 of which are located inside the hydrographic basin of the Baseu River (Havarna, Cal Alb, Avrameni) and 9 in proximity to the area of study (Figure 3a). The database was made available by the Prut-Bîrlad Water Administration, Iasi and the National Meteorological Agency, Bucharest. The spatial distribution model of annual average precipitation was generated in ArcGIS 10.2 by using residual kriging (Bissolli, Friedrich, Rapp, & Ziese, 2011; Bostan, Heuvelink, & Akçayrek, 2012; Li & Heap, 2013; Sun, Minasny, & McBratney, 2012; Wu & Li, 2013; Zhu & Lin, 2010). Compared to classical interpolation patterns, this method involves the use of additional spatial variables (e.g., altitude, latitude), combining the multiple regression with ordinary kriging (Equation 1) as follows:

\[ y = a + b_1 x_1 + b_2 x_2 \]  

where \( y \) is the average of annual rainfall, \( x_1 \) is altitude, and \( x_2 \) latitude.

The hydrological data were obtained from the Prut-Bîrlad Water Administration, Iasi. These data sum up information on the flow and the levels recorded at two secondary gauging stations (\( S_G \)) and a main gauging station (\( M_G \)) located on the Baseu River: \( S_G1 \) Havârna—monitoring period 31 years (1969–2000), \( S_G2 \) Ştiubieni—monitoring period 17 years (1980–1997), and \( M_G3 \) Ştefăneşti—monitoring period 50 years (1966–2016). Determining the flow rate corresponding to the probabilities of exceeding 0.1, 1, and 3% statistical calculations based on the flows recorded at the three gauging stations was necessary. The calculations consisted of determining the probability of empirical overflow according to Weibull’s formula (Equation 2) and the probability of occurrence of unregistered flows based on Person III (Equation 3) (Table 2):

\[ P_i^\% = i/(n + 1) \times 100 \]  
\[ Q_{p^\%} = Q_{avg} \times (1 + C_v \times \Phi_{p^\%}) \]

where \( P_i^\% \) is the probability of the occurrence of a measured flow, \( i \) is the order number of the orderly increasing flow, and \( n \) is the total number of terms of the string.

\[ Q_{p^\%} \] is the recurrence interval flow, \( Q_{avg} \) is the mean flow, \( C_v \) is the coefficient of variation, and \( \Phi_{p^\%} \) is the order of the recurrence interval curve for \( C_v = 1 \).

3.2 LiDAR DEM data

The DEM used to generate the HEC-RAS model was constructed by spatial processing in the GIS software (ArcGIS
10.2) of 4,676 LiDAR raster files generated in the national project SMIS-CSNR No. 17945: Works to reduce flood risk in Prut-Bîrlad River basin by Prut-Bîrlad Water Administration. A raster dataset was converted into a geodatabase to merge the LiDAR raster files. A DEM with a resolution of 0.5 m/pixel was filtered using flow direction, sink, and fill tools to reduce the errors generated by merging the .tiff files. Additionally, the raster filtering aimed to identify the null values and correct them according to the topography. The difference in resolution between the SRTM and the LiDAR elevation model is highlighted in Figure 3b,c.

3.3 | HEC-RAS model

In obtaining the flood hazard maps HEC-RAS 5.0.1 (Hydrologic Engineering Centers—River Analysis System), software developed by the U.S. Army Corps of Engineers in 1993 and HEC-GeoRAS, an auxiliary module for ArcGIS 10.2, were used. The open source software has multiple applications in hydro-sciences, such as one-dimensional and two-dimensional water flow simulation, space–time evolution of floods, and sediment transport modelling. Most commonly, this method is used for the statistical analysis of floodplain areas in small and medium river basins (Costache et al., 2015; Kaoje, 2016; Merwade et al., 2008; Patel & Gundaliya, 2016; Zaharia et al., 2015).

The pre-processing step involved creation of the thalweg, banks, flowpaths, and cross-section vector layers and the generation of the attribute table corresponding to each thematic layer, namely, length, hydroID, station, river's name, reach, left bank, right bank, left length, channel length, and right length. All the thematic layers were manually created in ArcGIS 10.2 software based on orthophotos and DEMs with a resolution of 0.5 m/pixel (LiDAR). More than 1,900 cross-sections with 20–200 m intervals between them were manually digitised based on hydro-geomorphological rules: digitization of the thalweg was made from springs to spill, for the determination of the flow direction; the digitization of the banks was done starting with the left bank, followed by the right bank; the digitization of the cross-sections was made from springs to spill, from the left bank to the right bank, perpendicular to the thalweg, and intersecting the drainage direction only once, without intersecting with each other and not extending longer than the DEM.

The processing step involved exporting to the HEC-RAS software and introducing the parameters required to run the flood simulation. The first parameter that was introduced was the one related to the roughness coefficient (Manning’s roughness coefficient), which has been calculated for each intersection between the cross-sections, thalweg, and banks (Table 3). For hydrological data, the flow rate was calculated corresponding to the 0.1% (430.0 m$^3$/s), 1% (248.1 m$^3$/s), and 3% (166.8 m$^3$/s) recurrence intervals using Weibull’s (2) and the Person Type III (3) equations (Table 2). The simulation was computed with steady flow data, and the boundary condition was set for normal depth with a value of 0.71. The post-processing step involved exporting the HEC-RAS results to the ArcGIS software and generating the flood areas with 0.1% (1,000-year), 1% (100-year), and 3% (33.33-year) recurrence intervals (Figure 3d). The validation process was performed by comparing the real discharge (ABA Prut-Bîrlad data) and computed discharge (HEC-RAS data) hydrographs at all the gauge stations (Figure 3e).

3.4 | Land use data

The land use polygon features, based on orthophotos collected in 2015, were obtained using on-screen digitising within the TNTMips software. The resulting layer contained 78,699 polygons with a 20 m$^2$ minimum mapping unit. All these features were classified into 27 land use categories according to the National Agency for Cadastre and Land
Registration of Romania: house, blocks, attachments building, yard, leisure park, administrative and cultural building, industrial building, railroad, exploitation road, local road, county road, national road, main street, secondary street, arable land, orchard, vineyard, grassland, forest, forest vegetation, shrubbery, unproductive land, degraded land, landfill, stream, lake and reservoir, and wetland.

4 | RESULTS AND DISCUSSION

4.1 | Probabilistic delineation of flood-prone areas

The present experiment was based on three modelling flood tests: T1 [1%] (SRTM based), T2 [1%] (LiDAR based), and T3 [3%; 1%; 0.1%] (LiDAR based). In the case of T1, the flooded area with the 1% recurrence interval provided by the CSDAF was used. The T1 [1%] flood extent was converted from an analogue format into a vector format using ArcGIS software. Table 4 shows that the results obtained after the intersection of the 1% flood model (CSDAF) and the vector layer containing the land use show an underestimated situation. This can also be attributed to the fact that the flood limit was drawn both on a DEM with a spatial resolution of 30 m/pixel (SRTM) as well as on topographic maps 1:25000 (Ed. 1975) used as support mapping for extracting hydro-geomorphological parameters (hydrographic network, elevation, slope, etc.).

In the case of T2 [1%], the results obtained show an exaggerated situation of potentially flooded areas. This is due to the numerous aquatic accumulations (e.g., reservoirs, ponds) and hydro-technical developments (e.g., dams, channels, polders) along the Bașeu River that were not introduced into the simulation model and did not take into account the volume of water they could retain in case of a flood with a probability of occurring once every 100 years. This test was conducted to highlight the role of the dams in mitigating floods and to indicate the flood hazard before the hydro-technical works (Figure 4a).

In the last test, T3 [1%] presents the real situation of the hydrological model, taking into account both the standard data used by HEC-RAS related to debits, precipitations, and morphology based on the LiDAR model, as well the storage areas along the river basin (Figure 4a). Based on the volumes of the lakes, their retention capacity was calculated in case of a flood. The difference between T2 [1%] and T3 [1%] can be seen in Figure 4b, where the Hânești reservoir takes a consistent flow, reducing the extent of the flood, and thus protecting the settlements on the Baseu River that are downstream from the reservoir (S19-Slobozia and S20-Hanesti).

4.2 | Flood hazard assessment with 1% (100-year) recurrence interval based on the T1, T2, and T3 results

Via the official flood areas obtained within the CSDAF project T1 [1%] (SRTM based) and the two models generated using the HEC-RAS software, T2 [1%] and T3 [1%] (LiDAR based), as well as the vector layer, which includes land use from the year 2015, a clear overview of the use of a complete and complex dataset to map the flood

### Table 4

| Code | Settlement | T1 [1%] (ha) | T2 [1%] (ha) | T3 [1%] (ha) |
|------|------------|-------------|-------------|-------------|
| S1   | Alba       | 33.01       | 49.11       | 33.25       |
| S2   | Bașeú      | 3.57        | 7.44        | 3.66        |
| S3   | Hudești    | 5.11        | 5.47        | 1.82        |
| S4   | Havârna    | 2.41        | 10.99       | 8.36        |
| S5   | Gârbeni    | 1.11        | 12.65       | 9.16        |
| S6   | Tâtărașeni | 7.12        | 12.76       | 8.86        |
| S7   | Balniți    | 7.74        | 12.01       | 7.11        |
| S8   | Niculea    | 0.15        | 0.35        | 0.19        |
| S9   | Negreni    | 3.93        | 4.58        | 3.94        |
| S10  | Știubieni  | 1.97        | 7.37        | 2.30        |
| S11  | Chișcăreni | 1.62        | 5.78        | 0.87        |
| S12  | Sat Nou    | —           | 9.53        | 2.85        |
| S13  | Petricani  | 2.57        | 21.12       | 6.38        |
| S14  | Șâveni     | 5.12        | 8.24        | 3.62        |
| S15  | Vlăsinești | 0.05        | 7.54        | 1.39        |
| S16  | Bozieni    | 2.38        | 7.80        | 4.99        |
| S17  | Șârbi      | 1.07        | 12.23       | 6.78        |
| S18  | Miron C.   | 0.90        | 4.73        | 3.70        |
| S19  | Slobozia   | 2.14        | 1.47        | —           |
| S20  | Hânești    | 8.86        | 14.14       | 1.89        |
| S21  | Moara J.   | 0.67        | 1.94        | 0.19        |
| S22  | Mihălașeni | 1.62        | 0.60        | —           |
| S23  | Negrești   | 2.87        | 0.58        | 0.06        |
| S24  | Paun       | 6.97        | 9.57        | 1.31        |
| S25  | Năstase    | 0.32        | 2.00        | 0.25        |
| S26  | Ștâncea    | —           | 11.23       | 0.97        |
| S27  | Ștefănești | —           | 11.25       | 7.94        |
| S28  | Bădiuți    | —           | 44.60       | 6.91        |
| S29  | Bobulești  | 0.38        | 7.10        | 1.86        |
| S30  | Românești  | 6.06        | 20.56       | 2.52        |

Note: The significant differences between values are highlighted with bold.
hazard along the Baseu River has been outlined. Thus, according to the T1 flood extent [1%], out of the total of 30 settlements adjacent to the Baseu River, 26 are potentially affected by the floods, and only four of them have no significant material losses. The most affected settlement is Alba (S1), located in the upper course of the Baseu River, with a potentially flooded area of 33.01 ha. Among the least affected settlements are the localities of Gârbeni (S5—1.11 ha), Niculcea (S8—0.15 ha), Vlăsinești (S15—0.05 ha), Năstase (S25—0.32 ha), and Bobulești (S29—0.38 ha). The settlements whose safety was underestimated are located both in the middle course of the Baseu River, namely, the Sat Nou (S12), and in the inferior course, such as Stâncea (S26), Ștefănești (S27), and Bădiuți (S28) (Table 4).

In the case of T2 [1%], the most affected settlement, as in the case of T1 [1%], is Alba (S1), with a potentially flooded area of 49.11 ha. The second most affected settlement is Bădiuți (S29), whose geographical position places it near the confluence of the Baseu River with the Prut River. The total area affected is 44.60 ha. Other strongly affected areas in T2 [1%] are Petricani (S13—21.12 ha) and Romanesti (S30—20.56 ha). The least affected settlements are located both in the upper course, Niculcea-S8 (0.35 ha), and in the lower course of the Baseu River, Mihălașeni-S22 (0.60 ha) and Negrești-S23 (0.58) (Table 4).

According to T3 [1%], the most affected settlement remains Alba (S1—33.25 ha). Additionally, 19 settlements have areas less than 5 ha potentially affected by floods, for example, Baseu (S2—3.66 ha), Niculcea (S8—0.19 ha), Șâveni (S14—3.62 ha), Bozieni (S16—4.99 ha), Păun (S24—1.31 ha), and Românești (S30—2.52); 8 of these have potentially flooded areas less than 10 ha, for example, Havarna (S4—8.36 ha), Șâveni (S5—9.16), Petricani (S13—6.38 ha), Bădiuți (S28—6.91 ha). Similar to T2 [1%], there are also settlements that are not affected by the possible occurrence of a flood with a probability of occurrence once every 100 years. Their number is very low, with Slobozia (S19), located in the middle course of the Baseu River and Mihălașeni (S22) located in the middle-lower course of the river. The lack of affected areas for these two localities can be explained by the fact that they are located outside the floodable area of the Baseu River but also by the presence of the of Șâveni reservoir, which takes over the flood flow (Figure 4b).

When the three generated situations, T1 [1%], T2 [1%], and T3 [1%] are compared, very large differences are observed regarding the built-up areas potentially affected by the floods. As previously estimated, T1 [1%] underestimates the vulnerability of localities along the Baseu River (Figure 5a), T2 [1%] overestimates it considerably (Figure 5b), and T3 [1%] indicates the actual situation of areas potentially affected by floods (Figure 5c). The T3 [1%] situation is also validated by the Slobozia locality (S19) and Mihălașeni locality (S22), which, due to their geographical positions, are protected from floods. The most significant differences between the three situations in terms of areas potentially affected by floods are recorded in the settlements Havarna (S4), Șâveni (S5), Sat Nou (S12), Vlăsinești (S15), Stâncea (S26), Ștefănești (S27), and Bădiuți (S28) (Figure 5d). This fact is also reflected in the populations.
potentially affected by the floods. The upstream cumulative upward trend indicates that T1 [1%] and T3 [1%] show a similar distribution, but T1 [1%] underestimates the number of potentially affected populations due to the coarse spatial database (SRTM) used to generate the model. T2 [1%] is far beyond the real distribution scale of the potentially affected population by flood events and is invalid (Figure 5e).

The process of properly assessing flood hazard is dependent on the accuracy of the hydro-morphological and climatic data used. The management of hydrological risk areas must be based on flood patterns as close as possible to topographical reality. If the flood extent model underestimates the potentially affected areas, as in the case of T1 [1%], then material losses and considerable human casualties can be recorded. At the same time, if the flood extent model overrates the potentially affected areas, as in the case of T2 [1%], then the cost of landscaping against hydrological risks would increase considerably. Improving the accuracy of predictive models based on high-density LiDAR data and the HEC-RAS software, as in the case of T3 [1%], contributes significantly to the realistic assessment of vulnerability of the territory and to the correct management of risk situations. For this reason, the assessment of flood hazard in the study area will be based only on T3 with 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals.
4.3 | Flood hazard assessment with 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals based on LiDAR and HEC-RAS data (T3)

Based on LiDAR data and the HEC-RAS software, the flood hazard assessment was computed using T3 [0.1%], T3 [1%], and T3 [3%] (Table 5). The surface area affected by floods in the case of T3 [0.1%] (1,000-year recurrence interval) is 170.33 ha (0.17% of the study area), where highly affected settlements include (S1) Alba (37.7 ha), (S5) Gârbeni (10.2 ha), (S13) Petricani (11.0 ha), and (S27) Ștefănești (3.2 ha); little-affected settlements include (S8) Niculce, (S21) Moare Jorii and (S25) Nastase. Due to their geographical positions, the (S19) Slobozia and (S22) Mihăilești settlements are not affected by floods according to the 0.1% recurrence interval (Figure 6).

According to T3 [1%] (100-year recurrence interval), over 133.09 ha (13% of the study area) are potentially affected by flood events (Table 5). The most affected localities are the same as in the case of the 0.1% recurrence interval ((S1) Alba (33.25 ha), (S5) Gârbeni (9.16 ha), (S13) Petricani (6.38 ha), and (S27) Ștefănești (7.94 ha)), but the areas are diminished. The settlements (S8) Niculce, (S21) Moara Jorii, and (S23) Negrești (<0.2 ha) are relatively less affected by flood hazards (Figure 7).

In the case of T3 [3%] (33.3-year recurrence interval), the total affected area is 116 ha (11% of the study area) (Table 5). Because the (S1) Alba settlement is not protected by man-made reservoirs with flood mitigation roles, it is the most vulnerable village (31.38 ha). Additionally, the (S5) Gârbeni and (S27) Ștefănești settlements have middle-low vulnerability due to local morphology. The vulnerability of the (S21) Moara Jorii, (S23) Negrești, and (S25) Năstase settlements is minimal (<0.3 ha), and that in the (S19) Slobozia and (S22) Mihăilești is null (Figure 8).

4.4 | Flood hazards with 0.1% (1,000-year), 1% (100-year) and 3% (33.3-year) recurrence intervals within the agricultural area

In the plateau-plain transition areas in the NE of Romania, the most affected areas are the agricultural ones, and the floods causing significant economic damage due to the excess water compromised the crops. Being a deeply rural area inhabited by a population dependent on subsistence farming, the area of study is frequently affected by extreme hydrological phenomena. Flood hazard assessment was conducted on four land use categories: arable land, vineyards and orchards, forest vegetation and grassland. Among these, the most affected categories are the arable land most commonly cultivated with wheat and maize. According to T3 [3%], the agricultural land potentially affected by floods in the vicinity of the village (S1) Alba exceeds 15 ha. Other localities with vulnerable agricultural land (>5 ha) are (S4) Havarna, (S5) Gârbeni, (S6) Tatarsani, and (S7) Balinti. In addition, the settlements located in the common floodplain of the Baseu and Prut Rivers (S24–S30) have more than 30 ha of arable land in the hydrological risk area (Figure 9a). Vineyards and orchards are another category of agricultural areas potentially affected by floods. The most vulnerable vineyards are located in localities such as (S6) Ștefănești, (S7) Balinti, (S18) Miron Costin, (S27)
**FIGURE 6** Flood hazard maps for each settlement (S1–S9, see Table 1) in the upper area of Bașeu River basin

**FIGURE 7** Flood hazard maps for each settlement (S10–S21, see Table 1) in the middle area of Bașeu River basin
Ştefăneşti, and (S28) Bădiuți, with an average flooded area between 0.1 and 0.3 ha (Figure 9b).

Regarding the forest vegetation, out of the 30 localities along the Băseu River, 28 of them have areas with vulnerable forest vegetation. The largest affected areas are found in (S1) Alba, (S4) Havarna, (S17) Sârbi, (S27) Ştefăneşti, and (28) Bădiuți (Figure 9c). Even if in the event of catastrophic floods (1 or 0.1%), the damage would be lower than that in the case of the agricultural land; the floods can significantly disrupt local and regional socio-economic activities. The same can be said about the grassland in the researched area, which, in the event of significant hydrological events, would incur disruption to the zootechnical activity specific to the area. From this perspective, 12 ha of pastures in the (S1) Alba area, a place with a very high density of sheep farming facilities, should record the most significant losses (Figure 9d).

4.5 | Flood hazards with 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals within the built-up area

The total built area of the 30 localities along the Băseu River is 38.25 km². According to T3 [0.1%], 1.703 km² of the built space (4.45% of the total) is in the floodable area; according to T3 [1%], 1.331 km² (3.47% of the total) is in the floodable area; and according to T3 [3%], 1.160 km² (3.03% of the total) is in the vulnerable area (Figure 10a,b). The cumulative curve of areas potentially affected by floods shows small differences between the flood extent with 1 and 3% recurrence intervals and a more significant increase in the case of the 0.1% recurrence interval. This distribution is generated by the shape of the hydrographic basin, the pluviometric regime and, above all, the heterogeneous character of the population concentration along the Baseu River (Figure 10c).

Of the total built area, the settlement with the most vulnerable houses is (S5) Gârbeni: T3 [3%] (25 houses), T3 [1%] (29 houses), and T3 [0.1%] (34 houses). Additionally, the localities (S5) Gârbeni, (S6) Tătărășeni, and (S7) Balinți from the upper course of the Baseu River, (S17) Sârbi from the middle part of the basin, and (S27) Ştefănești and (S28) Bădiuți from the lower sector of the common floodplain of the Baseu and Prut Rivers have a significant number of dwellings that are subject to hydrological risk (between 10 and 30 houses/settlement) (Figure 11a). To this end, a significant number of special annexes are added, generally livestock stables and farm storage stalls, which may be
affected by floods. From this point of view, the highest losses can be recorded within the administrative territory of the localities (S5) Gârbeni, (S6) Tătărașeni, (S17) Sârbi, and (S27) Ștefănești (Figure 11b).

As a predominantly rural area, the number of industrial buildings in the study area is very low. Only five factories and woodworking units are vulnerable in the case of the 0.1% recurrence interval flow and only two factories in the case of the 1 or 3% recurrence intervals. The locality (S18) Miron Costin has the highest number of industrial buildings exposed to the hazard, as well as the localities (S14) Săveni and (S30) Românești, but in a smaller percentage. Administrative-cultural buildings are the least exposed to hydrological risk.

**FIGURE 9** Flood hazard assessment based on T3 with 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals: (a) arable land, (b) orchards and vineyards, (c) forest vegetation, and (d) grassland within the administrative territory of each settlement.

**FIGURE 10** The boxplot showing the (a) T3 built up flooded areas based on (b) 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals. (c) Cumulative curve from upstream to downstream of potentially affected built up areas according to T3 with 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals.
However, in the event of a 0.1% recurrence interval flood, the school and church in (S12) Sat Nou would be flooded (Figure 11c).

From the point of view of the total areas occupied by buildings (Figure 12a) and yards (Figure 12b), the most vulnerable localities to hydrological hazard are (S5) Gârbeni,
(S6) Tătărași, (S17) Sârbi, (S27) Ștefănești, and (S28) Badiuti, which, in the event of a 0.1% recurrence interval event, would suffer significant damage (0.4 ha buildings/settlement; 1.1 ha yards/settlement). These values are especially important when it is desirable to quantify the probable damages, especially in the case of the areas occupied by buildings (Figure 12a).

Additionally, flood hazard assessment has taken into account the transport infrastructure. The largest surface of potentially flooded roads (1.5 ha) is found in the administrative territory of (S27) Ștefănești city. Other localities with vulnerable road infrastructure are (S1) Alba, (S5) Gârbeni, and (S6) Tătărași (Figure 13a). The street network exposed to floods corresponds to the settlements (S12) Sat Nou and (S14) Săveni. Thus, the surface of vulnerable roads in the (S12) Sat Nou is greater than 0.2 ha and greater than 0.1 ha in the case of (S14) Săveni city (Figure 13b).

5 | CONCLUSIONS

The present experiment was based on three modelling flood tests: T1 [1%] (SRTM based), T2 [1%] (LiDAR based), and T3 [3%; 1%; 0.1%] (LiDAR based). The main objective was to improve the accuracy of flood risk maps using high-density LiDAR data and various hydraulic modelling methods in GIS-dedicated software. When T1 [1%] generated based on SRTM data was compared with T3 [1%] generated based on the LiDAR data and the HEC-RAS methodology, the results indicate that LiDAR data improve the flood hazard assessment process. When the T2 [1%] results were compared with the T3 [1%] results, the role of man-made reservoirs in flood mitigation within the study area was highlighted. The secondary objective was to perform a high-accuracy assessment of flood hazards in the Bașeiu River basin using the validated results according to T3 with 0.1% (1,000-year), 1% (100-year), and 3% (33.3-year) recurrence intervals. The results indicate that in the case of a flood of 3% (33.3-year) recurrence interval, 112 ha are vulnerable to hydrological hazards, in the case of a flood of 1% (100-year) recurrence interval, 140 ha would be affected, and in the case of a flood with 0.1% (1,000-year) recurrence interval, ~170 ha would be under threat. The most affected land use category is arable land, given that the predominantly rural population is dependent on agriculture practised in the region. According to 1% flood extent areas, over 500 dwellings, annex buildings, yards and industrial and administrative buildings (schools, churches, etc.) are vulnerable to flood hazards, and more than 4,000 potentially threatened persons. Overall, the results obtained improve the accuracy of flood hazard maps and contribute to the small-scale delineation of flood-prone areas in the plateau-plain transition zone of Romania.

The HEC-RAS flow models and LiDAR DEMs prove to be the perfect combination methodology for flood hazard delineation due to their accurate representation of the complex hydraulic conditions found in a certain floodplain. For this reason, the SRTM data are no longer a solution for small-scale flood hazard assessment. On the other hand, the unavailability of high-resolution DEMs can result in underestimating the flood hazard and its dangers. However, a precise representation of reality is mandatory for accurate flood mapping processes in the context of climate change and modern societal development pressures and trends.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Andrei Urzica 🏢 https://orcid.org/0000-0002-8775-7932
Alin Mihu-Pintilie 🏢 https://orcid.org/0000-0002-1686-9558

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