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Changes in the Active Drainage Network and Their Impact on the Hydrological Response and Flood Risk Management Process: A Case Study for a Flysch Mountain Catchment

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Abstract: The active drainage network (ADN), as a dynamic component of a catchment, plays an important role in a catchment's functioning. Changes in the ADN are the most noticeable during extreme hydro-meteorological events, and they result from, among others, the incorporation of man-origin incisions into the ADN. Knowledge of the parameters of the "real" ADN is a key element in the field of catchment hydrology because the ADN affects the intensity of hydro-, geomorpho-, and biological processes. The goals of this study are to assess (1) the changes in the ADN during extreme hydro-meteorological events (with special attention paid to the human-induced impact on the ADN transformation) and (2) the consequences of the ADN changes on the hydrological response of a catchment and their impact on the flood hazard/risk management processes. The study was performed in a mountain catchment, prone to flash flood occurrences. The ADN was reconstructed with the use of ALS-LiDAR data using GIS tools, and the hydrological response was evaluated by using SCS-CN and GIUH models. The results revealed that the ADN functioning during heavy rainfalls is three to four times denser than the natural-origin river drainage network (RDN) (11.4 km·km^{-2} vs. 2.9 km·km^{-2}), and the RDN is significantly modified by human-origin elements (e.g., roads, ditches, furrows, etc.—they constitute ca. 1/3 of the ADN). Moreover, significant structural changes in the ADN have occurred, which were confirmed by the Hortonians' type of analysis. The changes in the ADN have affected the hydrological response of the catchment (predominantly an increase in the peak flow—up to 7%) and the dimensions of the 1% probable flood hazard zone (increase of ca. 5%). It may be concluded that significant changes in the ADN, in the catchment studied, had a moderate impact on the changes in the flood hazard level. The results give a new insight into the flood hazard/risk assessment processes in a small flysch mountain catchment.

Keywords: active drainage network—ADN; extreme rainfall; hydrological response; flood wave; GIUH; flood risk; Carpathians

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1. Introduction

The drainage network plays an important role in the hydrological cycle. The system distributes water, organizes sediment, and transports nutrients—e.g., [1–4]. These facts have implications for environmental functioning, including landscape transformation, and water-, bio-, and geochemical cycles—e.g., [2–4].

The drainage network is a dominant structure of catchments. The important role of this element in catchment functioning was the reason for intense studies in this research field. The studies started in the 1940s, and R.E. Horton [5], A.N. Strahler [6], and S.A. Schumm [7] were pioneers in this area. Since that time, the drainage network development or functioning has been studied many times—e.g., [2,5–12]. Those works have revealed that the drainage network is a dynamic component of the catchment (the so-called active drainage network—ADN), which changes in relation to different types of hydro-meteorological conditions, catchment relief, and geology [13–18]. Moreover, the natural-origin drainage network parameters reflect the geo-morpho-climatological conditions of the region, where this system was developed—e.g., [7,14]. Those conclusions were the basis for a lot of research in the field of applied geomorphology and hydrology. In the field of hydrology, one of the most important achievements was the statement that the dynamic feature of the ADN (its expansion/contraction—first reported by K.J. Gregory and D.E. Walling [18] and confirmed in many other studies [19–23]) is an important factor, which controls the hydrological response of a catchment to precipitation [13,15,19–28]. The majority of the works mentioned above concentrate on a natural-origin (rivers and valleys) drainage network pattern, development, and functioning. However, the transformation of the natural environment resulted in the development of man-origin incision networks (e.g., paved/unpaved roads, ditches, plough furrows, tourist trails, etc.). For example, in the flysch part of the Carpathian Mts., located under temperate climate conditions, the density of the valley system is usually up to 3.5 km·km^{-2} [29], whereas the density of roads (paved/unpaved) and their ditches may exceed 9 km·km^{-2} in some parts of the mountains [28–32]. In addition, smaller incisions resulting from agricultural works—e.g., plough furrows, which may be incorporated into the ADN—may reach up to 3.5 km·km^{-2} [33]. The natural- and human-origin incisions interfere during different hydro-meteorological events and operate as one "real" ADN, influencing the hydro-, geomorpho-, and biological aspects of catchment functioning—e.g., [15,25–28]. Knowledge of the parameters of the "real" ADN is one of the crucial elements in the field of catchment functioning. The research related to the "real" ADN has not been presented in the literature broadly and constitutes a research gap, hence the investigations. The major research problem in this study is related to the transformation of the drainage network during extreme hydro-meteorological events, with a special assessment of the human impact in this process, as well as the consequences of the drainage network transformation for catchment functioning, considering some aspect important for practice. The goals of this study are to recognize (1) how the ADN changes during heavy rainfall, focusing on the role of the man-origin elements (roads, ditches, plough furrows, etc.) in this process; (2) what the consequences of the changes in the ADN are, taking into account the hydrological response of a catchment; and (3) how the changes in the hydrological response of a catchment resulting from ADN transformation may affect the flood hazard assessment and, consequently, the flood risk management processes. Those three aspects, "as a chain of linkages", in the author's opinion, have not been recognized in the literature yet, and, therefore, the research framework presented in this study states the novelty in this research area and has the potential to be used by researchers interested in studies on catchment hydrology and by practitioners, giving insight into the flood hazard and risk assessment processes.

2. Materials and Methods

2.1. Study Area

Semi-natural catchments, where human activity has caused the development of dense incisions (roads, ditches, plough furrows, etc., as mentioned before), can serve as study examples for investigating the aspects described above. The Pielnica catchment chosen in this study is one example. The catchment (39.7 km^2, closed by the Nowosielce river gauging station) is located in the Bukowskie foothills (Polish part of the Outer Carpathians). It represents a typical flysch mountain catchment under temperate climate conditions, prone to flash floods [29]. The bedrock is composed of flysch rocks (thin sandstones and shales) covered by a 0.5–1.0 m mantle rich in clay mineral (usually >25%). Dystric Cambisols and Eutric Luvisols, characterized by a low filtration rate (<10^{-5} m·s^{-1}), which predispose rapid surface runoff (especially when rainfall intensity exceeds 1 mm·10 min^{-1} [34]), dominate in the soil cover [35]. More than 60% of the catchment's area has a slope gradient of 5–15° (Figure 1), with a mean value of 8.5°. The network density of the river is 2.9 km·km^{-2}. The main river channel (up to 20 m wide and 4 m deep) is incised into the wide (150 m in the headwater part to about 500 m in the lower part of the catchment in Nowosielce) terraced valley floor (Figure 1). The mean annual temperature and precipitation are 5 °C and 100–1200 mm, respectively [36]. The mean specific outflow ranges between 15 and 20 $dm^3 \cdot y^{-1}$ [37]. It is a forest–agricultural type of catchment, where agricultural land covers more than 54% of the area, whereas forest and settlement areas occupy 39% and 7%, respectively.

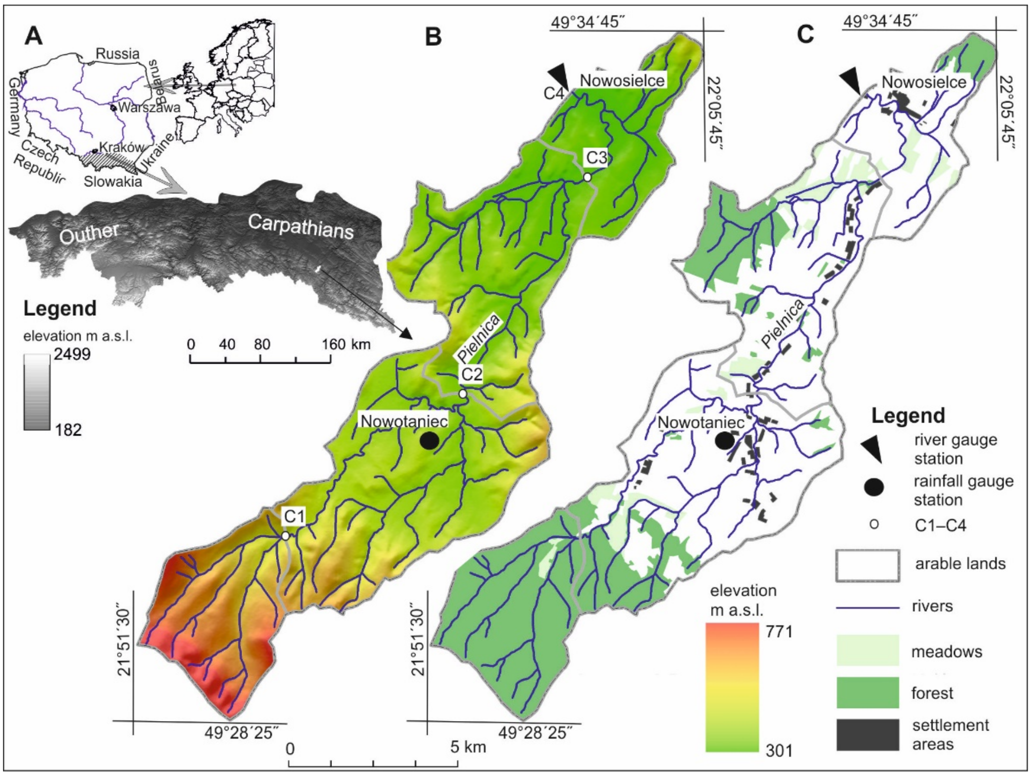

Figure 1. Location (**A**) of the Pielnica river catchment, relief (**B**), and land use cover LULC (**C**); C1–C4—sub-catchments. Source: Author's own elaboration based on ALS-LIDAR (DEM), aV-map 1:50,000 [38] and the BDOT 10k database 1:10,000 [39]. DEM was downloaded from www.geoportal.gov.pl (accessed: 1 September 2022).

For detailed studies, the Pielnica catchment was divided into 4 sub-catchments, which differ in terms of area, relief conditions, and land use and land cover (LULC) (Table 1). These factors influence ADN development and the hydrological response of the catchment.

Table 1. Physiographic parameters of the Pielnica sub-catchments.

Catchment	A (km^2)	Average Slope Gradient (°)	Land Use Land Cover (LULC) (%)			
			Forest	Arable Lands	Grasslands	Settlement Areas
1	6.4	13.31	100	0	0	0
2	21.8	9.48	46	47	2	5
3	33.2	8.96	39	49	5	7
4	39.7	8.51	34	53	5	8

Source: Author's own elaboration on the basis of Vmap [38].

The study was performed in 3 main steps: (1) reconstruction and characterization of the ADN operating during heavy rainfall with regard to the identification of human-induced changes in the ADN, (2) analysis of the hydrological response of the catchment and evaluation of how the human-induced changes in the ADN have affected flood wave parameters, and (3) analysis of the changes in the flood hazard zone extension resulting from the changes in the hydrological response of the catchment triggered by the ADN transformation. The main steps of the methodology are briefly described in the next subsections.

2.2. Reconstruction and Characterization of the ADN Operating during Heavy Rainfall

During heavy rainfall, the ADN reaches its maximum extension, which provides the opportunity to analyze changes in the ADN and detect the main factors affecting those changes. The ADN operating during heavy rainfall was reconstructed according to the methodology developed by Kroczak and Bryndal [28,40]. The main steps of this methodology include the following:

(1) Developing a high-resolution (0.5 × 0.5 m) digital elevation model (DEM) to enable detection of natural and man-made incisions, which differed in terms of their type and size (e.g., concavities/incisions resulting from relief, paved/unpaved roads, ditches, plough furrows, etc.). The DEM was developed based on ALS-LiDAR data (ground layer). The density of points was 4–6 pct·m^{-2}, and vertical errors were up to 0.15 m.

(2) Pre-processing the DEM and adapting it for hydrological analysis. The DEM, created from LiDAR data, reflects a "real" terrain surface. This means that bridges, culverts, footbridges, etc., which normally allow water to flow through them, are reflected as "artificial dams" disturbing the natural gravity flow. In order to create the ADN, which is similar to a drainage network functioning in real conditions, the DEM must be hydrologically correct. The bridges, culverts, and footbridges were "burned" using a typical algorithm implemented in GIS software according to the procedure presented by Bryndal and Kroczak [40].

(3) Delineating streams. The streams were generated using a typical procedure implemented in GIS software. The D8 algorithm was selected for the flow accumulation procedure. The streams were identified using the head channel areas (Table 2) calculated for models of catchments contributing to first-order stream development, according to the methodology proposed by Bryndal and Kroczak [40].

Table 2. The models contributing to the development of the first-order streams in flysch Carpathian catchments. Reproduced from [41] with permission from Elsevier, 2023.

Model	Type of the Land Use and Land Cover (LULC)	The Head Channel Area (ha)
I	Arable land	0.29
II	Forest	0.88
III	Grasslands	0.45
IV	Build-up areas	0.11
V	Roads	0.11

Source: [41].

Changes in the ADN were evaluated by comparing the river drainage network (RDN, blue lines) and the ADN, which operates during heavy rainfall (reconstructed from the DEM). The parameters of the river system were calculated based on the river layer from BDOT 10k database (1:10,000) [39]. Changes in the drainage network were evaluated by total length (km) and density of streams (km·km^{-2}) and the parameters related to Horton drainage network analysis [5,7], including the number of maximum stream order (Ω_{max}), the number of streams (n) and the bifurcation ratio (R_B), the mean stream length (km) and mean stream length ratio (R_L), the mean catchment area drained by *i*-order stream (km^2), and the area ratio (R_A). Changes in the ADN were evaluated in relation to the catchment scale as a whole and the catchments drained by *i*-order stream, classified according to Strahler's topology [6], for the RDN (blue lines) and the ADN reconstructed using a methodology described above. Factors affecting changes in the ADN were detected by looking at the factors influencing ADN development in relation to (1) natural elements, evaluated by the physiographic characteristics of the sub-catchments (Table 1), and (2) man-made elements, evaluated by the structure of the ADN.

2.3. Evaluation of the Influence of Human-Induced Changes in the ADN on Flood Wave Parameters

2.3.1. Selection of the Hydrological Model

Hydrological models have become indispensable tools for the study of hydrological processes and the impact of anthropogenic factors on hydrologic systems (e.g., [42,43]). In this study, the geomorphological unit hydrograph (GIUH) model, in which a unit hydrogram is interpreted in the context of the geomorphological characteristics of a catchment and probability distribution function (pdf) of a raindrop [44,45], was used. This hydrologic model incorporates channel network information in instantaneous unit hydrograph format [42,44] using Horton's [5] and Schumm's [7] ratios. Changes in the ADN, which occur during heavy rainfall, are reflected in Horton's bifurcation (R_B), mean length (R_L), and Schumm's area (R_A) ratios. Therefore, changes in the ADN quantified by the R_B, R_L, and R_A ratios provide the opportunity to evaluate how those changes influence the flood wave parameters. Two scenarios were considered. In the first scenario, the R_B, R_L, and R_A ratios described the river drainage network, which is a typical approach when using the GIUH model (e.g., [1,45,46]). In the second scenario, R_B, R_L, and R_A described the ADN operating during heavy rainfall. The differences in flood hydrographs can be treated as a surrogate measure, which indirectly allows an assessment of the influence of the modified ADN on flood wave parameters.

2.3.2. Testing and Evaluation Stages

The first stage was a simulation of flood hydrographs. The SCS-CN [47] and GIUH [44] models were used to assess the hydrological response of a catchment to a rainfall event (in which heavy rainfall generated a flash flood) between 14 and 17 May 2014 recorded at the telemetry-type rainfall station in Nowotaniec (Figure 1). The rainfall data were downloaded directly from the website managed by the Institute of Meteorology and Water Management—Polish Institute of Research (IMGW-PIB in Polish). The data had 1 h resolution. The hydrographs were developed for two scenarios in which the R_B, R_L, and R_A ratios described (1) the river network and (2) the ADN operating during heavy rainfall. Taking into account the 5-day sum of precipitation (>53 mm), the third level of antecedent soil moisture conditions was assumed in the SCS-CN model.

The second stage was a comparison of simulated and observed hydrographs. The hydrograph observed at the telemetry-type river gauge station in Nowosielce (Figure 1) was compared to the GIUH-simulated hydrograph for two scenarios (RDN and ADN). The flow data were also downloaded directly from the IMGW-PIB website. The flow data, similar to rainfall, had 1 h resolution. The observed and modeled hydrographs were compared using statistical measures including correlation (R), coefficient of determination (R^2), and root mean square error (RMSE) based on Gupta et al. [48] and Legates and McCabe [49]. Note that the GIUH estimations are optimal if R, R^2, and RMSE are close to 1, 1, and 0, respectively. Two additional measures were calculated: percentage difference between observed and simulated peak flow (Qmax) and difference between simulated and observed peak time (tp). These are the most important measurements during flash floods in small catchments because they determine the extent of the flood hazard zone and influence the flood risk management process [50].

2.4. Evaluation of Changes in a Flood Hazard Zone Extension Conditioned by Human-Induced Changes in the ADN

HEC-RAS [51] software, developed by the US Army Corp of Engineers, was used to evaluate the flood hazard zone extension conditioned by changes in the ADN. According to the Floods Directive [52], the delineation of a 1% probable flood inundation area is of special relevance in the flood risk evaluation and management process, as those areas should be protected. Therefore, a 1% probable, 120 min long [53] rainfall event (potentially the most dangerous precipitation that could generate a flash flood in the study area) was used as input data for hydrological analysis. The same approach as described before was used for the analysis. The 1% probable rainfall was transformed into a 10 min-step hyetograph using the DVDT method [54]. The sum of excess rainfall and the hydrological response of the catchment in the two scenarios (RDN and AND) were calculated by using the SCS-CN [47] and GIUH models [44], respectively. The difference in flood zone area for the scenarios was expressed as a percentage.

3. Results

3.1. Changes in the Active Drainage Network

Table 3 and Figure 2 present the changes between the river drainage network (RDN) and the active drainage network (ADN) operating during heavy rainfall, while Figure 3 presents the development of drainage systems based on Horton analysis [5,6]. Those data indicate that the ADN operating during heavy rainfall is better developed, which is confirmed by the parameters used for drainage network characteristics. Horton analysis indicates that the maximum stream order Ω_{max} for the ADN increases by one order (source part of the Pielnica catchment, C1) or two orders (C2–C4). Changes in the ADN are reflected in a significant increase in stream number. What is more, it seems that the land use type has a significant influence on this increase. In the forested, upper part of the catchment (C1), the number of streams is 2–6 times higher during heavy rainfall compared to the RDN. However, as the proportion of arable land increases (C2–C4), and more human-related elements of the drainage network appear (e.g., roads, ditches, plough furrows, etc.), the differences between the RDN and ADN are more noticeable, especially in the first- to third-order streams, where the number of streams during heavy rainfall is 7–15 times higher compared to the river system (Table 3). The exponents in the regression lines (Figure 3) indicate that the dynamics of RDN and ADN system development are comparable in each sub-catchment; however, there are some differences related to the rate of network development expressed by the R_B ratio. A higher number of streams (n) in the ADN operating during heavy rainfall determines higher values of R_B in the sub-catchments (R_B = 3.5–3.8 for RDN vs. 3.5–4.8 for ADN). These parameters confirm that the ADN operating during heavy rainfall is better developed.

Changes in the ADN are also reflected in significant increases in the length and density of the network. For the RDN, the mean density reaches ca. 3 km·km^{-2}, and there is low internal diversity in this parameter between sub-catchments (2.9–3.0 km·km^{-2}) and *i*-order streams (2.1–3.7 km·km^{-2}). Slightly higher values in the RDN related to *i*-order streams in the headwater part of the Pielnica catchment (C1) may be explained by the relief conditions: steeper slopes in the source part of the catchment (Table 1), forcing more efficient development of the river drainage network. The ADN length and density significantly increase during heavy rainfall. In relation to all catchments (C4), the ADN density is at least 2–3 times higher compared to the river drainage network (11.4 vs. 2.9 km·km^{-2}). What is more, it seems that LULC is a factor that affects internal changes in stream density related to sub-catchments and *i*-order streams. In the forested headwater part of catchment C1, the differences between the RDN and ADN for first- to third-order streams range from 2 to 2.8. When the arable area content increases (C2–C4; Figure 1, Table 3), the density of the ADN is at least 3–6 times higher compared to the RDN.

Table 3. Statistics of the river drainage network (RDN) and ADN operating during heavy rainfall.

Stream Order (Ω_{max})	Number of Streams (n)		Total Stream Length (km)		Mean Stream Length (km)		Stream Density ($km \cdot km^{-2}$) *		Mean Catchment Area (km^2)	
	RDN	**ADN**	**RDN**	**ADN**	**RDN**	**ADN**	**RDN**	**ADN**	**RDN**	**ADN**
C1 (6.4 km^2)—100% forest										
1	27	155	8.9	30	0.33	0.19	3.7	7.5	0.09	0.026
2	9	27	5.8	10.2	0.65	0.38	3.3	9.4	0.464	0.187
3	2	4	5.7	5.6	2.87	1.40	2.1	4.8	3.456	1.556
4		2		3.8		1.92		18.1		3.218
Average	R_B = 3.8	R_B = 4.8	-	-	R_L = 3.2	R_L = 2.4	3.0 **	7.7 **	R_A = 6.3	R_A = 5.9
Sum	-	-	20.4	49.6	-	-	-	-	-	-
C2 (21.8 km^2)—46% forest, 47% arable areas, grasslands 2%, sett. areas 5%										
1	90	777	30.5	133.5	0.34	0.17	3.2	10.4	0.107	0.016
2	23	176	16.9	40.8	0.73	0.23	3.2	11.3	0.644	0.093
3	6	44	9.8	22.8	1.64	0.52	2.4	7.1	3.145	0.446
4	2	11	7.5	9.3	3.74	0.85	2.5	15	10.955	1.841
5		2		8.5		4.23		6.1		10.824
6		1		2.2		2.23		14.7		21.799
Average	R_B = 3.6	R_B = 4.0	-	-	R_L = 2.2	R_L = 2.2	3.0 **	10.0 **	R_A = 4.8	R_A = 4.5
Sum	-	-	64.7	217.1	-	-	-	-	-	-
C3 (33.2 km^2)—39% forest, 49% arable areas, grasslands 5%, sett. areas 7%										
1	140	1301	45.2	211.9	0.32	0.16	3.1	10.8	0.103	0.015
2	38	297	26.2	63.1	0.69	0.21	3.3	11.6	0.592	0.085
3	9	75	12.4	37.2	1.37	0.50	2.7	8.3	3.007	0.394
4	3	17	8.4	13.6	2.8	0.80	2.5	9.3	10.144	1.825
5	1	5	6	9.4	6.03	1.89	2.1	6.1	33.328	6.512
6		2		2.2		1.11		14.6		16.357
7		1		6.4		6.36		12.2		33.235
Average	R_B = 3.5	R_B = 3.5	-	-	R_L = 2.1	R_L = 2.3	2.9 **	10.3 **	R_A = 4.4	R_A = 3.8
Sum	-	-	98.2	343.8	-	-	-	-	-	-
C4 (39.7 km^2)—34% forest, 53% arable areas, grasslands 5%, sett. areas 8%										
1	159	2425	54.1	260.9	0.34	0.11	3.1	10.9	0.112	0.010
2	43	536	28.8	92.9	1.01	0.17	3.4	13.9	0.612	0.057
3	9	131	14.4	50.5	2.6	0.39	2.7	10.3	3.527	0.271
4	3	36	8.4	21.4	5.4	0.59	2.5	12.5	11.705	1.033
5	1	7	9.7	16.5	15.1	2.36	2.1	10.4	39.765	5.541
6		2		2.2		1.11		14.6		19.470
7		1		10.3		10.26		13.4		39.704
Average	R_B = 3.6	R_B = 3.8	-	-	R_L = 2.6	R_L = 3.2	2.9 **	11.4 **	R_A = 4.5	R_A = 4.2
Sum	-	-	115.4	454.7	-	-	-	-	-	-

Source: This study; *—calculated in relation to part of catchment drained by *i*-order catchment; **—calculated for whole catchment area. C1–C4—number of sub-catchments. Typology after Strahler [6].

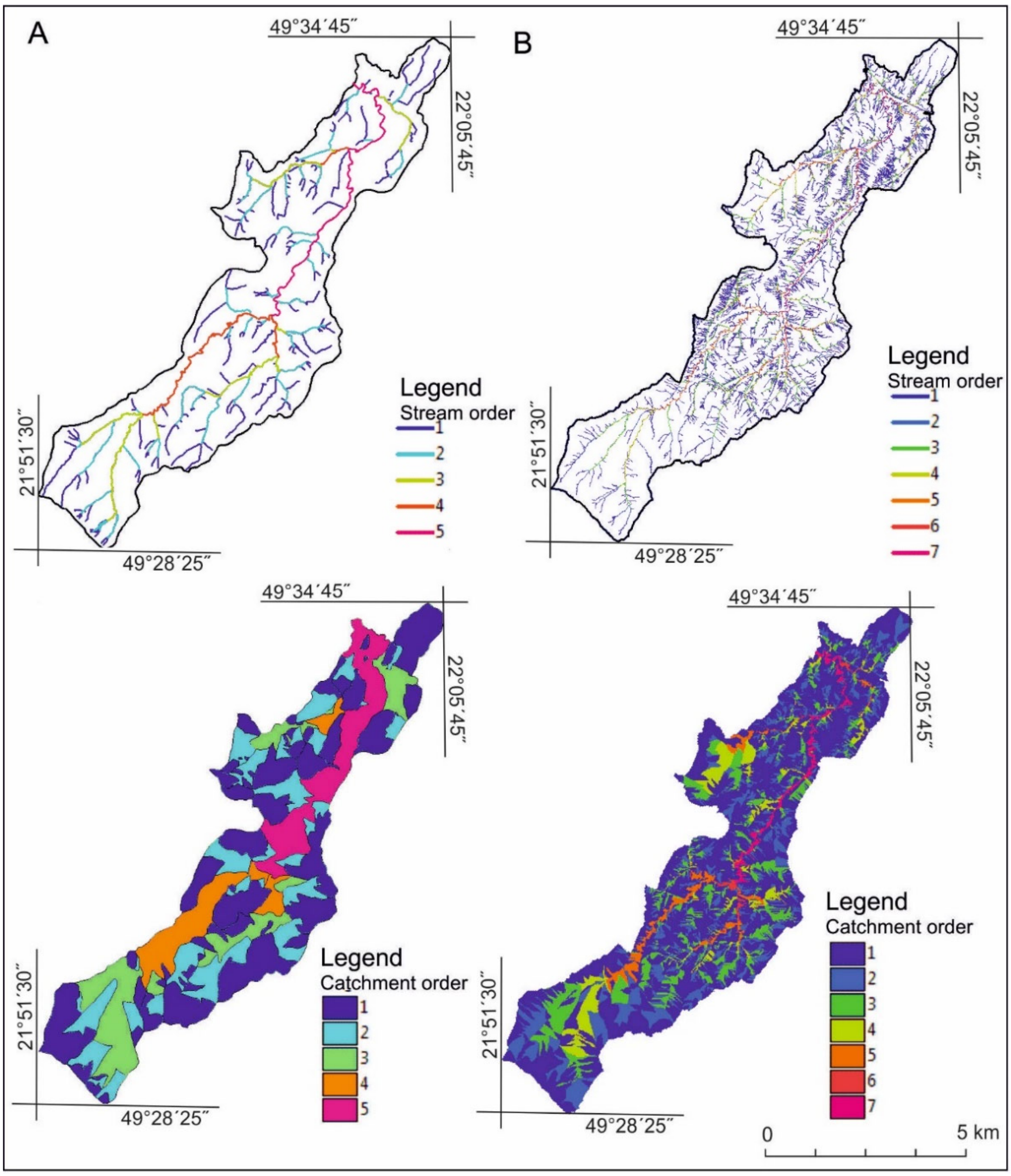

Figure 2. Comparison between river drainage system (**A**) and surface drainage system operating during heavy rainfall (**B**). Typology after Strahler [6]. Source: Author′s own elaboration.

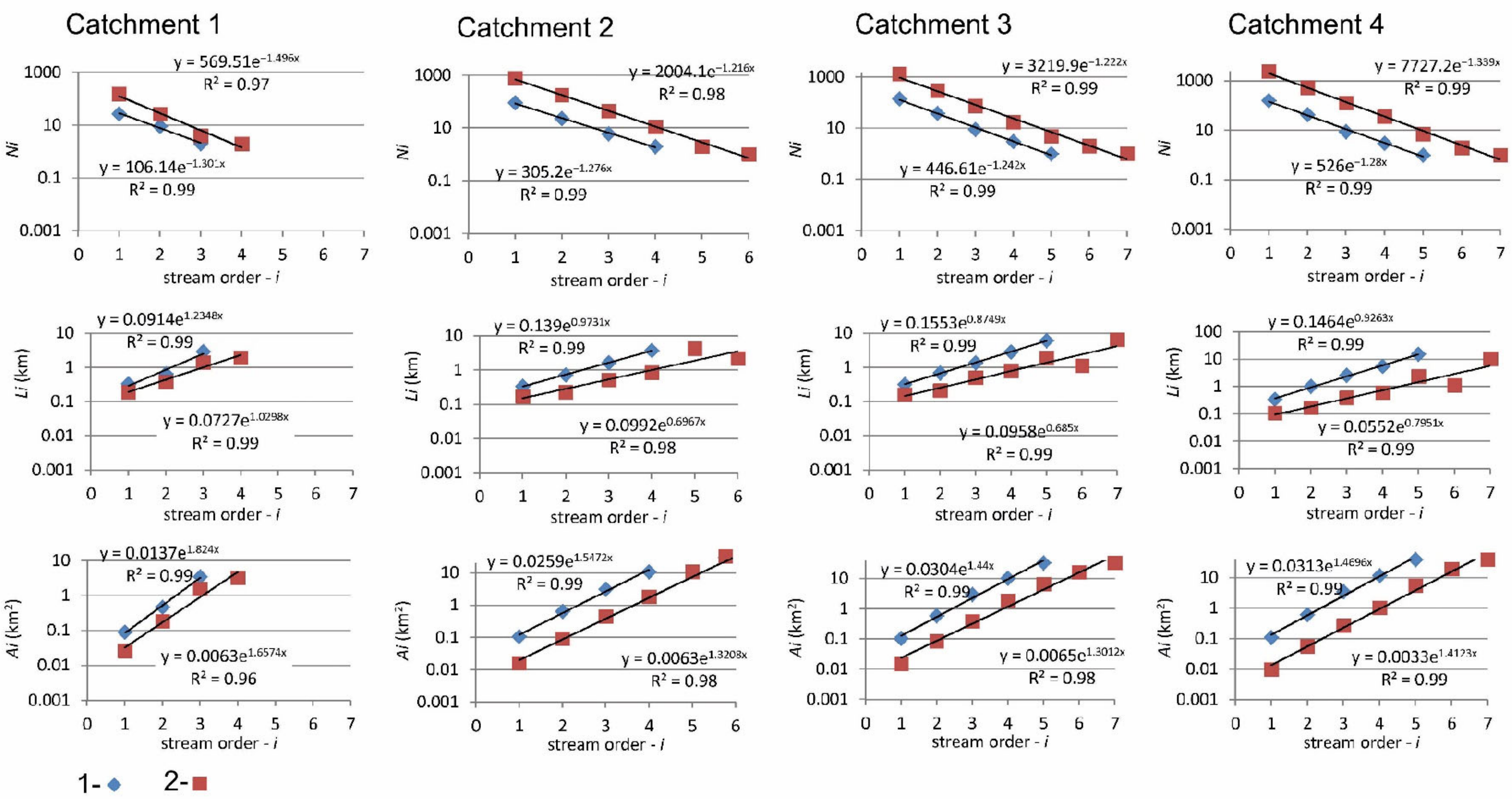

Figure 3. Changes in the development of the river drainage network (RDN)—1 and ADN—2 operating during heavy rainfall in context of the Hortonian-type analysis. Changes in number of steam number—*Ni*, the mean stream length—*Li*, the mean catchment area—*Ai*. Source: This study.

Another change in the ADN is related to a significant decrease in the mean stream length and the rate of drainage network development (Table 3, Figure 3). For the river drainage network, the mean stream length of the first-order stream reaches ca. 0.33 km. The RDN development, expressed by the R_L ratio and the exponent (Ex) in the regression line, is higher in the headwater part of the catchment (C1 R_L = 3.2; Ex = 1.3) compared to the other parts of the catchment (C2–C4: R_L = 2.5–2.6; Ex = ~0.9). These spatial differences may be explained by the relief condition (more dynamic development of the drainage network in the steeper part of the catchment). During heavy rainfall, the mean length of the first-order stream decreases (in the range of 0.10–0.19 km). Moreover, it seems that LULC may be considered as an important factor that has a major influence on this parameter. In the forested catchment (C1), the *i*-order streams are the longest and about 2–3 times shorter than their counterparts in the RDN. As the arable land content increases and more human-made incisions appear, the mean length of the *i*-order streams decreases (3–9 times lower than their counterparts in the RDN). As a result, the ADN operating during heavy rainfall is composed of shorter *i*-order streams, and the dynamic of system development is lower than the RDN, which is confirmed by lower values of exponents in the regression line (Figure 3) and R_L ratios (Table 3).

Similar changes were observed in the mean catchment area. For the river network, the mean catchment area of the first-order stream amounts to about 0.1 km^2, and the rate of RDN development differs between sub-catchments (C1–C4), which can be explained by relief condition (Tables 1 and 3). In the steeper headwater part of the catchment (C1), the drainage network is better developed, and the mean area drained by consecutive *i*-order streams is about six times larger (R_A = 6.3). As the catchment area increases (C2–C4) and the slope gradient becomes lower (Table 1), the rate of drainage system development, expressed by R_A, decreases (R_A = 4.4–4.8). During heavy rainfall, the mean area drained by *i*-order streams decreases, and LULC may be considered to be the predominant factor affecting changes in the ADN. In the forested headwater part of the catchment (C1), the mean catchment areas drained by first- to third-order streams are 2.2–3 times lower compared to the RDN. When the arable land content increases and there are more human-made incisions in the ADN, the mean catchment area drained by i-order streams decreases, and the mean *i*-order stream catchment area is 7–10 times smaller compared to the RDN. The influence of LULC on ADN development is also reflected in the dynamic of ADN development. The R_A ratio (Table 3) and the exponent in the regression line (Figure 3) are lower in the catchment where arable land prevails (C2–C4: R_A = 3.8–4.5) compared to the forested part (C1: R_A = 5.9).

The partial conclusion reached from this part of the analysis is that when the ADN is operating during heavy rainfall, LULC is a major factor influencing these changes. In order to explain this aspect, the proportions of natural elements (e.g., rivers, valleys, flow lines conditioned by micro-relief) and human-made elements (roads, ditches, plough furrows, etc.) of the ADN were analyzed.

The data in Table 4 reveal that as the arable land content increases, the number of human-made elements (e.g., roads, ditches, plough furrows, etc.) that are included in the ADN during heavy rainfall rises. In fact, natural elements dominate in the ADN, but their proportion significantly decreases as the arable land content increases (from 92.4% in the forested catchment (C1) to 64.4–67.2% in more rural catchments (C2–C4)). Generally, human-made elements constitute about one-third of the ADN when operating during heavy rainfall.

Table 4. Structure of the active drainage network (ADN) operating during heavy rainfall.

	Natural-Origin Elements		Human-Origin Elements	
Sub-Catchment	**Rivers and Smaller Lateral Valleys (Figure 4 sig. A)**	**Flow lines Conditioned by Micro-Relief (Figure 4 sig. B)**	**Plough Furrows, Unpaved Rural Roads (Figure 4 sig. C)**	**Paved Roads and Ditches (Figure 4 sig. D)**
Catchment 1	92.4	-	-	7.6
Catchment 2	37.5	26.9	20.4	15.2
Catchment 3	33.8	33.4	17.9	14.9
Catchment 4	30.2	34.9	20	14.9

Source: This study.

Figure 4. The examples of the surface drainage system organization during heavy rainfall. A—concentrated flows in the stream channels and small lateral valleys, B—concentrated flows in small incision on the hillslopes conditioned by micro-relief (A, B—natural-origin sub-system), C—plough furrows, D—roads, ditches (C, D—man-origin sub-system). Source: Author's own elaboration, based on ortophotos from www.geoportal.gov.pl (accessed: 1 September 2021).

The final conclusion reached from this part of the analysis is that the natural river drainage network changes significantly during heavy rainfall, and the changes, to a great extent, result from the incorporation of human-made elements in the ADN, strictly related to land cover. The changes in the ADN cause slopes to be better drained, which should consequently affect flood wave parameters. In order to evaluate this issue, the hydrological response of a catchment was studied.

3.2. Changes in ADN vs. Hydrological Response of a Catchment and Flood Hazard Zone

3.2.1. Changes in the ADN and Their Influence on Flood Wave Parameters

The recorded hydrological response of the Pielnica catchment to rainfall between 14 and 16 June 2014 is presented in Figure 5. Site B represents observed and simulated hydrographs where the R_B, R_L, and R_A ratios describe the RDN. Site C represents observed and simulated hydrographs where R_B, R_L, and R_A describe the ADN operating during heavy rainfall. The statistical measures (Table 5) indicate good agreement between observed hydrographs (signature 1) and those predicted by hydrological models (signatures 2, 3). The coefficients of correlation (R) and determination (R^2) were close to 1 for both scenarios. However, when Horton's ratio was used to describe the ADN operating during heavy rainfall, the values were higher (R = 0.98, R^2 = 0.97). Even the root mean square error (RMSE) indicates that the systematic difference between the measured and predicted hydrographs is lower when Horton's ratio is used to describe the ADN operating during heavy rainfall.

Table 5. Statistical measures between observed (OB) and simulated hydrographs for the river drainage system (RDN) and the drainage system operating during heavy rainfall (ADN) in the Pielnica catchment (C 4).

Coefficients	OB vs. RDN	OB vs. ADN
R (-)	0.97	0.98
R^2 (-)	0.95	0.97
RMSE (-)	1.17	0.94
Qmax diff (%)	18.3	11.6
Tp diff (h)	1	0

Source: This study. R—correlation coefficient, R^2—determination coefficient, RMSE—root mean square error, Qmax diff—differences between observed and simulated maximum flow, Tp diff—differences between peak flow.

The largest differences are observed in the maximum peak flow (Table 5, Figure 5). This parameter is more underestimated in the first scenario, where Horton's ratio describes the river network (4.3 $m^3 \cdot s^{-1}$, 18.3%), than in the second scenario, where Horton's ratio describes the ADN operating during heavy rainfall (2.8 $m^3 \cdot s^{-1}$, 11.6%). The difference in maximum peak flow for the two scenarios is 1.5 $m^3 \cdot s^{-1}$, or 7%. The difference in peak time between scenarios is 1 h (Table 5, Figure 5B). It can be concluded that the reconstruction of flood wave parameters is more accurate when Horton's ratio is used to describe the ADN functioning during heavy rainfall.

The differences observed in the hydrographs developed for two scenarios in each sub-catchment (Figure 6, Table 6) allowed the indirect evaluation of how changes in the ADN within the catchment affect the flash flood wave parameters. It can be concluded that predominantly the modified ADN influences the maximum flow. Generally, in the sub-catchments where the proportion of man-made elements of the ADN is higher (C2–C4), the difference in maximum flow is more noticeable, increasing to 7%.

Table 6. Statistical measures between simulated hydrographs for the river drainage network (RDN) and the ADN operating during heavy rainfall in the Pielnica sub-catchments.

Coefficients	Catchment 1	Catchment 2	Catchment 3	Catchment 4
R (-)	0.99	0.99	0.99	0.99
R^2 (-)	0.99	0.99	0.99	0.99
RMSE (-)	0.13	0.09	0.47	0.47
Qmax diff (%)	2.0	5.0	7.0	7.0
Tp diff (h)	0	0	0	0

Source: This study. R—correlation coefficient, R^2—determination coefficient, RMSE—root mean square error, Qmax diff—differences between observed and simulated maximum flow, Tp diff—differences between peak flow.

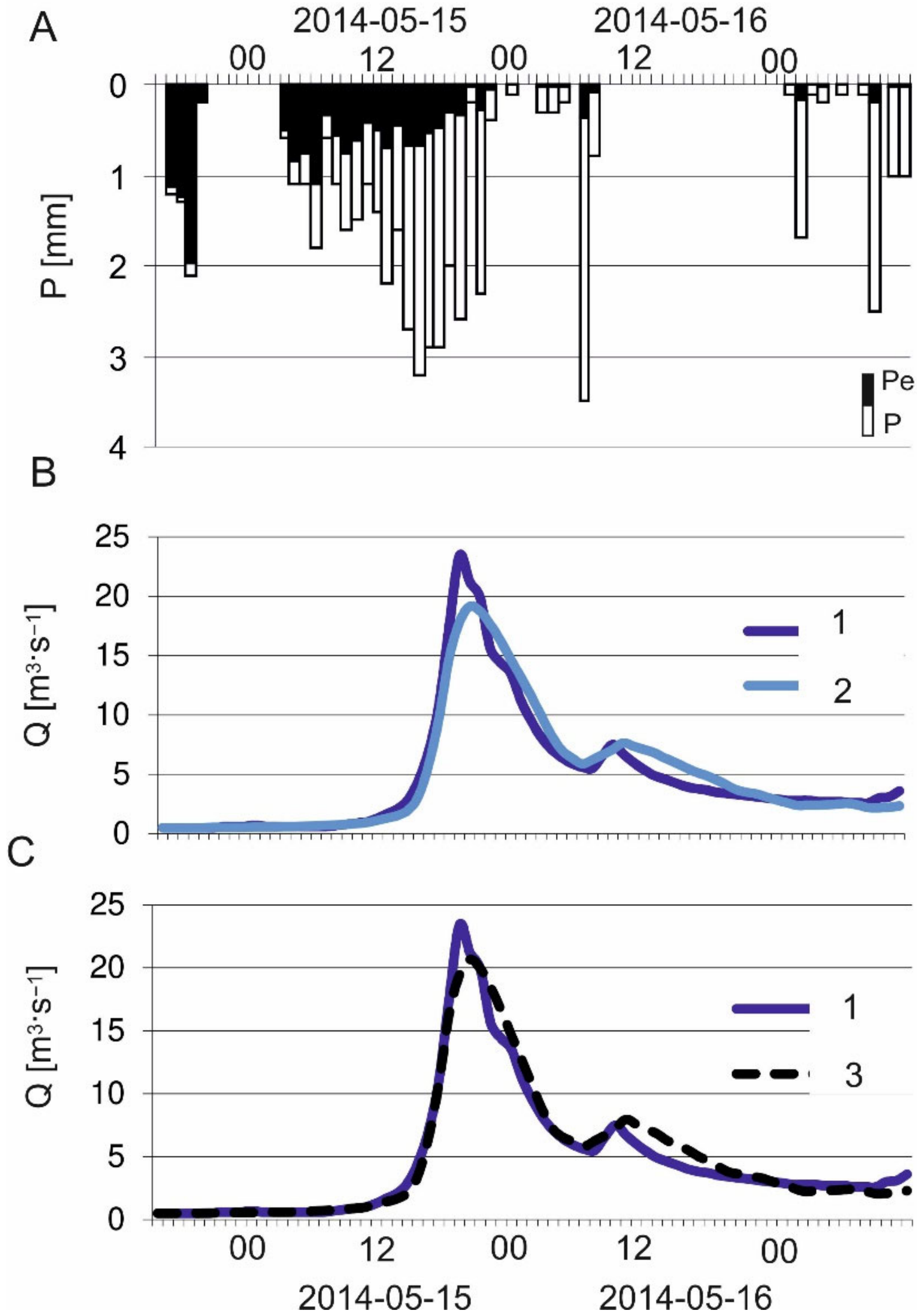

Figure 5. Comparison between observed (signature 1) and simulated hydrographs in the Pielnica catchment (signatures 2—RDN, 3—ADN). Rainfall (**A**) and the flood hydrograph developed for the scenario when Horton's and Schumm's ratios describe the river network RDN (**B**) and ADN operating during heavy rainfall (**C**). P—precipitations, Pe—excess precipitations. Source: Author's own elaboration. Precipitations and observed hydrograph developed on the basis of data from the Institute of Meteorology and Water Management—National Research Institute. The source of the data is the Institute of Meteorology and Water Management—National Research Institute. The data of the Institute of Meteorology and Water Management—National Research Institute have been processed.

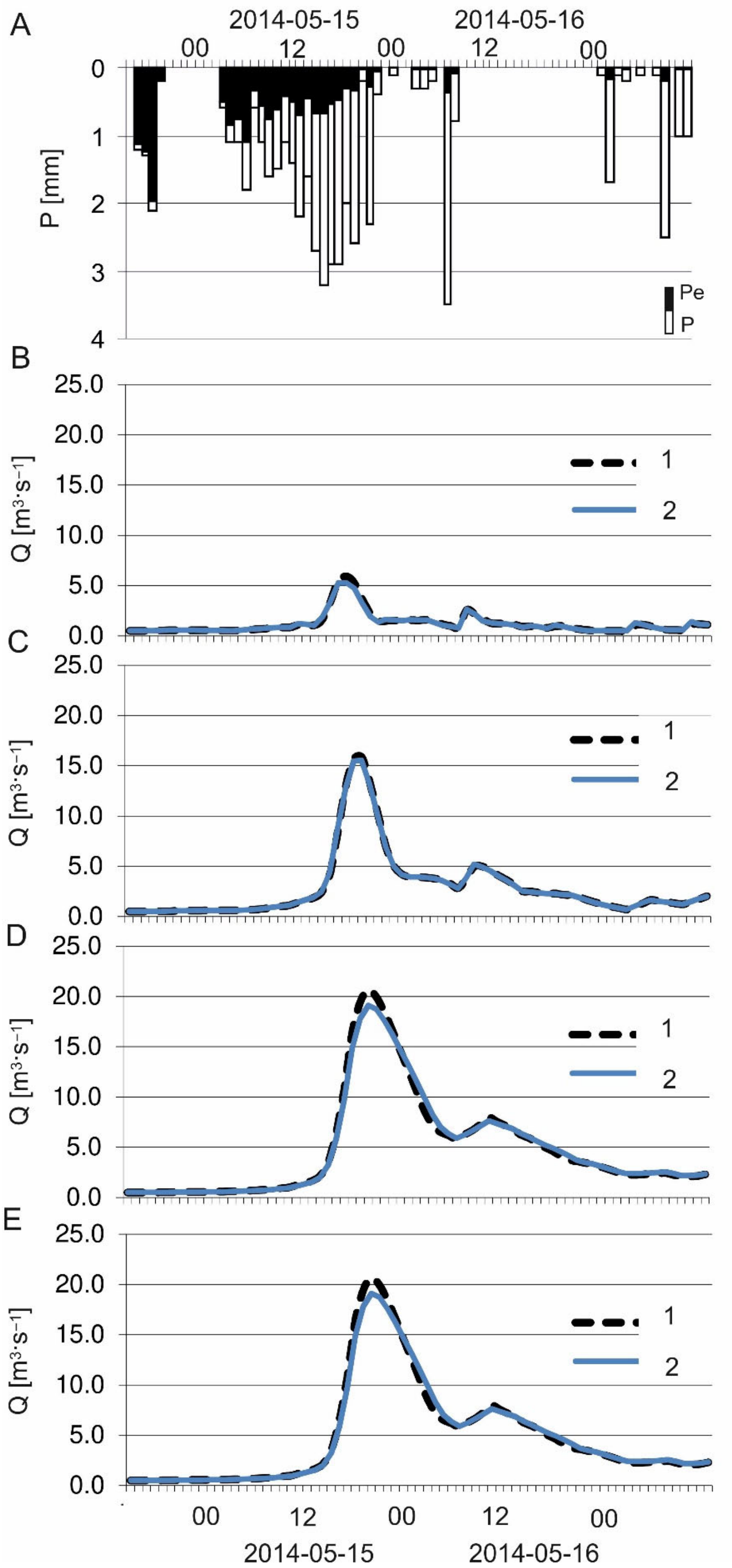

Figure 6. Comparison between the hydrographs in the Pielnica catchment. Rainfall (**A**) and flood hydrograph developed for the scenario when Horton's and Schumm's ratios describe the river network (signature 2) and ADN operating during heavy rainfall (signature 1) for the catchment: C1 (**B**), C2 (**C**), C3 (**D**), C4 (**E**). P—precipitations, Pe—excess precipitations. Source: Author's own elaboration.

3.2.2. Changes in Flood Wave Parameters and Their Influence on Flood Hazard Zone Extension

Figure 7 presents the hydrological response of the sub-catchments to the 2 h long 1% probable rainfall event (site C) in two simulated scenarios: (1) with R_B, R_L, and R_A ratios describing the RND (signature 2) and (2) with R_B, R_L, and R_A ratios describing the ADN operating during heavy rainfall (signature 1).

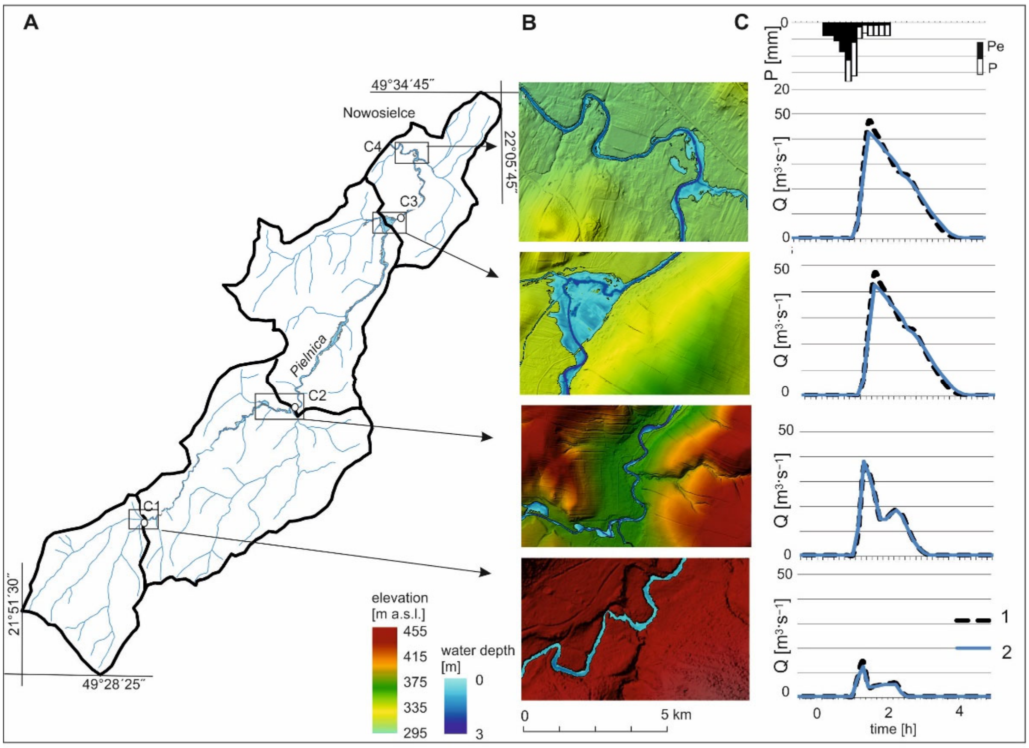

Figure 7. Changes in the 1% flood hazard zone in the Pielnica catchment. Location of the example areas (**A**), changes in the inundated areas (**B**) and flood hydrographs (**C**) for the scenario when Horton's and Schumm's ratios describe the river network (signature 2) and the ADN operating during heavy rainfall (signature 1) for the catchment: C1, C2, C3, C4. P—precipitations, Pe—excess precipitations. Source: Author's own elaboration based on ALS-LIDAR DEM data from www.geoportal.gov.pl (accessed: 1 September 2022).

The differences in hydrological response are related to the maximum flow, and this parameter is higher for the second scenario. At the catchment scale (all catchments (C4)), the inundation area reached 0.474 km^2 for the RDN (scenario 1) and 0.499 km^2 for the ADN (scenario 2), meaning that the inundated area is about 5% larger in the second scenario. It can be concluded that changes in the flood hydrograph resulting from changes in the ADN have a minor influence on flood hazard zone extension (Figure 7B,C).

4. Discussion

4.1. Changes in the ADN

This study examined the changes in an ADN during extreme hydro-meteorological events. In the flysch Carpathian Mountains, located in a temperate climate region, the natural drainage system has developed since the Late Pliocene, and its density is up to 3.5 $km \cdot km^{-2}$ [29]. This density is typical for mountainous areas in the world [31]. The settlement development and economic changes in the 19th and 20th centuries influenced the LULC structure [55], resulting in the creation of a dense man-made incision network in one of the highest mountainous areas in the world [31]. During heavy rainfall, natural and man-made incisions interfere. As a result, the density of the ADN is several times higher in comparison to the river network (2.9 vs. 11.5 km·km^{-2} in the RDN and ADN, respectively, during heavy rainfall). A significant part of the ADN (about one-third) comprises man-made elements, and the LULC has been determined to be an important factor influencing ADN parameters within the catchment. As the proportion of arable land increased, the proportion of human-related elements of the ADN reached 35%. Paved roads and ditches constitute about 15%, whereas the remaining part of human-related elements of the ADN (about 20%) constitute elements strictly related to the functions of arable land such as plough furrows and unpaved rural roads. Horton analysis indicates the internal structural changes of the ADN. The changes were mainly related to (1) an increase in the maximum stream order (from 4 to 6), (2) an increase in the number of *i*-order streams (9–17 times), and (3) a decrease in mean stream length (4–5 times) and mean stream area (9–14 times) drained by the *i*-order streams. It is worth noting that the most important changes were related to first- to third-order streams, which drain stormwater from the slopes (Figure 2), and those streams were usually man-made incisions. A comparison between natural and human-related elements of the ADN led to the conclusion that the human impact on ADN development is important.

In the literature, only a few studies analyzed changes in ADNs caused by human impact [12,19,40,41,56]. The structure of an ADN allowing evaluation of the human impact on ADN development was presented by Wigington et al. for the first time in 2005 in Oregon (USA) [12], with five agricultural catchments (21.6–47.8 km^2 in area) located under Mediterranean climate conditions. They revealed that during rainstorms in winter, the density of the ADN could reach up to 8 km·km^{-2} (Spoon Creek), and man-made elements constituted an important part of the ADN (roads, up to 27%, and furrows cut in poorly drained agricultural fields removing standing water, 3% to 8%, with the maximum 31% in Spoon Creek). Studies performed in three catchments located in moderate climate regions in the foothills and medium-high mountains of the Carpathians [40,41] confirmed that the ADN functioning during heavy rainfall was better developed (density was 6–8 times higher compared to the river network), and man-made elements constituted about 35% of the ADN. These studies also confirmed the structural changes of the ADN, which were similar to those found in the Pielnica catchments in this study by Horton analysis. Taking into account these results, it can be concluded that drainage systems in small catchments that operate during heavy rainfall seem to be similar. This similarity may be strongly related to the presence of human-related elements such as paved/unpaved roads with ditches, plough furrows, etc.

4.2. Changes in an ADN and Their Influence on Hydrological Response and Flood Risk Management in a Catchment

The generally accepted view is that floods occur not only because of rainfall but also because of surface features, by which rain runoff collects, converges, and diverges through natural or artificial channels [57]. With a more efficient drainage system, water moves into streams faster, causing peak flows to be larger and occur sooner. As a result, floods tend to occur more frequently and are more severe, often turning into flash-type floods. Therefore, the second goal of this study was to assess how modifications in ADNs could influence flood wave parameters. The literature review (e.g., [58–62]) indicates that only a few studies have focused on changes in the hydrological response of a catchment resulting from changes in an ADN. The results presented in those works indicate that the peak flow is better reconstructed when the simulated hydrograph considers the parameters of a real ADN, and incorporating the roads in the ADN resulted in an increased peak flow up to 7% [58,59]. The mentioned studies were experimental and were carried out in very small catchments or plots (area <0.1 km^2) using sophisticated physics-based distributed hydrological models which require the elaboration of many parameters [58,59]. For this reason, using those models in larger catchments could be problematic. Therefore, the lumped-type GIUH model, which has been tested worldwide to simulate flood wave parameters in ungauged catchments at different scales (e.g., [1,2,60,61]), was used in this study. Following the suggestion of Kirkby [62] that hydrological models should take into account the dynamic adjustment of channel extension during storms, the dynamic nature of the ADN was characterized by Horton's [5] and Schumm's [7] ratios. Hydrographs were developed for two scenarios, with the R_B, R_L, and R_A ratios describing (1) the river network and (2) the ADN operating during heavy rainfall. They revealed that (a) the differences predominantly occurred in peak flow and (b) the difference between measured and simulated peak flow was lower in the second scenario. A better-developed ADN contributed to an increase in peak flow (up to 7%) in the studied catchment. The results of this study are comparable with those in the literature [58,59], suggesting that changes in ADNs affect the hydrological response of catchments by increasing peak flow up to several percent.

The reconstruction/simulation of maximum flood peak has practical importance. One example is the delineation of flood hazard zones, which is the basis of flood risk assessment and management in a catchment [52]. The use of the Pielnica catchment as a case study provided the opportunity to draw some kind of conclusion about small catchments located in mountainous areas of the internal part of the continent, where locally restricted (<150 km^2), short-duration (<4 h) rainstorms generate flash floods [50]. The delineation and analysis of the dimension of a 1% probable flood inundation area, which according to the Floods Directive [52] is of special interest for flood risk assessment and management, revealed that changes in the ADN had a minor influence on the flood hydrographs and flood hazard zone extension. The changes at the catchment scale did not exceed 5% and occurred in the lower parts of the river valley. This case study seems to indicate that significant changes in the ADN have a small impact on flood hazard levels and the flood risk management process in the studied catchment.

4.3. Importance of the Results, Limitations of the Study, and Further Research

The broad knowledge about natural drainage networks comes from extensive investigation in this topic area (see Instruction section). Changes in a natural drainage network (especially those involving the human impact on ADN transformation) and their consequences have rarely been investigated. In the author's opinion, this aspect deserves research attention because ADNs have a significant influence on the functioning of catchments (e.g., [15,25–28]), and changes in the network provide great potential for practice. This work is an example showing an analysis of changes in an ADN in the context of the hydrological consequences, considering some aspects important for practice (flood hazard/risk management). Some statements related to the importance of the results of this study can be made:

(1) A detailed analysis of changes in an ADN gives new insight into the field of catchment hydrology, showing general and internal structural changes in the ADN and the role of human-induced elements in those changes. The easy accessibility of high-resolution data allowing the reconstruction of surface terrain and GIS-supported analysis gives new opportunities for investigation in this research field. It is worth emphasizing that changes in ADNs, apart from the hydrological response and the consequences (presented in this study), also influence many aspects of catchment functioning, including relief transformation, sediment delivery, the intensity of erosion/denudation processes, etc. The author hopes that this research will attract the attention of other researchers and that more studies will be conducted to recognize how changes in ADNs influence catchment functioning.

(2) The results of this study are comparable to those obtained in other small experimental catchments [60,61] in terms of the hydrological response. This suggests that the influence of a modified ADN on hydrological response (increased Qmax) may be comparable in small catchments (up to several km^2 in area), and the combination of two simple, well-known models in the scientific community, SCS-CN and GIUH, allows the assessment of the dynamic nature of changes in an ADN. The second

conclusion confirms the usefulness of those hydrological tools for further studies in this subject area.

(3) Taking into account the practical importance of the results, this case study reveals that a significant alteration in an ADN can moderately influence flood hazard zone extension. On the one hand, this may suggest that using the GIUH model in its "traditional" form (with the natural river network serving as input data for R_B, R_L, and R_A calculations) gives acceptable results in terms of flood hazard zone delineation. On the other hand, it is worth remembering that flood hazard zone dimensions are conditioned by the river channel and the valley floor relief. The low influence of the modified ADN on the 1% flood hazard area revealed in this study resulted from the large retention capacity of the river channel/river valley floor (deeply incised channel and terraced valley in the study area), resulting from paleogeographical circumstances [29]. In this case, where the channel/valley floor retention capacity is lower, the influence of the modified ADN on the 1% flood hazard area may be more noticeable and have a greater effect on flood hazard/risk assessment. Therefore, more studies are needed in order to expand our knowledge in this research field and draw conclusions that may be important for practitioners, with insights into p-probable flood hazard zone delineation in small ungagged catchments and its influence on flood hazard/risk management.

The results of this investigation are attributed primarily to the approach, which allowed for the assessment of changes in the ADN with special assessment of the human impact on this process, as well as the consequences of ADN transformation on catchment functioning and flood hazard/risk management processes. The important element in this type of study, which guarantees comparability of results, is the quality of the input data used to reconstruct the ADN in GIS software. Those aspects are pointed out briefly in the Methodology section and presented in detail in the literature [40]. This kind of study is very time-consuming and requires hardware appropriate for high-resolution DEM development and preparation for hydrological analysis in GIS software. Moreover, part of the ADN analysis (identifying the human-related elements) requires a manual approach of looking at high-resolution orthophoto maps. Those aspects could be considered as disadvantages at the ADN analysis step. However, in the author's opinion, this is the only way to collect data allowing a complex analysis of changes in ADNs. This disadvantage may be one of the reasons why the investigation has not yet captured the attention of the community. The methodology in this study uses typical, well-known methods in the scientific community in the fields of (1) drainage network analysis, (2) hydrological modeling of flood waves, and (3) hydraulic modeling of inundated areas (described in the literature, see Methodology section). This guarantees that the investigations can be imitated by other researchers.

5. Conclusions

An active drainage network (ADN) is a dynamic component of a catchment and changes during different hydro-meteorological events. During heavy rainfall, the ADN reaches the greatest expansion, and its influence on catchment functioning is the most noticeable; therefore, this moment of ADN functioning is worth investigating in detail. The main conclusions reached in this study can be summarized as follows:

(1) The ADN operating during heavy rainfall in the Pielnica catchment was several times better developed than the river system (2.9 vs. 11.4 $km \cdot km^{-2}$), and man-made incisions may contribute up to one-third of the ADN. Changes were also observed in the structure of the ADN, related to (a) an increase in the maximum stream order (by one to two orders), (b) an increase in the number of *i*-order streams (especially first- to third-order streams draining slopes; by 7–15 times); and (c) a decrease in the mean length of streams (2–9 times) and the mean area drained by *i*-order streams (2–10 times).

(2) Changes in the ADN caused better drainage of hillslopes and catchment, which was reflected in the hydrological response of the catchment. Assessing these changes using

the SCS-SN and GIUH models, in which the dynamic nature of the ADN was reflected in changes in the Horton and Schumm parameters, revealed the following:

(a) The differences between simulated and observed maximum peak flow were smaller when the R_B, R_L, and R_A ratios described a real ADN operating during heavy rainfall, not only the river network, which is a typical approach in practice. It can be concluded that characterizing a real ADN by Horton's ratio improves the model simulation of flash flood wave parameters in small catchments.

(b) Changes in the ADN were reflected predominantly in increased peak flow and were within the range of 2 to 7%. This range may be interpreted as a surrogate measure of how changes in an ADN affect the hydrological response of a catchment.

(3) Accurate reconstruction/simulation of flood wave parameters is important for flood hazard zone delineation, the most important element in flood risk assessment and management in a catchment. The delineation of a 1% probable flood inundation area, which is of special interest for flood risk management, revealed that changes in the flood hydrograph resulting from changes in the ADN moderately affected the flood hazard zone (about 5%). It seems that significant changes in an ADN have rather a low impact on flood hazard/risk assessment and management.

(4) This study presents changes in an ADN and its consequences, taking into account (a) the hydrological response of a catchment and (b) the impact on flood hazard assessment and consequently the flood risk management process. These aspects, as a "chain of linkages", are still not well recognized; therefore, more investigations into this research topic are needed. However, it is worth emphasizing that changes in ADNs affect many aspects of catchment functioning. Therefore, changes in ADNs in relation to relief transformation, sediment delivery, the intensity of erosion/denudation processes, etc., are the research fields that should be explored in the future.

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