


Article

Influence of Changes of Catchment Permeability and Frequency of Rainfall on Critical Storm Duration in an Urbanized Catchment—A Case Study, Cracow, Poland

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Received: 23 October 2019; Accepted: 1 December 2019; Published: 3 December 2019



Abstract: The increase of impermeable areas in a catchment is known to elevate flood risk. To adequately understand and plan for these risks, changes in the basin water cycle must be quantified as imperviousness increases, requiring the use of hydrological modeling to obtain design runoff volumes and peak flow rates. A key stage of modeling is adopting the structure of the model and estimating its parameters. Due to the fact that most impervious basins are uncontrolled, hydrological models that do not require parameter calibration are advantageous. At the same time, it should be remembered that these models are sensitive to the values of assumed parameters. The purpose of this work is to determine the effect of catchment impermeability on the flow variability in the Sudół Dominikański stream in Cracow, Poland, and assess the influence of the frequency of rainfall on values of time of concentration (here it is meant as critical storm duration). The major finding in this work is that the critical storm duration for all different scenarios of catchment imperviousness depends on the rainfall exceedance probability. In the case of rainfall probability lower than 5.0%, the critical storm duration was equal to 2 h, for higher probabilities ($p \geq 50\%$) it was equal to 24 h. Simulations showed that the increase of impermeable areas caused peak time abbreviation. In the case of rainfall with exceedance probability $p = 1.0\%$ and critical storm duration $D_{kr} = 2$ h, the peak time decreased about 12.5% and for impermeable areas increased from 22.01 to 44.95%.

Keywords: time of concentration; impervious; frequency of rainfall

1. Introduction

Urbanization brings a range of environmental challenges for the local, regional, and wider environment as a direct result of the changes it brings to local hydrologic regimes [1–4]. The loss of pervious surfaces reduces infiltration into soils, while the introduction of artificial drainage replaces natural pathways. This combination has a considerable effect on a catchment's hydrological response to rainfall, such as faster response [3,5], greater magnitude of river flow [3,6], higher recurrence of small floods [3,7,8], and reduced baseflow and groundwater recharge [3,9].

Deficiencies in retaining, draining, and transporting rainwater in urban areas are often exposed only during heavy rainfall, when the capacity of the drainage ditch, stream, or river is exceeded and

there are nuisance or even catastrophic floods, which causes material and financial losses. In the light of the potential for significant human and ecological health impacts as a result of urbanization, more extensive research and scientific analyses is prudent to help with developing of storm water management strategies in urban areas. These research also should involve developing of flood-warning systems [10]. This is critical when considering worldwide population growth and migration towards built and urban areas [3]. An example of the management challenges of excess runoff can be seen in Cracow, Poland, an expanding city dealing with the implications of land use change. For instance, in 2014, 7346 new flats were commissioned in the city of Cracow, including 1127 in individual housing [11]. Moreover, between 2007 and 2010, 381 multi-family buildings were built in Cracow [12]. There are a number of environmental (noise, urban traffic, air pollution), economic (expensive housing in the city), and social factors (relocation to the family, the desire to improve the quality of life), which significantly affect the movement of population between urban and suburban areas. To estimate the peak discharges direct methods are commonly used, in which different probability distribution are applied, for example the Two-Components-Iacobellis-Fiorentino TCIF model is based on the assumption that two distinct runoff mechanisms are responsible for ordinary and extraordinary flood events [13]. In case of ungauged areas the rainfall–runoff models for prediction and forecasting of floods are using. Many of models include spatial heterogeneity of catchments parameters and thus runoff forming, like hydrological models referred to as variable source area models [14,15]. In case of urban areas simple rainfall–runoff models are still used, where runoff process are based on Hortonian law.

The effects of impervious areas on urban water balances and its influence on parameters of hydrological models are often noted in literature [16–20], but their influence on the speed of runoff transport can be overlooked. The time of concentration (TC) is an idealized concept and is defined as the time taken by a water parcel of runoff to travel from the hydraulically most remote part of a watershed to its outlet, where remoteness relates to time of travel rather than distance. In reality, the time of concentration is correlated to different watershed parameters such as watershed area, main channel length, basin slope, soil type, and vegetation (roughness) [21]. In case of forecast of hydrological phenomena, the time of concentration significantly influences on tends of time interval [22]. Commonly the time of concentration is interpreted as critical storm duration (D_{kr}). D_{kr} means storm duration that gives the maximum peak discharge [23]. An essential problem with using rainfall–runoff models is the assessment of time of concentration [24,25]. TC is traditionally obtained based on monitored rainfall–runoff events or by using one of many empirical equations [26], is required for estimating peak discharge by the Rational method or the rainfall–runoff models [23,27–29]. However, when these traditional methods are exploited and TC is treated as a fixed parameter, it can lead to underestimates of TC by not considering the runoff hydrograph shape, consequently leading to overestimation of the maximum flows [30].

One particular deficiency in literature is that TC is assessed without regard to the influence of rainfall frequency. Thus, a novel and innovative aspect of this work is an assessment of the influence of rainfall frequency on values of critical storm duration in an urban catchment. The purpose of this work is to determine the effect of catchment impermeability on the flow variability in the Sudół Dominikański stream and provide a case study of the influence of rainfall frequency on values of time of concentration. Specifically, we will investigate how the increase of impermeable areas in the catchment influences the hydrological parameters characterizing the catchment, and focus on the critical storm duration for different design rainfalls.

2. Materials and Methods

The Sudół Dominikański is an ungauged stream located on the Proszowicki Plateau in the Małopolska Upland and in a small part on the Nadwiślańska Lowland in the Northern Podkarpacie—Figure 1. The stream is in the highland climate region of Poland and is greatly influenced by the urban-industrial Cracow agglomeration. The average air temperature from the multiyear 1981–2010 is 8.5 °C and the mean year rainfall is 671.9 mm [31]. The Sudół Dominikański is

a left-bank tributary of the Prądnik river and flows into it at km 1.2 of its course. The total catchment area is equal 16.4 km², while the length of the stream is between 8.95 and 9.3 km. The difficulty in accurately identifying these values results from the fact that at a certain section in Cracow, the entire stream is running in a closed channel up to the estuary of the Prądnik River. Thus, the exact network connected to the stream is difficult to exactly determine.

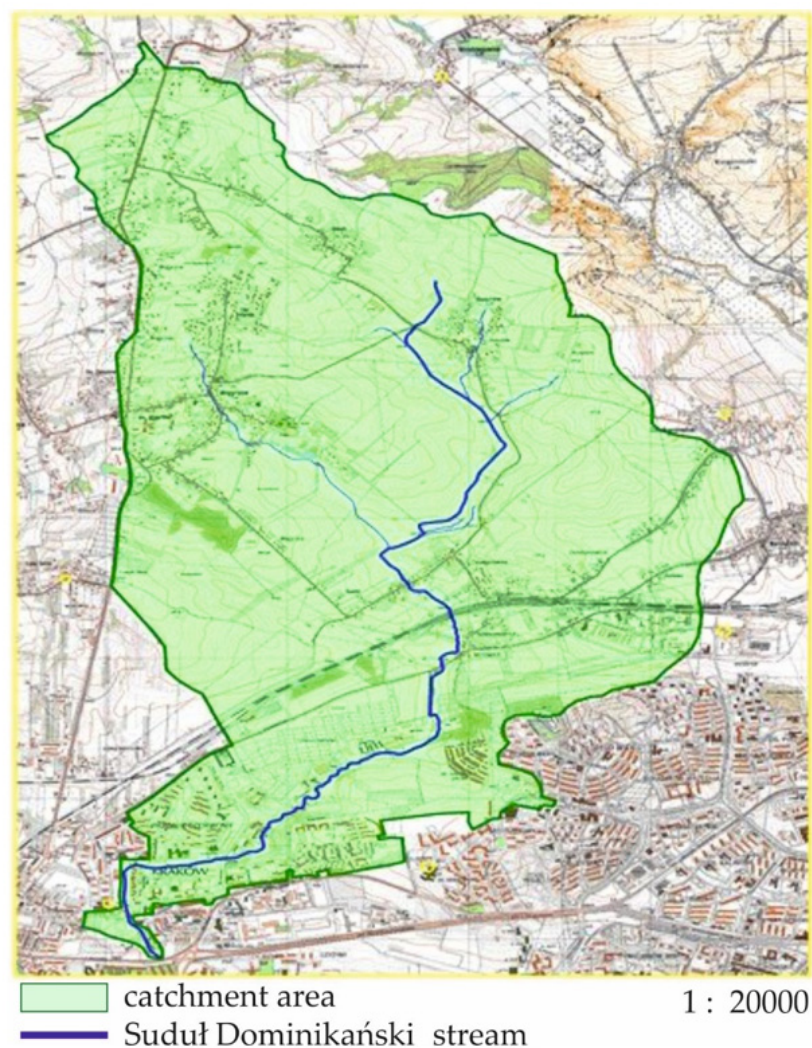


Figure 1. Catchment of the Sudół Dominikański stream.

The catchment is covered by various land uses. In the southern part, in the administrative borders of Cracow, the catchment is highly urbanized with transport infrastructure (streets, squares, and railway lines), municipal (cemetery), economic (industrial facilities), and small green areas (forests) dominating. The central area is dominated mainly by agricultural areas with a few trees and buildings. The western and north-west catchment regions are covered by rural housing with low or medium intensity—Figure 2. Based on the soil maps taken from the Institute of Soil Science and Plant Cultivation—State Research Institute (IUNG-PIB), soils in Cracow were classified to B and C categories according to National Resources Conservation Service NRCS [32]. Topographic maps were used to assess catchment area.

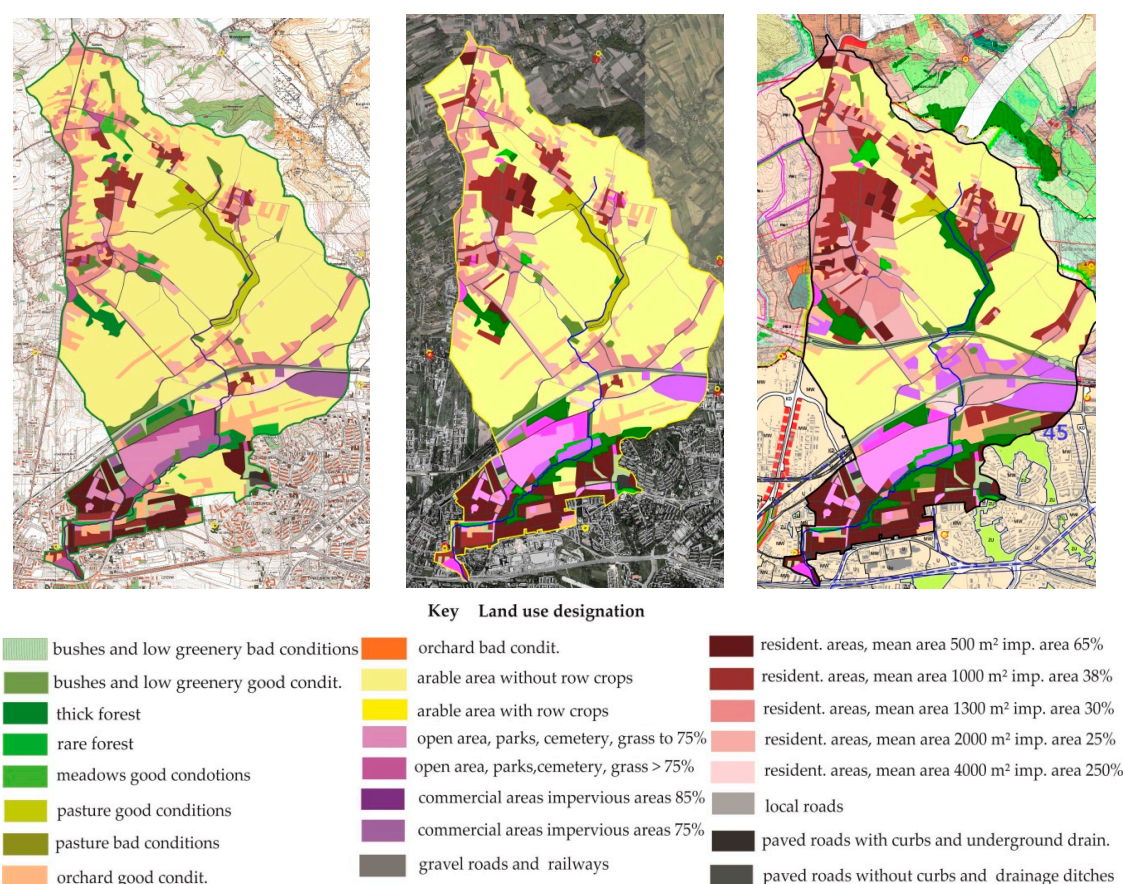


Figure 2. Land use of Sudół Dominikański catchment for variant historical (U1), present (U2), and future (U3).

The Sudół Dominikański stream, in addition to its natural functions, is also used as a receiver of rainwater, especially from the drainage network of the city of Cracow. The number of rainwater collector outlets on the urban section, based on our own inventory, is about 30. In addition, due to the watercourse route, numerous engineering structures contact or are in close proximity to the stream, such as culverts and bridges along the city streets or railway line no. 8 Cracow-Warsaw. The water flow in the stream is free, there are no hydrotechnical objects such as reservoirs or weirs.

The research approach in this urbanized catchment is based on the rainfall–runoff model that was described by Banasik et al. [33]. Among the available rainfall–runoff hydrological computational models, a commonly utilized Nash model was chosen [33]. The Nash model is based on the idea of a single cascade of linear reservoirs. The linear reservoir is characterized by the function binding outflow with water retention in a hypothetical reservoir [33]. The calculation scheme used in the paper is shown in Figure 3.

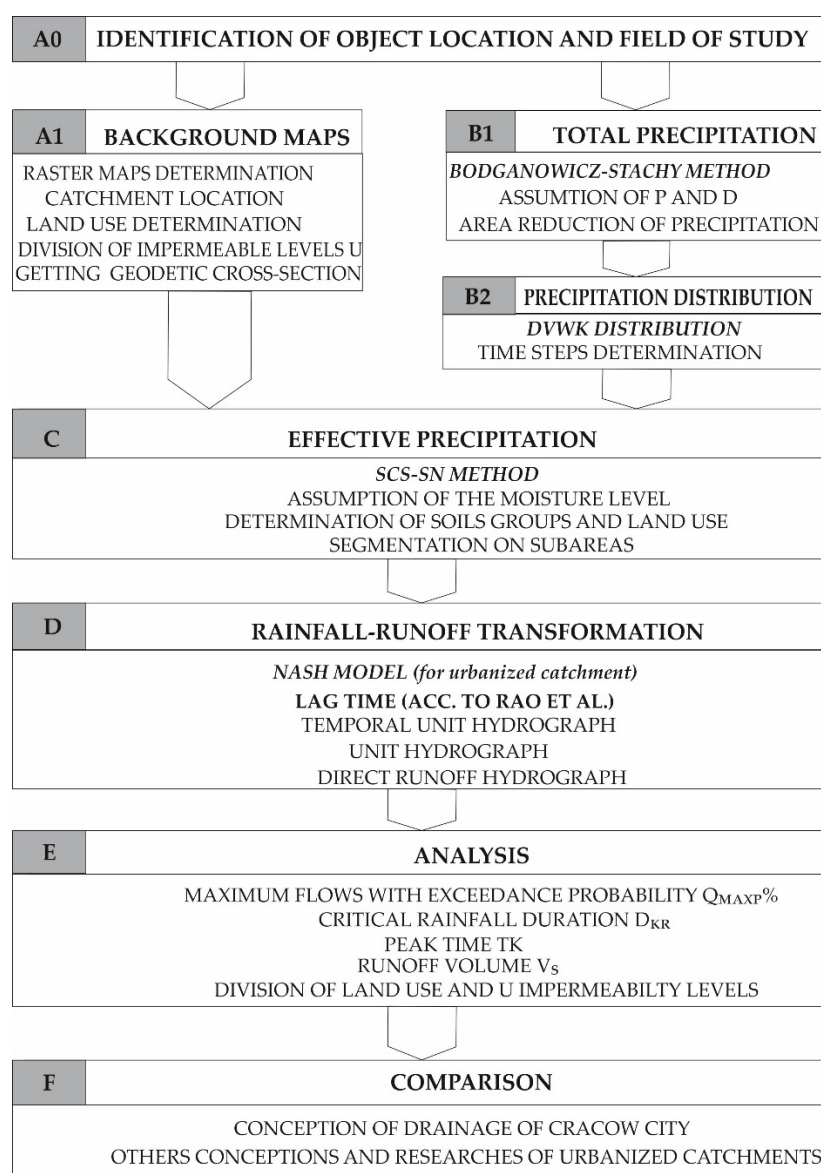


Figure 3. Scheme of the methodology of the research work.

To characterize change in land cover over time, and thus change in outflow, three unrelated maps for the northern parts of the district and the city of Cracow were obtained and developed to represent historical (U1), present (U2), and future (U3) conditions—Table 1 and Figure 2. The variant with the least urbanized catchment area was marked as U1 and the most urbanized as U3. Summary statistics and the data used to create each scenario are presented in Table 1. Changes in the land use over time (i.e., from U1 to U3) are presented in Figure 2.

Table 1. Classification of background maps of the catchments for U impermeability variants.

Type of Background Map	Condition	Years Represented	Impermeability Variant	Percent of Impermeability (%)
Topographic map	Historical	1996	U1	22.01
Orthophotomap	Present	2013	U2	29.52
Map of conditions studies and directions of the land development and the local development plan	Future	*	U3	44.95

* it is not possible to give represented years of the future land cover because the data comes from [34]. In this document, changes in land cover in Cracow are presented without time horizon. Local government in Cracow is supposed to act according to this plan in the future.

The topographical map represents the historical state of land use for this study. It is based on topographic surveying resources from 1996 and represents the land use at that time. The second background map was made on the basis of orthophotomaps, presenting the current state of catchment land use and development. Similar to topographic maps, orthophotomaps have a different execution period, namely from 2013. This is the result of the lack of a unified database by the survey authorities of the city of Cracow and the Małopolska voivodship. The future potential development of the catchment is illustrated by the last map based on graphical annexes adopted for the study of conditions and directions for land development [34] and the local land development plan (LLDP).

The total rainfall with a given probability of exceedance was calculated using the Bogdanowicz and Stachy method, according to the following formula [35]:

$$P_{pD} = \varepsilon(D) + \alpha(R, D) \cdot (-\ln p)^{0.584} \quad (\text{mm}) \quad (1)$$

where:

R—rainfall region characterized area with statistical homogenous annual maximum precipitation time series,

p—probability of occurrence,

D—time of rainfall duration (min),

$\varepsilon(D)$ —scale parameter (mm), calculated by the formula:

$$\varepsilon(D) = 1.42 \cdot D^{0.33} \quad (2)$$

$\alpha(R, D)$ —location and scale parameter of Weibull distribution

The formula is created on the basis of historical annual maximum rainfall for multiyear 1960–1990 for 20 rainfall gauge stations located in Poland, without mountain regions.

The rainfall distribution for storm event was based on Deutscher Verband für Wasserwirtschaft und Kulturbau DVWK method [33]. Direct runoff was calculated based on the Soil Conservation Service-Curve Number SCS-CN method [32,36,37] according to the following formulas:

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10 \right) \quad (-) \quad (3)$$

where:

S—maximum potential catchment's retention,

CN—parameter defining the number of the distribution curve of the average total rainfall for effective rainfall and losses.

The amount of accumulated effective rainfall is calculated using the equation:

$$H_i \begin{cases} \sum_{i=1}^t H_{i(t)} = 0 & \text{if } \left(\sum_{i=1}^t P_i - 0.2S \right) \leq 0 \\ \sum_{i=t}^t H_{i(t)} = \frac{(\sum_{i=1}^t P_i - 0.2S)^2}{\sum_{i=1}^t P_i + 0.8S} & \text{if } \left(\sum_{i=1}^t P_i - 0.2S \right) > 0 \end{cases} \quad (4)$$

where:

H_i —height of effective cumulative rainfall (mm),

$\sum_{i=1}^t H_{i(t)}$ —total height of average effective rainfall (mm),

$\sum_{i=1}^t P_i$ —total height of average rainfall in the catchment (mm).

It was assumed that the CN parameter could be determined for the second stage of catchment moisture (Antecedent Moisture Condition II—Average Conditions). AMCII is commonly adopted to assessing design discharges in catchments. In this case, 5-day sums of precipitation prior to storm event are not known. Nevertheless, in Polish methodology, the AMCII is recommended to assessing the net rainfall from design storms [33].

Transformation of direct runoff into a hydrograph was performed using the Nash model. The basis of calculations is the probability density function of the gamma distribution with two parameters described by the equation [33]:

$$u(t) = \frac{1}{k \cdot \Gamma(N)} \cdot \left(\frac{t}{k} \right)^{N-1} \exp\left(-\frac{t}{k}\right) \quad (5)$$

where:

$u(t)$ —coordinates of instantaneous unit hydrograph (h^{-1}),

t —time from the beginning of the coordinate system (h),

k —parameter of reservoir retention (h),

N —number of reservoirs (-),

$\Gamma(N)$ —gamma function which value for the total number of reservoirs is: $\Gamma(N) = (N - 1)!$

Lag-time was calculated according to the relationship developed by Rao et al. [33] from the formula:

$$LAG = 1.28 \cdot A^{0.46} \cdot (1 + U)^{-1.66} \cdot H^{-0.27} \cdot D^{0.37} \quad (6)$$

where:

A —catchment area in (km^2),

U —share of impervious areas in the basin

H —height of effective rainfall (mm),

D —time of effective rainfall (h),

The k parameter of reservoir retention was calculated from the formula [33]:

$$k = 0.56 \cdot A^{0.39} \cdot (1 + U)^{-0.62} \cdot H^{-0.11} \cdot D^{0.22} \quad (7)$$

The N parameter of number of reservoirs was calculated from the formula:

$$N = \frac{LAG}{k} \quad (8)$$

The direct runoff hydrograph was calculated using the formula:

$$Q_i = \sum_{k=1}^k h_k \cdot H_{k-i+1} \left(\text{m}^3 \cdot \text{s}^{-1} \right) \quad (9)$$

3. Results and Discussion

3.1. Effect of Land Use Change on Maximum Flow and Hydrographs Shape

As anticipated, the three map variants (U1–U3) showed increasing impervious areas over time, with notable trends of suburbanization in the northern communes adjacent to Cracow (Figure 2). The changes in land development are particularly visible in the decreasing of the dominant land use, i.e., arable land. According to the local law, agricultural areas will cover only 4.63 km² in the future (variant U3), while at the beginning of the comparative period (U1 variant) the identified agricultural area is 7.39 km², which is over one and a half times greater. In addition, the share of land use by orchards and gardens decreases from 0.85 km² to 0.57 km² for the variants U1 and U3, respectively.

At the same time, the process of land development by residential buildings is noticeable. In the U1 scenario, the residential development occupied the area of 2.09 km², in the U2 variant (present condition) it covers the area of 3.05 km², while in the U3 variant the existing and planned building area will already occupy 4.70 km². This represents a substantial increase in development, almost doubling the footprint of residential buildings. It is regrettable that no local plans and laws in the analyzed area provide and even require the construction of stormwater controls that would help to compensate an increase in catchment impermeability [38]. Another land use category that follows the development of housing is roadways. As long as no significant changes are expected for railway lines, the development of transportation routes is necessary and evident. For the U1 variant, the total road area is 0.53 km², for the U2 variant it increases to 0.57 km², while for the U3 variant to 0.62 km².

The economic development of the catchment area is also visible in the form of over two-fold increase in industrial areas, from 0.32 km² in the U1 variant to 0.69 km² in the U3 variant. Interestingly, the share of forested area also increases. From the least to the most impermeable variant of the catchment, these areas rise from 0.32 km² through 0.53 km² to 0.83 km². This is extremely important in the context of retention compensation in the form of forest and grasslands, as increases in impervious land uses are expected [39]. According to [40], increases in urban/residential development may cause decreases in watershed ET. This may be mitigated to some degree by increasing green spaces, in particular if impervious connectivity is reduced by routing urban runoff to these spaces [41]. It also should be noted that the area of open spaces and bushes varies for a given scenario (U1–U3).

The comparison of hydrographs for direct runoff under scenarios U1, U2, and U3 is shown in Figure 4 for a 1% probability storm using a storm duration equal 2 h. As expected, the highest maximum flow Q_{\max} for $D = 2$ h was for the most impermeable scenario (U3), for which the direct outflow curve is also the steepest. The smallest maximum flow (Q_{Ux}), and largest time to peak (T_p) was in the least urbanized scenario (U1). The curve of this outflow is also more flattened and elongated over time. According to Figure 4, the time until the peak flow also changes with impervious area. The maximum flows Q_{\max} occur at different times and show shorter critical storm duration (please notice: the critical storm duration is the same as the time of concentration) as impermeable area percentage increases: for U1, $D_{kr} = 2.00$ h; for U2, $D_{kr} = 1.92$ h; for U3, $D_{kr} = 1.75$ h. Changes of land use have an influence on parameters of rainfall–runoff model, mainly on CN value. In case of land cover variant U1 with 22.01% of impervious areas, average CN was equal 74.9, for variant U2 with 29.52% of impervious areas, $CN = 76.1$ and for variant U3, where impervious was 44.95%, the CN is equal 77.3. It is visible that there is slight increase of CN, but it is not dramatic. Thus, peak discharge and runoff volume will be increased but differences are moderate. It should also be noted that the sub catchments within the Sudół Dominikański may have their own critical storm durations depending on their size and land use, a further complicating factor in holistic watershed management. Regardless, the increase

of urbanization contributes to both flow and volume increases, and even slight changes in the CN that occur due to underestimation or changes in land use policy could exacerbate this problem [41,42]. Further, the lowering of time of concentration has a substantial impact on peak flows yet is often not given as much consideration as land use change. Again, routing urban land use to green spaces may aid in delaying this time of concentration, reducing flood risk. Overall, the larger volume of runoff and the higher efficiency of water conveyance through artificially straightened channels can lead to wider stream channels, as well as to increasingly frequent and severe floods [41,42]. When a large-scale flood occurs, the rainfall intensity is greater than the infiltration rate, which causes more surface runoff [43]. For cities such as Cracow, this is of significant concern as increased flooding may occur without adequate interventions that address increases in runoff volume and reduced time of concentration.

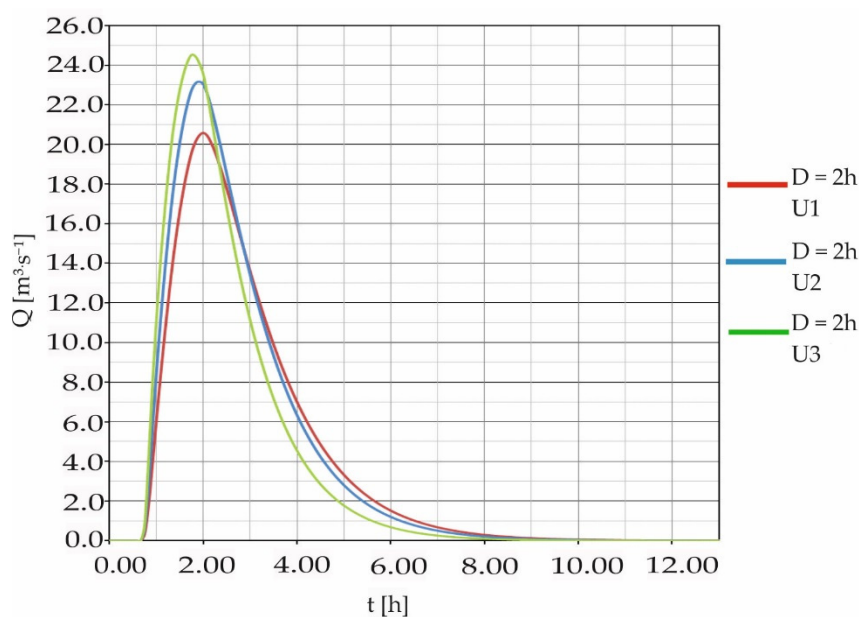


Figure 4. Hydrograph of a direct runoff for rainfall of $p = 1\%$ and $D = 2$ h for catchment impermeability in the U1, U2, and U3 variants.

Considering land use changes in the catchment over time allows an analysis of how maximum flows and runoff values are affected for different rainfall duration and exceedance probabilities. Based on changes in land use in the Sudół Dominikański, the examination of influence of land use changes on the maximum flow variability—Figure 5 was possible. Land use was grouped into three clusters, which were also assigned a percentage share in the whole catchment area. Impermeable areas (% U as in Table 1) represent roads, railway lines, car parks, squares, and industrial areas. Agricultural areas correspond to cultivated areas. Grasslands are forests, orchards, bushes, pastures, and cemeteries. The historical change in the maximum flow for conditions $p = 1\%$ and $D = D_{kr}$ (2 h) is also presented on a percentage scale. The baseflow $Q_{U1, D_{kr}} = 20.58 \text{ m}^3 \cdot \text{s}^{-1}$ was adopted as a threshold for comparison, and its value was 100%. On the x-axis, A represents the percent share of land use (impervious, arable, and grassland) in the catchment.

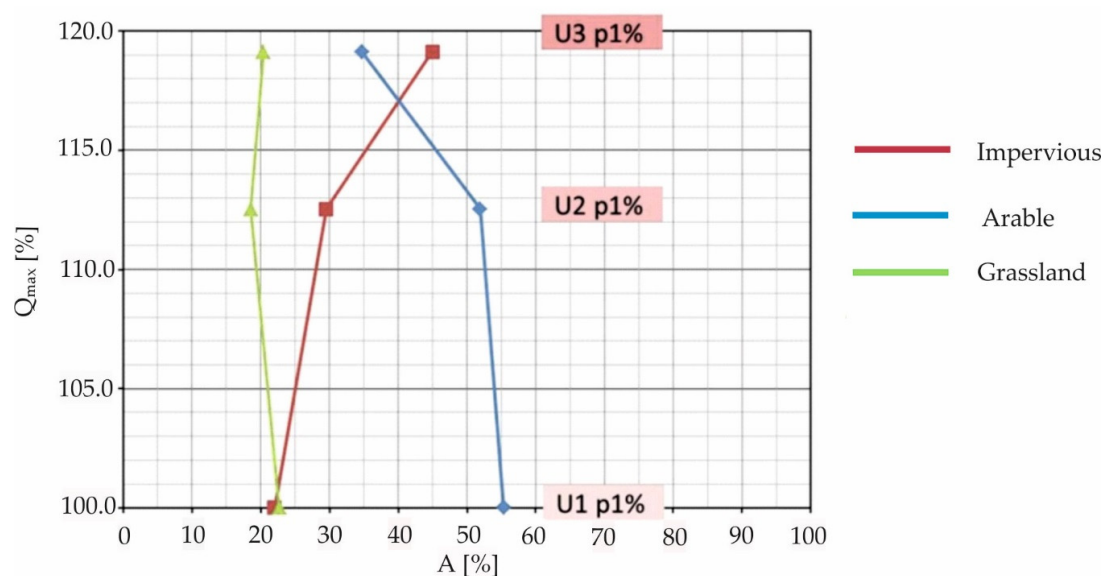


Figure 5. The increase of maximum flows for time of concentration (TC) of rainfall when changing the share of catchment land use for impermeable levels of the U1, U2, and U3 variants.

For the variants U1, U2 and U3 of land use, the CN and Nash model parameters (k and N) were calculated and used in the simulations of peak discharges for critical storm durations. Finally, the percentage difference between peak discharges for historical and future scenarios was calculated. An increase of flow by 13.0% and 19.0% for the U2 and U3 catchments (as compared to U1) results from notable increases in impervious area and decreases agricultural land—Figure 5. However, the highest change in maximum flow was observed between U1 and U2, not U2 and U3 as might be expected by the larger increase in imperviousness anticipated between present and future conditions. That is, the increase in impervious area was only 10% between U1 and U2, and 15% between U2 and U3. The rapid change for the U1 and U2 catchments in relation to the U3 can also be explained by changes in grassland areas with retention capabilities. For the U1, its share is 22.67%, while for the U2 it is already 18.58% and increases for the U3 to 20.37%—Figure 5. It must be remembered that built-up areas are the most sensitive areas for the occurrence of floods, but also that green space has potential for rainwater collection and its subsequent reuse [20].

Changes in the land use of urban areas, and the subsequent implications for hydrology, seem to be neglected by developers. The developers themselves are not interested in losing land that could be used for residential or commercial development to allow water retention. The change in retention quantified in urbanized areas is not enforced by any strong law in Poland. At the same time, as the impermeable areas increase, the values of storm flows is higher, and subsequently increases flood risk [44,45]. Modern technologies that would reduce surface runoff may offer some relief, for example filter strips and biofilters [46], which are recommended in other cities to restore hydrology, bring resilience to climate change, and provide a host of additional ecosystem services [47]. In this context, the knowledge of development scenarios and their effect on the behavior of urban catchments is essential in the country, where we lose surface water at a mesmerizing rate.

3.2. Influence of Land Use and Rainfall Frequency on Critical Storm Duration

Shortening the critical storm duration of maximum flows can also be observed in relation to the length of rainfall duration. This relationship is shown in Figure 6. Critical storm duration for each impermeability percentage (U1–U3) are very similar for a 1-h duration storm. However, as rainfall duration D increases, the critical storm duration shows increased deviations among the variants. Specifically, critical storm duration decreases as impermeability increases (for larger durations). Overall, the higher the percent of impermeability, the more the curve is flattened, and thus the time to flow culmination is shorter.

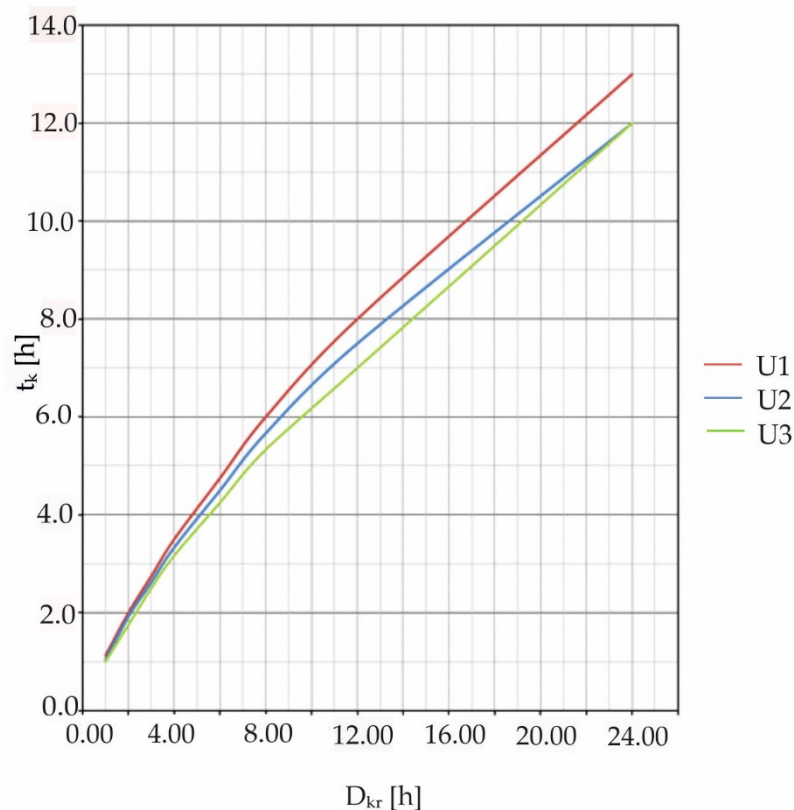


Figure 6. Relationships for critical storm duration for maximum flows in relation to the rainfall duration D_x at $p = 1\%$ for catchment impermeability in the U1, U2, and U3 variants.

The deviation between critical storm duration among the scenarios is largest for rainfall characterized by the duration of $D = 12$ h. In fact, the maximum flows (Q_{max}) determined for different rainfall probabilities showed that different time of concentrations were responsible for producing peak flows for the different variants. It is therefore necessary to identify individual times of concentration for a certain exceedance probability and given level of impermeability. To better illustrate this relationship, Figure 7 was produced.

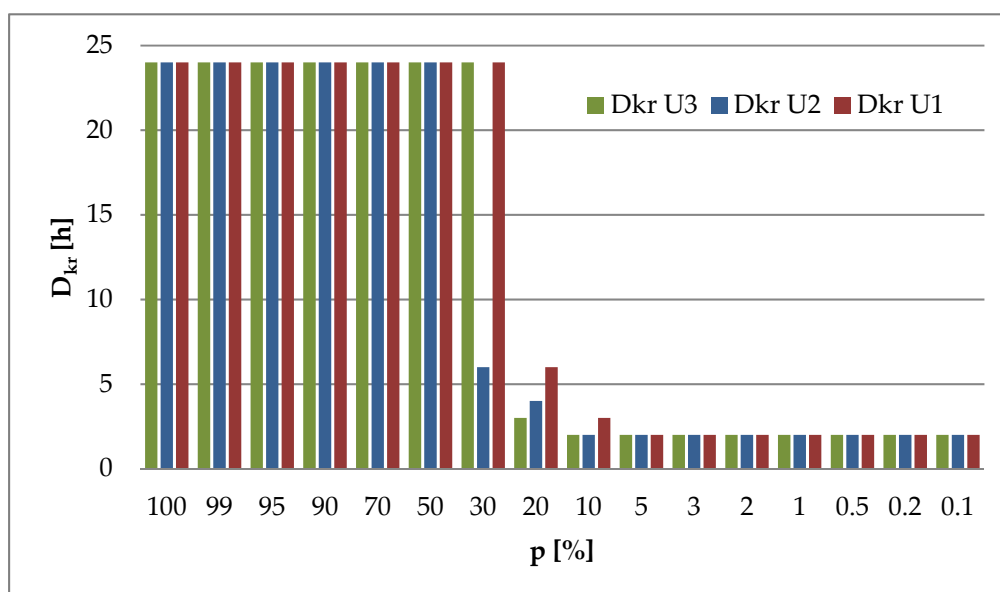


Figure 7. Critical storm duration producing maximum flows for various exceedance probability storms for variants U1, U2, and U3.

For probabilities $p \leq 5\%$, the D_{kr} is 2 h for all scenarios, while for probabilities $p \geq 50\%$ the D_{kr} is rainfall equal 24 h. However, differences in the values of D_{kr} for each scenario occur for the probability $p = 10\%$, $p = 20\%$ and $p = 30\%$. Interestingly, for the maximum flows for $p = 20\%$, the D_{kr} decreases with the increase of the percent of impermeability areas. The D_{kr} may be used in the future to develop an early warning system against the occurrence of intense rainfall. An example of how to develop such a system can be found in the work of [48]. These data indicate that such a system must be temporally adaptive whereby the warning is provided more quickly during low probability events. Proper choose the critical storm duration and of course appropriate calculation of frequency rainfall can decrease uncertainty of results achieved from rainfall–runoff model [49]. It should also be noted that the subcatchments within the Sudół Dominikański may have their own critical storm durations depending on their size and land use, a further complicating factor in holistic watershed management.

This outcome is significant, as critical storm duration is often not considered in watershed management and regulation. For instance, in many locations in the USA, stormwater management designs for flood mitigation interventions (such as retention and detention ponds) are based on a 24-h storm event for all storm probabilities [50]. These results suggest that a blanket regulation that doesn't consider how critical storm duration changes with storm probability may lead to undersized interventions. This is a concern as the level of flood protection anticipated to exist in these regulated watersheds may not be present. Further, calculations that aim to determine the peak flow that a given area will experience for a certain probability storm (for the purpose of assessing flood risk) may be inaccurate. In short, this outcome points to the need for more site-specific regulations for watersheds.

Proposed method of critical storm duration calculation can be used in urban catchment, where streams often have many hydraulics structures, that significantly changes the travel time of water - Figure 8. In many case the structures lag the travel time and thus the time of concentration. Commonly used formulas for calculation of time of concentration do not include these structures and thus time of concentration could be over- or under-estimated. In addition, many methods for assessing the time of concentration give results characterized by high variability. In the work of Wałęga et al. [51], it showed that the time of concentration, calculated with use 7 methods, has varied between 1.99 to 3.08 h and did not depend on rainfall probability. These results are similar to those obtained in this study of the critical storm duration which is equal 2 h, for probability between 0.1 to 10%.

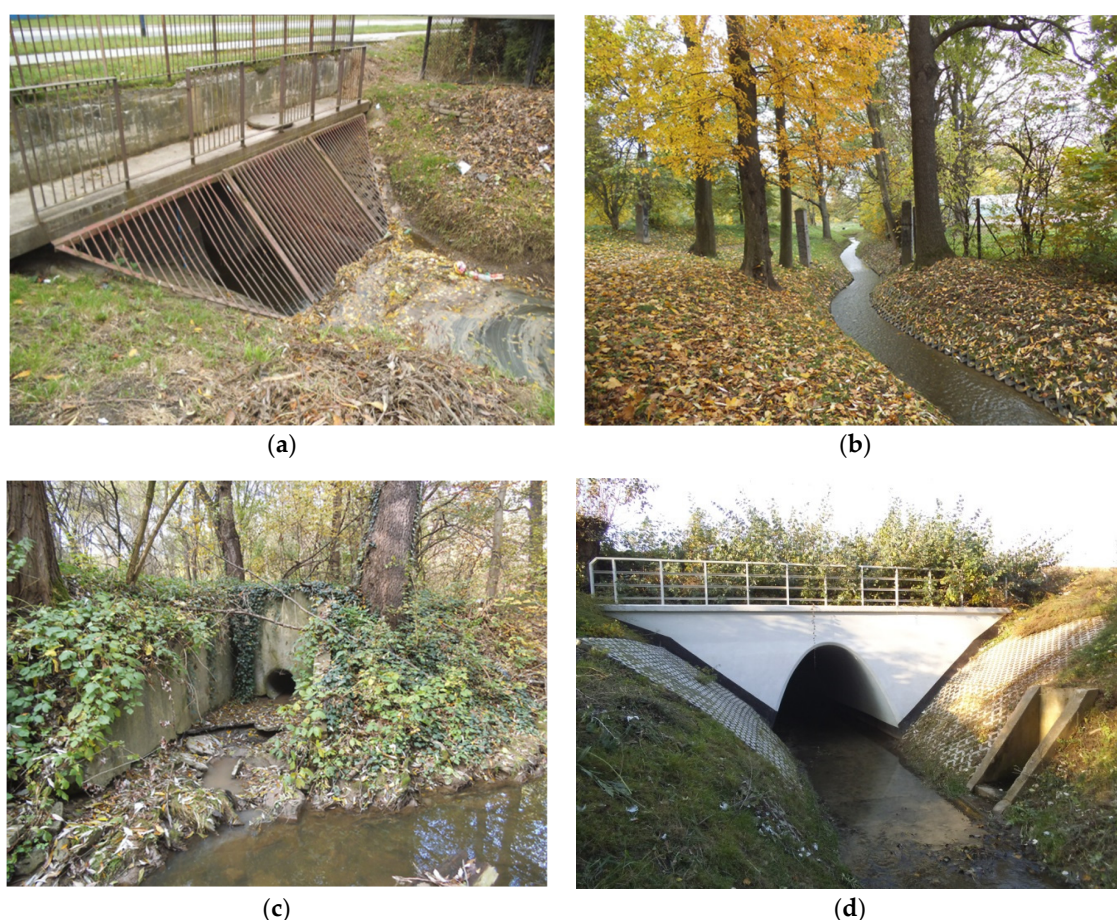


Figure 8. Pictures of Sudół Dominikański stream: (a) watercourse inlet to the culvert under the street at the estuary of Sudół Dominikański stream to the Prądnik river, (b) stream bed in the urban area, (c) outlet of the rain collector to the Sudół Dominikański stream, (d) culvert under the railway line.

4. Conclusions

Hydrological analysis of the Sudół Dominikański stream in Cracow, was performed for historical, present, and future conditions labeled U1, U2, and U3, respectively. An increase in maximum flows was noted over time (variant U1 to U3) and linked to an increase in catchment imperviousness. For rainfall with exceedance probability $p = 1.0\%$ and critical storm duration $D_{kr} = 2$ h, the increase of impermeable areas by 10% between catchments in variants U1 and U2 caused an increase of maximum flow by 12.54%, while between catchments in the U1 and U3 variants, these increases in imperviousness and maximum flow amounted to 19.14% and 22.94%, respectively.

The analysis of maximum flows showed that the D_{kr} of rainfall for all variants of the catchment depends on the rainfall exceedance probability. With some exceptions (i.e., $p = 10\text{--}30\%$), for rainfall with probability $p \leq 5.0\%$ it is 2 h, while for higher probabilities ($p \geq 50\%$) it is 24 h. Moreover, the increase of impermeable areas caused peak time abbreviation. And so, for rainfall with exceedance probability $p = 1.0\%$ and $D_{kr} = 2$ h between catchments for the U1 and U2 variants, peak time decreased by 4.00%, but between catchments in variants U1 and U3, this decrease was 12.50%, respectively. The highest maximum flow was for $p = 0.1\%$ and $D = 2$ h, for the U3 variant, while the lowest flow for $p = 99.0\%$ and $D = 2$ h for the U1 and U3 impermeability variants. Additionally, the shape of direct runoff curves for extreme conditions (high U, short D, small $p\%$) was much steeper than for milder conditions (low U, long D, large $p\%$).

Overall, this work highlights the influence of rainfall frequency on D_{kr} . This is important, since D_{kr} is often considered to be a static parameter in hydrological models. This assumption can lead to

under or over estimation of maximum peak discharge. It is also an important parameter to consider when managing impervious surfaces in urban catchments and it is worthy of more study in the future using more examples and case studies. Considering critical storm duration as different values for a particular rainfall frequency can lead to a more suitable assessment of design peak discharges. Such analyses will aid decision makers in the efforts to reduce urban flooding and the ecological detriments of imperviousness.

Author Contributions: Conceptualization, A.W. methodology, A.W. and M.P.; software, M.P.; formal analysis, A.W. and A.R.-P.; investigation, M.P.; resources, A.C., A.R.-P. and J.H.; data curation, M.P.; writing—original draft preparation, A.W. and M.P.; writing—review and editing, A.C., A.R.-P. and J.H.; visualization, M.P.; supervision, J.H.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank Dean of the Faculty of Environmental Engineering and Land Surveying, University of Agriculture in Krakow, for financial support. We thank the anonymous reviewers for their constructive comments which helped to substantially improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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