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Investigating the effective factors influencing surface runoff generation in urban catchments – A review

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ABSTRACT

The natural water cycle in an urban catchment normally results from climate, physical characteristics and natural surface coverage. The hydrological process in urban catchments can drastically change due to urbanization, human activities, modified physiography and climate change. Urbanization typically results in a larger runoff volume, higher peak discharge, faster time of concentration as well as lower infiltration. It also has a significant impact on the precipitation intensity and patterns. Antecedent soil moisture, steep slopes and roughness will lead to uncertain rainfall-runoff behavior as well. Climate change will usually alter temperature, precipitation intensity and duration along with the runoff timing and magnitude. Various number of studies have proved that urbanization and climate change would have stronger effect on urban rainfall-runoff behavior than other factors. We have reviewed and investigated various and the most effective factors influencing urban runoff generation in this paper. Particularly, the anthropogenic, geomorphologic and meteorological impacts on urban surface runoff have been the focus of this review paper. The study gaps and suggestions for further research have also been discussed at the end. Finally, the best measures to be taken into consideration to mitigate urban excess runoff have been suggested in the final section.

Keywords: Climate change; Hydrological process; Stormwater runoff; Urban catchment; Urbanization

1. Introduction

In a natural watershed, there is a unique climate, topography, vegetation and coverage resulting in a natural water cycle and hydrological response. Different factors can affect this unique natural hydrological process and cause adverse effects to the catchment. Although geomorphological features of urban areas, such as topography, geology, soil characteristics, slope and roughness have profound impact on runoff generation, the anthropogenic effects are specifically important in this respect. The continuous growing population and large human activities in urban areas as well as water resources development plans have led to some issues on water scarcity in different parts of the world [1]. Population growth and urbanization reinforce the pressure on the environment and is usually a threat to water resources sus-

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tainability [2,3]. Land use changes in the process of urbanization can have a severe impact on runoff generation, too [4]. Hydrological processes are also significantly affected by human activities in urban catchments [5]. Due to the growing population and the resultant impacts on urban hydrology, it is of high interest to understand how various factors, including human activities, influence the hydrologic variables in urban catchments [6].

The main reason for many alterations in the natural hydrological processes in urban areas is population growth and the pertinent human activities, changing the natural features of urban catchments. Based on the United Nations reports, a great deal of people are residing in urban or urban-like areas throughout the world [7]. Also, based on the population projections, urban population will reach 80% of the total population by the year 2030, especially with the highest growth in megacities and developing countries [8].

This population growth, along with the migration of people from rural areas to mega cities, have led to the vast development of urban areas. As a result, natural pervious surfaces have been modified into a wide range of sealed surfaces, such as paved roads, parking lots and roofs that typically clear the vegetation and compact the soil [9]. This process is broadly known as urbanization which greatly affects urban catchments. Therefore, urbanization usually results in the modification of natural landscapes; and eventually vegetated surfaces are replaced with impermeable surfaces [10].

The main results of urbanization are: increase of road surface areas [11–13]; reduction of drainage capacity [14]; channelization and engineered water exchanges, especially among major surface waters [15]; as well as land modification for agriculture [16]. Another consequence of urbanization is that the runoff pathways in urban catchments will be altered [17]. This would significantly affect urban hydrologic cycles [18].

Urbanization is occurring rapidly in many areas of the world and has gained high interest in the international political issues [19–21]. This rapid urbanization has been mainly addressed from a scientific and socioeconomic aspect [22–24]. The urbanization process has produced numerous modifications to the natural environment. Future projections show that it will rise from 75% in 2000 to 83% in 2030 in developed countries, whereas it is estimated to rise from 40% to 50% in developing countries at the same period [25].

Apart from the local and regional environment, urbanization brings about different challenges to the wider environment as well. The biological and physical characteristics of hydrological systems will significantly be affected [26,27]. The infiltration of runoff will also decrease with the reduction of pervious areas, although artificial drainage can replace the natural pathways. This can possibly have a substantial impact on the hydrological response of a catchment, including faster response [28], higher river flow [29], greater return period of small floods [30], reduction in base flow, and groundwater change [15].

The most significant difference between urban and non-urban catchments is related to sealed surfaces versus vegetated areas. The impact of soil sealing, which decreases infiltration and increases surface runoff in storm events, is the most common urban feature to be modelled [8]. A storm event in urban areas is an event in which the rainfall depth is usually greater than 0.8 mm, which is the least amount to initiate runoff [31] . When the runoff volume and peak flow increase in urban areas, the ecosystem, human and their property and the water quality will be adversely affected. Urbanized catchments are typically much smaller compared to natural watersheds and have been designed by engineers in such a way to be able to drain the runoff efficiently [32].

Various factors, such as land use, soil texture, antecedent soil moisture, and rainfall intensity can affect urban runoff, which usually have complicated interactions. Urbanization is the most significant one, leading to higher runoff volume, and therefore cause flood disaster [33].

An urban catchment consists of a heterogeneous mixture of natural and artificial surface coverage. It should also be noted that the natural and artificial processes interact with each other in urban catchments (Fig. 1). Therefore, achieving a standard definition for the urban water cycle is difficult. However, in modified natural network, water still follows the traditional hydrological paths network in the natural part of catchment. For instance, infiltration will happen on locations in which the soil has not been sealed. The water movement in the subsurface is also affected by urban soil composition which is not normally natural soil. Groundwater discharge will also be affected in different locations if the surface and the groundwater systems are not naturally connected. Also, flow of waste water in sewers, flow of water supply, stormwater flow, leakage from pipes, irrigation, infiltration of water due to artificial ponds and septic tanks, and wastewater release into surface water are part of the water cycle in an urban catchment [8].

Hydrological processes in urban environments and natural catchments are different from each other because urbanization changes the physical environment which influences both water quantity and quality. Natural hydrological processes, such as infiltration and overland flow are modified and new processes will replace them

The hydrologic process in an urban catchment typically encompasses precipitation, evapotranspiration (ET), overland flow, infiltration, depression storage, and surface runoff. Part of the precipitation will infiltrate into the ground and part of it will return to the atmosphere via ET. Part of the rainfall neither retains on the surface nor infiltrates deep into the soil which is known as excess rainfall, or effective rainfall. Excess rainfall flows over the surface and turns into direct runoff at the catchment outlet [34]. The flow regimes in a watershed are determined by watershed characteristics which are typically inclusive of climate, geology, topography, soil vegetation, and human activities [9]. Different factors might impact the amount and extent of surface runoff generation as discussed in the following sections.

Fig. 1 gives a summary of a wide range of hydrologic processes which could possibly take place in a normal urban catchment system. Each one of these variables has a different unique complexity and has been investigated separately in different studies in the past years. The scales of time and space noticed in urban catchments, precipitation, overland flow, infiltration, depression storage, and surface runoff are widely known as the main hydrologic variables to be deeply comprehended and simulated in urban areas [32].

Erosion and sedimentation are other adverse effects of surface runoff increase in urban areas. The increase in

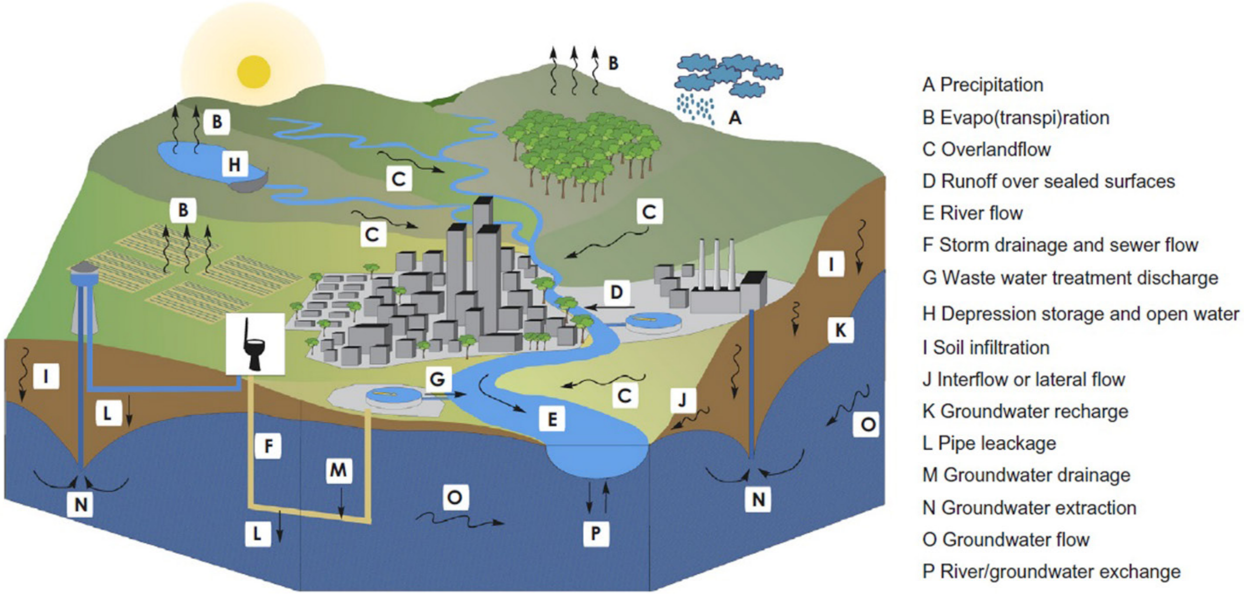

Fig. 1. Water cycle in an urban catchment which is not typically homogeneous and undergoes different physical phenomenon and interactions [8].

storm runoff volume, frequency and peak flow can lead to intense erosion in stream channels and severe downstream flooding. The most significant influence is the degeneration of natural stream channels. The eroded sediments will be deposited downstream, harming the aquatic life and ecosystem [35].

Another significant factor, which plays an important role in both intensifying and mitigating surface runoff, is the surface sealing particularly in smaller rainfalls. In these events, the runoff generation is typically lower than the infiltration due to the permeability or impermeability of the surface soil. Therefore, alterations of the surface cover in urban areas will result in a great effect on the surface runoff in severe annual rainfall events [36].

Several methods are used to control the quantity and quality of urban stormwater runoff. Traditionally, the urban drainage has been used to direct and harvest the urban stormwater runoff. The newly developed “Low Impact Development” (LID) “Best Management Practices” (BMPs) are broadly used nowadays to mitigate the devastating impacts of stormwater runoff. They have been widely studied in the past years by different researchers. For instance, [37–41] are few examples to be mentioned in this respect.

Temporal and spatial scales of runoff flow mainly depend on the geo-morphodynamic characteristics of catchments. Hence, the runoff from river is typically faster than the surface flow and based on that its temporal scale varies mostly according to the precipitation intensity and the channel morphodynamic properties. The river runoff time scales characteristics and surface flow usually lie in the range of minutes to days [8]. However, a wide range of factors impact the natural hydrologic process and flow regime in urban catchments. An increasing number of studies have been performed to investigate these factors. So far, climate change, land use/ land cover, urbanization, soil characteristics, slope, topography, and precipitation characteristics have been the focus of a great deal of research, investigating urban runoff.

One main factor influencing the surface runoff and hydrological processes in urban catchments is urbanization. The main factor leading to hydrological changes in urban areas is the catchment imperviousness which directly affects the runoff [10]. Urbanization decreases the natural temporal and spatial scale of runoff process because urban surfaces are usually spatially heterogeneous and also because urbanization reduces the catchment response time to precipitation [8].

Another important factor is the rainfall intensity and patterns in urban areas. It seems that urbanization can mostly affect precipitation intensity and patterns, whereas the rainfall spatial and temporal scales are not severely affected [8].

The catchment physical characteristics, such as soil type, slope, and topography also affect the runoff generation in urban catchments. Climate change is another significant factor to impact precipitation, and consequently the runoff generation. Many studies have been carried out to investigate this phenomenon over the past few years. Although many studies have investigated climate change and human activities separately, it has been proved that both factors play an important role in urban runoff generation. So, studying both factors simultaneously will help to figure out the contribution of each to the runoff generation.

The aim of this review paper is to provide an overview of the main factors influencing surface runoff generation in urban catchments, while primarily focusing on the physical characteristics of urban catchments, human activities, and climate change. The hydrological response of urban catchments is usually affected by a wide variety of factors, including imperviousness and engineered drainage systems, typically increasing peak flow, flow variability, and annual runoff volume, while decreasing lag time and infiltration rate [26]. As far as the water resources perspective is concerned, urban catchment runoff is the most significant component of the hydrologic process in urban areas. That is why many researchers are eager to widely study hydrological modelling, human activities, and climate change effects on the hydrological response of catchments [43–45]. Identifying the factors contributing to runoff generation in urban catchments will help researchers to consider the optimal control measures in urban planning. This review paper aims to summarize the literature on the most challenging and significant factors influencing runoff generation in urbanized catchments. There are various factors contributing to surface runoff; among which anthropogenic factors, geomorphologic characteristics, and atmospheric factors (climate change and precipitation) play the most important role in the hydrologic response of catchments.

The review will summarize the most significant factors, influencing runoff generation and discuss the research gaps for further studies. This review will also discuss the most important measures to mitigate and control the excess runoff in urban catchments.

2. Anthropogenic impacts

Human activities significantly influence runoff generation in urban catchments. As a result, they have gained a great deal of attention in the past few years [46]. The anthropogenic impacts (sometimes integrated with climatic impact) on runoff generation have been the focus of many studies by researchers recently: (e.g. [47,48]. Human activities have also severely changed the agricultural environments [49–51]. The development of agricultural practices has motivated a large portion of population to immigrate to cities and mega-cities in the past three decades [52–55]. This has largely resulted in urban catchments land use/land cover modification which has influenced the runoff variability [56]. The anthropogenic effects and urbanization have led to the extreme modification of urban pathways, which sometimes become more complicated when water is imported from other catchments (Fig. 1) [57]. Urbanization is the most significant aspect of anthropogenic impacts in urban areas, affecting surface runoff. Field data has also been used by some studies to investigate the hydrological effects of urbanization [58–62]. Urbanization results in land use changes and imperviousness, which greatly affect the runoff generation. Nevertheless, very few studies have been directed towards surface runoff response of urbanization.

2.1. Urbanization

The process of urbanization results in considerable and drastic hydrological effects on natural catchments, including runoff volume and peak discharge increase, and base flow reduction, which is due to the alteration in imperviousness percentage and the decrease of infiltration rates [63–66]. Another consequence of urbanization would be that the hydrological response of a catchment to precipitation will change, i.e. the volume, peak flow, flood risk and pollution will increase, and the low flow will decrease [67,68]. What is more, the impacts of urbanization on runoff processes are not only dependent on the urban area but also on the extent of urban catchment development. The small-sized and heavily urbanized river basins are more prone to urban runoff rather than large river basins, which flow through cities. In the large-sized river basins, the runoff peaks constitute only a small portion of the flow [69].

Urbanization results in enormous effects on watershed [70]. It will cause water to more quickly flow across catchments because the land surfaces have less hydraulic resistance, which are mainly due to the sealed surfaces, compacted soils, and subsurface drainage [57]. Due to urbanization, the landscape capacity to infiltrate precipitation runoff will significantly be reduced, as the runoff will increase [71,72], lag times or concentration times will be shorter [73], and the water table recharge will decrease, which leads to the decline of base flows [74]. Heavily urbanized areas can also alter evapotranspiration regime of catchments, which is mainly due to the vegetation removal, precipitation patterns, and the intensity of 'heat island' effects [75–77].

As far as the hydrological impacts of urbanization is concerned, it is originated from the increase of imperviousness in urban areas, resulted from the disturbance of natural lands. Buildings, roads, and other types of impervious coverages decrease rainwater infiltration and increase surface runoff. Various factors affect the amount of runoff, but according to the findings of S. Rose and N.E. Peters [78], peak flows in urbanized catchments are 30% to more than 100% greater than the less urbanized and non-urbanized catchments. It is also worth mentioning that according to the Manning's equation, the flow velocity of water and the surface roughness are inversely proportional [79]. Based on this, stormwater flows faster on smooth surfaces than rough surfaces.

On natural surfaces, water encounters the natural hydrological processes of catchments. Impervious surfaces, however, have low permeability and smooth surface, which leads to the generation of higher amount of runoff. Therefore, imperviousness is a significant environmental index [81]. It should also be mentioned that impervious surfaces are considered as substantially important in hydrological analysis because their spatial distribution and connectivity is the most effective factor in determining flow velocity and volume [10,27,82]. Connectivity to stormwater system has a high effect on the amount and running of surface runoff [3,83–85]. In post developed surfaces (Fig. 2), the lag time, which is the time interval between the center of storm mass and the center of the resultant hydrograph mass, decreases due to the high flow velocity [86,87]. This high velocity results in higher flood peaks, compared to pre-urbanized conditions [88], amplifies erosion, which brings about slope instability and produces more suspended sediments [26], and leads to an overall higher flood risk and intensity [18,89,90].

According to Fig. 2, we can perform an assessment of urbanization effects on the hydrological analysis using the modified outlet hydrograph that results in the reduction of flow time [91], increase of volume [92], peak flow [28,93], and total discharge [94–96]. Furthermore, the combination of climate change with the geologic, topographic, and vegetative characteristics of a catchment leads to a unique hydrological regime. Urban development changes the natural hydrologic regime that will lead to a new hydrologic balance, alteration of peak flows distribution, as well as changing the duration and magnitude of both high and low flows.

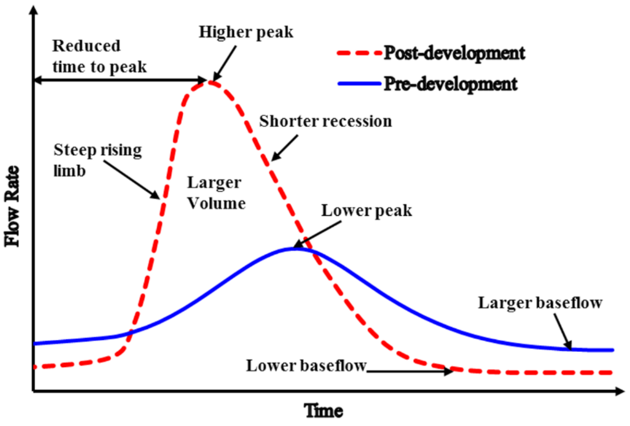

Fig. 2. Schematic graph of the relative effects of urbanization on catchment hydrology: Adapted from [80].

Yang et al. [97] investigated the hydrologic response of a catchment to urbanization in tropical areas. Their purpose was to evaluate to what degree the hydrologic response of a watershed would be proportional to the degree of urbanization. Their findings confirmed that base flow, interflow and evaporation decreased with urbanization, and at the same time, streamflow, surface runoff, and peak streamflow increased, proportional to the urban change. All the changes happened at varying rates. Similarly, Miller et al. [98] explored the effect of urbanization on runoff using a peri-urban catchment. They aimed to study the influence of rural landscape transformation into peri-urban area on the storm runoff, considering the alteration of imperviousness in the catchment. Their findings showed that increasing the imperviousness in rural catchments will result in higher effect on peak flows and flood duration, compared to the previously existing urban catchment.

Urbanization brings about two major problems to the natural surfaces of urban areas, namely land use/land cover changes and imperviousness. Both have enormous effects on runoff generation in urban areas.

The alteration of land use will change the hydrological processes, such as interception, infiltration, and evaporation, which can influence the runoff generation and flow patterns. This will result in the alteration of intensity and frequency of surface runoff and flooding [4,89,99,100]. Numerous studies have proved that land use alterations will have significant effects on watershed hydrology, especially by changing the frequency of flood [101], base flow [99], and annual discharge [102]. Yu et al. [103] conducted a research to investigate the impact of land use alteration on runoff response. They used a distributed model in their research. Their results proved that land use change can increase total runoff and peak discharge. Urban surface cover change can significantly decrease infiltration rates across the land surface and reduce the runoff response time [104]. This will lead to higher flow peaks and larger total stream flow volumes. It will also alter subsurface flow to surface flow, and will increase flood frequency [105,106].

Canopy interception, evapotranspiration, and percolation might also be affected by land use alteration which can ultimately result in flood or drought disasters or even ecological problems [89,107,108]. Another impact of land use change would be its profound effect on the characteristics of runoff and related hydrological processes of a watershed. Sajikumar and Remya [110] conducted a research on two watersheds with the area of 145 km^2 and 322.5 km^2, respectively to evaluate the influence of local land cover and land use on the runoff nature over the past few decades. They observed a 15% increase in discharge peaks, whereas the flows during dry seasons decreased, which shows the reduction in percolation and the resultant decrease in base flow.

A number of studies have widely investigated various aspects of land use alteration effects on urban runoff throughout the world [106,111–113]. The direct effects of land use changes on urban runoff generation have been well proved in all these studies. For instance, Ozdemir and Elbaşı [109] conducted a research in a small urban catchment with 9.33 km^2 area. They aimed to study the impact of land use modifications on runoff in an urban catchment using SCS model. The results of their research proved that the runoff in the watershed significantly increased, which was due to the land use modification. They also concluded that land use changes to impervious land covers in urban catchments have a stronger effect on runoff depth than rainfall characteristics. This is because different runoff depths have been observed from the same type of rainfall in different urban catchments, according to the land use conditions.

Very recently, Algeet-Abarquero et al. [114] also studied the effect of land use on runoff generation at the plot scale in a humid tropic experimental catchment. They investigated various land use types, such as main land covers, forest plantations, grassland, and oil palm plantations. Runoff responses of these land covers were analyzed at two spatial plot scales: 1 - the plot of (150 m^2) under natural rainfall conditions and 2 - simulation of runoff on microplots (0.0625 m^2). They found that land use alterations have a profound effect on surface flow generation. For example, they observed the highest runoff response in oil palm plantations, which was 20-fold higher than secondary forests in natural storm conditions and went up to 75% runoff coefficient in extreme rainfall intensity. Table 1 summarizes some of the investigations on catchment runoff response to urbanization and land use.

Urbanization leads to the disturbance of natural landscapes; and vegetation covered surfaces are replaced with impervious surfaces [10]. Impervious surfaces are generally known as materials with natural or anthropogenic sources preventing the infiltration of surface water into sub-layer soils [115]. Human activities and habitation are the main reasons for the growth of impervious surfaces in urban areas, by constructing structures such as roofs, parking lots, and roads. The growth of impervious areas decreases infiltration capacity, increases runoff generation and direct runoff, improves the connectivity of flow, and reduces groundwater recharge paths [10,84,116,117]. These alterations will ultimately result in the modification of magnitude and duration of urban catchment floods [118]. Although pavements and Streets are generally known as impervious surfaces, their hydrologic behavior is directly affected by the intensity and duration of rainfall in real situations [119].

The runoff generation can usually be augmented with the increase of smaller rainfall events which is caused by the increase of imperviousness [120]. Likewise, Booth

Table 1
Summary of the studies investigated catchment runoff response to urbanization and land use

Factor investigated	Reference	Type of catchment	Catchment area	Materials and methods	Runoff response (Findings)
Land use change	[103]	Sub-tropical urban catchment	35 km^2	They have used satellite images to classify land-use alteration	Total runoff and peak discharge increased
Urbanization impact	[9]	Urban watershed	19.3 km^2	Analysis of two-year in-situ quantity-quality data monitoring and sampling	Surprisingly, there was no significant urban effect on the runoff generation
Land cover	[124]	Urbanized catchment	45 km^2	They used the physically-based model (WetSpa) to assess the land-cover effect on runoff	Runoff values showed high spatial variability with various scenarios in their modelling
Urbanization (Impervious cover change)	[98]	Peri-urban catchment	Two catchments of similar size of 5 km^2	They used a semi-distributed model (CAT) to evaluate the effects of urbanization on storm runoff	The impervious surfaces in rural watersheds can lead to much higher effect on floods duration and peak flows
Urbanization (Land use)	[97]	Urban tropical watershed	40.6 km^2	They used a hydrological model (MOBIDIC) to study a tropical catchment response to urban transformation	Surface runoff, streamflow and peak streamflow increased
Land use changes	[125]	Urban catchment	5042 km^2	They used the SWAT model to study the runoff responses based on daily, monthly and annual time scale	The greater land use changes will lead to greater runoff generation
Land use changes	[109]	Urban watershed	9.33 km^2	SCS-Curve number model was applied to two urban catchments to investigate the effect of land use on direct runoff	The modification of land use will significantly increase the watershed runoff
Land use change	[114]	Humid tropic experimental catchment	150 km^2	A combined study of natural rainfall-runoff and in situ rainfall simulation response measurements along with statistical analysis was carried out to study the impact of land use modification on the generation of runoff	Runoff increased 20-fold in oil palm plantation in the secondary forests
Urban development	[126]	Urban Catchment	Two control sub catchments of 0.31 km^2 and 0.13 km^2	A developing catchment was monitored and compared with two control catchments to investigate the runoff generation alterations during construction period	Urbanization can significantly increase the runoff volume and depth as well as the peak flows, and the catchment lag time was decreased in the warm season
Imperviousness	[127]	Urban catchment	Very small	A residential catchment was analyzed using SWMM model under two various types of imperviousness to study the effect of rainfall-runoff process under different storms in urban areas	Total impervious area (TIA) is a dominate factor influencing total runoff compared to directly connected impervious area (DICA)

[121] showed that if imperviousness increases by 10%, the increase in runoff generation amount would be the same extent as a 2-year storm in the post development, which could possibly be produced in a pre-development 10-year storm.

Imperviousness is a simple index that can easily be measured, and this has made it to be widely recognized and accepted as a key index for the prediction of urbanization impacts on rainfall-runoff process [81]. Previous studies have generally proved that surface runoff volume and velocity will increase with the increase of impervious coverage [10,27,122]. Fig. 3 depicts runoff variability with increased impervious surfaces.

Total impervious area (TIA) is the most well-known imperviousness type used in these studies, which is stated as the whole fraction of impervious area in a catchment [127]. Schueler et al. [66] pointed out that runoff volume can increase with the increase of TIA. The magnitude of

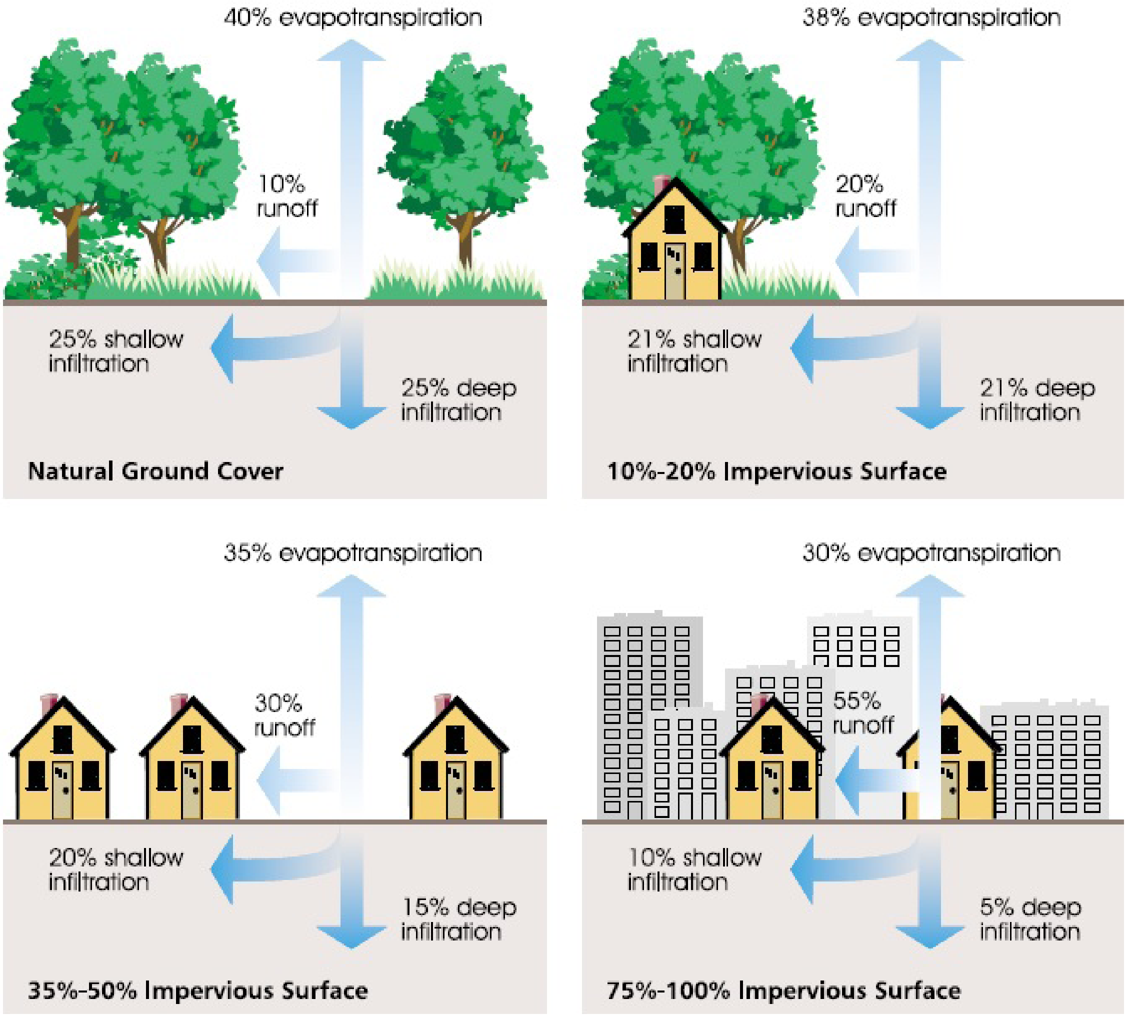

Fig. 3. Runoff variability with increased impervious surfaces [123].

urbanization is also directly proportional to this quantity. However, TIA does not reflect the relative relationship of impervious surfaces to the drainage system, which may result in unexpected matching proximity between TIA and runoff parameters [10]. As an example, rooftops typically drain runoff onto pervious areas, and therefore have less contribution to runoff than roadways that directly drain runoff to a drainage system. On the other hand, directly connected impervious area (DCIA), accounts for the part of TIA which is connected to a drainage network hydraulically, such as streets with gutters drained to an outlet [127]. Lee and Heaney [3] carried out a hydrologic modelling to study the hydrologic performance of DCIA and found out that DCIA has the most significant effect on urban hydrology. Yang et al. [128] and Burns et al. [129] also pointed out that the majority of hydrologic modification in urbanized areas is due to DCIA. Similarly, a disconnected or ineffective impervious layer [116,130] drains runoff to pervious areas [131]. It should be noted that total imperviousness of a catchment is an index which is widely used to measure the hydrologic effects of urbanization [132,133].

Numerous studies have investigated the impact of various types of imperviousness on catchment hydrological processes in the past few years. Yao et al. [127] conducted a research to analyze the effect of different types of imperviousness on rainfall–runoff process, such as runoff depth, peak discharge, and lag time. They reported that TIA is a more significant factor affecting total runoff rather than DCIA; and under different storm conditions, its impact remains relatively stable. Moreover, they found that using a combination of TIA and DCIA as indicators, can lead to a more effective prediction of peak runoff, compared to using one single measure. Wang et al. [134] carried out a research to evaluate the spatial-temporal effects of imperviousness on hydrological response of different parts of an urbanized watershed. The results showed that the time to peak will decrease by nearly 15% if the modifications of downstream imperviousness (marked urbanization) is large, while the increase in peak discharge was found to be more than 40%.

In a research conducted by Yang et al. [135] on 16 small watersheds in Indiana, USA, it was found out that when impervious surface increases by 10%, the flow variation and flow frequency increases by 15% and 19%, respectively. They concluded that impervious cover was the key significant factor in the selected hydrologic measures trend. Kong et al. [136] found that a 33.3% reduction in pervious area will increase runoff and runoff coefficients up to 92.9% and 90.9%, respectively. Therefore, in traditional urban development, TIA will increase, while surface permeability and water storage capacity will decline, which result in dramatic increase of surface runoff, runoff coefficient, and peak flow rate. Table 2 summarizes some of the studies investigated the effect of imperviousness increase on the amount of runoff generation.

There are various types of land use alterations in urban areas which typically have different percentage of imperviousness, including residential, industrial, roof tops, and pavement. Surface coverage in residential and industrial areas are different and can be more than 50% in residential areas, whereas it can often reach 70–80% in industrial areas [140]. Nevertheless, urban paved surfaces are not fully impervious and runoff losses can go up to 30–40% of the total runoff [141], while the infiltration on roads of residential areas has been measured about 6–9% of the total annual rainfall [142]. Depending on the given rainfall event, the surface area contributing to runoff generation will reportedly be varied [141]. However, the size and complexity of landscapes in large urban catchments are always greater than that of small catchments, which lead to varied runoff discharges and travel times [128,143].

3. Geomorphologic impacts

Geomorphological and physical characteristics of urban surfaces are significantly important for overland runoff. Compaction of the topsoil due to urbanization, construction, and moving vehicles make it impermeable with less infiltration and more surface runoff. Surface roughness is also contributory to the runoff velocity. The less rough the topsoil is, the higher the runoff velocity will be. On steep slopes, water will move faster, leading to smaller lag time and vice versa.

3.1. Topography and slope impact on runoff

The rate that water moves downslope in soil is controlled by topographic gradients which indicate whether the stormwater is flushed to the drainage network or remains in soil [57]. The runoff volume is directly proportional to slope; steep slopes result in larger overland flow, whereas gentle slopes lead to more infiltration [144]. Land slope, imperviousness, and vegetative cover influence both runoff volume and lag time to peak flood flows; as an example Leopold [117] could be mentioned. But the fact is that not many studies have been directed towards the effect of slope on runoff in urban catchments. This is mainly because field measurements, which characterize the impact of slope, is difficult to obtain. To study the impact of slope on runoff in details, we need to have two equal urban catchments which are similar in all features except for slope, which would be difficult to find in post-developed urban catchments [27].

The results of studies from agricultural areas can be helpful because pervious areas in urban catchments are typically covered by vegetation. These studies point out that characterizing the impact of slope might be naturally difficult [27]. For instance, various field studies have been cited by Joel et al. [145] which are mostly in agricultural lands and indicate that the impacts of slope on runoff are not similar, sometimes the runoff increases with the increase of slope, whilst in some other cases it decreases or does not make any significant difference. However, the differences of multiple studies might be due to the uncertainties in experimental methods. Although some slope effects may be taken into account in runoff infiltration modelling, many hydrological models do not fully consider slope in the modelling process [27].

Table 2
Impact of imperviousness on stormwater runoff generation in urban catchments

Reference	Type of catchment	Catchment area	Increase in Imperviousness (%)	Runoff Response (%)
[134]	Urban catchment	–	–	Peak discharge 40% increased
[135]	Urban catchment	–	10	Flow frequency increased by 19%
[137]	Urban catchment	–	20 to 100%	50% increase in total runoff
[138]	Urban catchment	–	After a period of urbanization	Runoff coefficients increased by 50%, the maximum peak discharge increased three-fold
[139]	Urban catchment	–	30% increase in imperviousness	100-year flood peaks would be doubled
[110]	Urban catchment	145 km^2	–	15% increase in discharge peaks
[109]	Urban catchment	9.33 km^2	–	Significantly increased
[78]	Urban catchment	50 km^2	–	Peak flows are from 30% to more than 100% greater
[109]	Urban catchment	9.33 km^2	58.32%	Runoff increased from 182.7 mm to 1397.99 mm
[136]	Urban catchment	8.38 km^2	33.3%	Runoff and runoff coefficients increased 92.9% and 90.9%

3.2. Depression storage impact

Part of precipitation will retain on the land surface in ponds, puddles, and ditches. It is typically known as depression storage. The rest of overland flow will transform into surface runoff. One of the features describing hydrological losses in the process of rainfall-runoff is depression storage. It accounts for the retention of rainfall in the ground local depressions. If the runoff is generated by the impervious areas of a watershed, then the depression storage is usually representative of all types of hydrological losses, including evaporation and wetting losses [146]. The depression storage is mainly considered as effective on outflow of a catchment, which has small depth rainfalls [147–149]. Depression storage is significantly important in the computations of small outflows from a catchment surface and flushing of pollutant loads [150], particularly in the first flush effect. In urban catchments, the surfaces are either natural or sealed, and precipitation runs off to receiving water bodies, pervious surfaces, or stormwater collectors. The range of depression water storage capacity in natural surfaces is usually from 0.5 mm to 15 mm, and in impervious surfaces reduces to 0.2 mm and 3.2 mm, respectively [80]. Furthermore, at low rainfall intensities, depression storage is more significant, whilst it is not influential in heavy storms [8].

Although the effect of depression storage in hydrological modelling has been well documented in many case studies, some researchers have found it insignificant for catchment simulation modelling. Skotnicki and Sowiński [146], for example, conducted a research to investigate the influence of depression storage on runoff generation from impervious surfaces of urbanized areas. They found out that the impact of depression storage spatial distribution in the watershed is not significant for the outflow simulated hydrographs. They also indicated that if the runoff modelling is carried out in other similar catchments, they can use the same amount of depression storage for all sub-catchments as well.

3.3. Soil characteristics impact

When the topsoil is removed from pervious areas of urban catchments, and is compacted as well (because of construction, traffic, loss of organic matter, and vegetation), rainfall-runoff will have uncertain behavior [104,116,151]. Another factor affecting the surface runoff response to rainfall is antecedent soil moisture. In wet soil condition, the runoff is averagely two times higher compared to dry soil condition [33]. In their research, Shi et al. [33] investigated the influence of land use/land cover alteration on surface runoff. They calculated the runoff coefficient using SCS model. Based on their findings, the runoff coefficient will increase with the increase of antecedent soil moisture content. They concluded that the land use alteration will be less effective on runoff, if antecedent soil moisture increases.

Liu et al. [144] also studied the influences of different types of landuse on runoff in a catchment of 407 km^2 with different classes of land use and soil types (Table 3). They indicated that the highest runoff contribution is from urban areas, which mainly contribute to direct runoff. They concluded that the main factor contributing to storm flow is runoff from urban areas and as a result, it is the prevailing factor contributing to flood events in urban areas, in comparison with other types of land use. Likewise, it is worth mentioning that the amount of runoff generation is directly proportional to land use alteration intensities. In other words, surface runoff will increase with the increase of land use alterations [125,144].

Table 3
Area, different types of soils, and slope description for different land use types [144]

Land use	Area	Main soil types
Cropland	94.0	Loamy sand, Silt
Grassland	97.3	Clay loam, silt, sandy clay loam
Woodland	115.6	Loamy sand, silt, silt clay loam
Mining area	10.2	Loamy sand
Urban	83.4	Silt, silt clay loam
Water surface	6.50	Clay loam, silt clay loam
Total	407	Silt, loamy sand, silt clay loam

3.4. Infiltration impact

Infiltration magnitude is determined by the soil characteristics and the imperviousness of land cover. The more the surface cover is sealed, the more the surface runoff will be. Hence, surface infiltration is an important part of surface runoff process, even for superficially impervious surfaces [152].

Pervious areas that are supposed to be developed and are situated among impervious areas, usually become compacted and less pervious due to construction activities. For instance, by constructing a highway, the adjacent areas will be disturbed and compacted which are typically more pervious in their natural state. Thus, the infiltration of runoff into soils will be slowly, and surface layers will get saturated faster than the natural state. Under these conditions, higher runoff will equivalently be generated even by lower rainfall rates. The spatial impacts of this process are considerable because runoff from impervious areas, flushed into nearby pervious surfaces, can saturate soils relatively faster, and thereforethe runoff-generating area is expanded. Compacted areas can also behave similarly (as the expansion of impervious areas), which increase runoff generation from a large surface [115].

For the infiltration scenarios, in which the profile is controlled, the rate of infiltration into pervious surfaces reduces with time, because the soil water storage capacity decreases [153]. As for the pervious surfaces, which are variable, and the runoff takes place based on the profile-controlled infiltration, we might need to determine the soil water dynamics as well as the hydraulic conductivity function of unsaturated lower soil layer. This will also be important in the prediction of runoff volume and timing. Nevertheless, it should be noted that when the percentage of impervious surfaces increases, the opportunities number for water to be stored in the soil may also decrease [121].

4. Meteorological impacts

Although human activities and physical characteristics of land surface have resulted in a great deal of alterations in surface runoff generation, meteorological impacts have also been a significant factor in this respect. Having considerable effects on hydrological processes, climate change has received huge attentions by many researchers. Climate change, coupled with anthropogenic factors, has severe impacts on rainfall-runoff process. Precipitation intensity and duration, along with the spatial-temporal variability, also play a significant role in surface runoff extent and volume. The urban heat island phenomenon has also increased in urbanized areas, leading to more evapotranspiration, local low-pressure area, and ultimately to more rainfall.

4.1. Climate change impact

The climate change has gained a lot of attentions recently because of its significant influence, particularly on the urban hydrology. Thus, understanding the rainfall behavior alteration at the urban scale is urgently vital. We also need to assess the effects of such alterations on the efficiency of stormwater management systems for controlling flood, hygiene, and environmental protection [26]. It is usually anticipated that the climate change will alter the timing and magnitude of runoff, which is a significant factor in the water resources management [113]. In addition, the precipitation intensity might also be affected by climate change which can be augmented hydrologically by land-use alteration and soil compaction. Easterling et al. [154] proved that nearly all precipitation increases resulted from global climate change are due largely to the rainfall intensity increase.

Based on the literature review conducted, although urbanization almost always affects the urban runoff directly, by increasing the magnitude of runoff in urbanized areas, the effect of climate change on urban runoff can be both positive and negative. Zhang et al. [113] used a hydrologic simulation model to study the effects of climate change on runoff generation. They found out that alterations in precipitation has a more significant effect on runoff than alterations in the temperature. Their findings also generally showed that the whole basin runoff might also increase in the future, although the runoff alterations will not be spatially distributed consistently over the basin. However, climate change can sometimes have a negative influence on the runoff generation by decreasing the amount of surface runoff which can adversely affect the water resources availability.

As an example, Xu et al. [155] explored the climate change effect on the hydrology of a river basin. They aimed to study the effect of climate change on both hydrology and the uncertainties related to river runoff projections. They found out that the river runoff in the basin will considerably be reduced in the future, with some uncertainties in the analysis. On the other hand, some studies found the positive effect of climate change on runoff generation. Wagesho et al. [156] investigated two agricultural watersheds in a semi-arid tropical climate in Ethiopia. Their simulation of future runoff showed increased daily extreme events at both stations that would result in the increase of annual runoff.

The effect of climate change, combined with urbanization, on runoff has also been investigated in different studies [157–159]. It seems that both topics will be important in the future research [26]. Wang and Cai [160] indicated that we can use the recession characteristics to assess the relative impacts of climate change and land use modification. The basin surface and/or subsurface topography might attenuate or augment the impact of climate change and land use alteration on streamflow, and generally, we should consider these factors in the evaluation of streamflow response to human activities [161,162].

Studies which have evaluated the hydrologic response to land use modification, considering the long-term variations in climate, have proved that hydrologic response to land use alteration is much more severe than climate fluctuations [74,163,164]. The results of these studies are in consistent with Tomer and Schilling [165] research, who indicated that the effects of climate change resulted from human activities are more delicate than continuous climate fluctuations. On the contrary, some investigations have found climate change more significant on surface runoff than land use/land cover alteration. Liu et al. [45] studied the effects of climate change and land use on the hydrologic cycle of a large basin. They found that climate change was more effective on hydrologic processes than land use, which reduced the surface water and base flow. They also found that the effect of climate change on surface runoff variation was more noticeable compared to other hydrologic alterations. It is worth mentioning that the effect of climate change on the reduction of surface runoff was amplified by land use alterations. What's more, annual ET and streamflow also decreased in the study area due to climate change. Table 4 summarizes some of the studies on the catchment runoff response to geomorphological and meteorological factors.

4.2. Precipitation impact

Precipitation is a significant meteorological factor affecting hydrological process [44]. The alteration of both precipitation and temperature significantly affect the runoff. Studies have proved that a 10% change in precipitation will possibly result in about 15–25% alterations in runoff [56,166–172]. Moreover, the effect of climate change on runoff in arid or semi-arid areas is much stronger compared to humid areas [173]. Joel et al. [145] conducted a research on experimental plots of two different sizes of 0.25 m^2 and 50 m^2 to measure surface runoff in different rainfall scenarios. They found significant fluctuations in the responses of runoff to different rainfall rates for the two plot sizes.

The flow coefficient and the amount of runoff generated from different areas are widely proportional to the intensity, duration, volume, and shape of a storm. For instance, if the antecedent soil moisture is similar, then a big and long duration storm with high intensity will generate more runoff [144]. Qin et al. [174] indicated that rainfall amount, duration, and intensity have profound effects on runoff in small urban catchments. Guan et al. [175] reported that rainfall patterns significantly affected the runoff generation in a residential catchment of 12.5 ha, that was under development; in which case urban runoff increased by high rainfall peak intensity.

Table 4
Summary of the studies investigated the catchment runoff response to geomorphological and meteorological factors

Factor investigated	Reference	Type of catchment	Catchment area	Materials and methods	Runoff response (Findings)
Rainfall rates	[145]	Experimental plots of two different sizes	Small plot of 0.25 m^2 and large plot of 50 km^2	Two plots of different sizes were set up in an experimental center and the water level was monitored and measured using an automatic system	The two plot sizes showed significant variations in runoff responses to different rainfall rates
Soil moisture condition	[33]	Coastal (rural) watershed	1948.69 km^2	They used the SCS model for the simulation of surface runoff and combined it with the land use data to check the effect of urbanization and soil moisture on surface runoff and peak discharge	Runoff increased with the increase of antecedent soil moisture content and in wet soil conditions. Peak discharge also increased
Climate and land use change	[45]	River watershed	13,262.93 km^2	Variable Infiltration Capacity (VIC) model and Mann-Kendall test were used to study climate and land use alteration effect on runoff	1 - Climate change impact on hydrology, especially runoff, is stronger than land use change 2 - Climate change resulted in surface runoff reduction as well
Climate change impact	[155]	River basin with sub-tropical humid climate	19,460 km^2	SWAT model was used to evaluate the effect of climate change on the future hydrology of a river basin. The uncertainties were also taken into account	It was found that annual river runoff will probably be reduced
Climate change and human activities	[42]	River basin	8,645 km^2	They used the observed hydrological data to calibrate the VIC model. The model was used to simulate the natural runoff to check the effect of climate change and human influence on runoff alterations	The results showed that climate change and human impacts were both effective in the reduction of runoff
Climate change	[156]	Two Agricultural watersheds in the Semi-arid tropical area	166.5 km^2	The General Circulation Models (GCMs) and the statistical downscaling model were used to study the effect of climate change on runoff generation	They found that the annual water yield for both basins increased
Depression storage	[146]	Urban catchment	6.7 km^2	They used SWMM model for the simulation of runoff, to check the effect of depression storage on runoff	The effect of depression storage on runoff simulation is not significant

When the infiltration of soil is lower than precipitation, the pervious surface will behave like an impervious surface and produce runoff as infiltration excess. Forested areas, bare ground, and open urban surfaces are examples of pervious surfaces that can be changed with the intensity and duration of precipitation; in which case there would be extra amount of precipitation available to be infiltrated or transformed into runoff [176]. Church et al. [177] found that the grasslands by the highways, which were not pervious, seemed to produce as much runoff as generated by highway itself. For pervious areas, these characteristics should be measured and delineated based on the existing surface cover condition, the lower soil layers hydraulic, hydrologic qualities, and geologic conditions. Lin et al. [125] achieved similar results in their research on catchment runoff. They stated that the alteration in runoff response was associated with the precipitation volume: There was a smaller change in runoff in wetter years but in drier years, there was a greater change, and the monthly change in runoff declined with the increase of precipitation within a wet season.

Also, urbanization influences atmospheric dynamics at a local scale. Thus, the most important factors affecting precipitation are [8]:

1. The energy balance will be changed by the modification of surface land cover, which along with the energy released by anthropogenic activities, will produce the urban heat island. This would influence precipitation patterns and intensity.
2. Land surface cover modification will lead to the surface roughness change and surface cover homogeneity which in turn affects the wind circulation and ultimately may alter precipitation patterns.
3. Air pollution, with the micro particle release in the atmosphere, will change the chemical composition of precipitation (e.g. acid rain), which can impact the runoff generation process as well.

Previous studies have stated that there might be a relationship between urbanization and precipitation intensity. It seems that urbanization mostly influences the precipitation intensity and patterns, whereas it does not severely affect the spatial and temporal distribution of rainfall. However, more research should be performed to figure out the possible effect of urbanization on precipitation projections [8]. What's more, as the urban systems are highly dynamic and heterogeneous,it would be essential to precisely measure the spatial-temporal distribution of precipitation [178–181].

4.3. Temperature and evapotranspiration impact

Apart from precipitation, temperature is a significant meteorological factor affecting the hydrological process [44]. It is estimated that when the temperature increases by 2-degree, the runoff will reduce by 5% to 12% [166–168,170,172]. Evaporation from land surface is also another major component of surface runoff even for the surfaces which are nominally impervious [152].

Evapotranspiration can also be affected by urbanization which in turn affects the runoff generation. ET in rural areas might be substantially more than urban catchments, primarily due to the lack of vegetation [89,182]. The phenomenon of urban heat island (UHI), or the increase of temperature in urbanized areas, which is mostly due to urbanization, is also another well-known and the most studied impact of urbanization on local climate [183–185]. Hydrologically speaking, the effects of UHI are relevant because the direct evaporation from surface depression storage, plant canopy, and reservoirs increases with the increase of temperature [8].

In their research, Li et al. [44] investigated the effect of future climate change on runoff generation. They anticipated that runoff might reduce annually in the future, even though precipitation might increase. However, the benefit of precipitation increase would be overshadowed by the evaporation increase which is primarily due to the temperature increase. They also stated that the distribution of seasonal runoff in the future would be more even as well. This would be mainly due to the temperature increase, which may result in more evapotranspiration.

5. Summary

The hydrologic process in the catchment usually includes precipitation, evapotranspiration, depression storage, overland flow, surface runoff, and infiltration. Part of the precipitation is typically lost through evapotranspiration and depression storage and part of it percolates into the ground and the rest is transformed into surface runoff. Various factors impact the surface runoff generation extent and volume. Human activities in urban areas, land surface physical characteristics, and meteorological phenomena play the most significant role in this respect.

The large population growth in urban areas and their potential activities has brought about significant alterations in the natural hydrological processes in urban areas. The urban runoff can severely be affected by urbanization and land use change. The more the surface cover is sealed, the more runoff will be generated. The impermeable surface cover leads to both higher peaks and larger volume of runoff in urban catchments. In addition, more surface runoff and higher peak discharge is generated by urbanization in a shorter course of time because when impervious surface increases, the infiltration and the time of concentration will decrease [186]. This excess runoff from urban areas is widely considered as a threat to both human and aquatic ecosystems.

The physical characteristics of urban surfaces can also be a significant factor resulting in runoff surplus in urban areas. Top soil characteristics, topography, slope, and roughness should also be taken into account in the urban catchment response to runoff. Steep slopes and soft surfaces generate greater runoff with higher velocity and less infiltration. Antecedent soil moisture and soil compaction will also lead to uncertain rainfall-runoff behavior in urban areas.

Another important concept used in the urbanization process is the threshold effects of impervious surface. The threshold effects of impervious surface are usually expressed in terms of altered flow regimes [187,188], which is particularly emphasized on base flows [74,81], and channel morphology change [189,190]. Most of the researches in establishing a threshold impervious surface area have been conducted to assess the ecosystem response to a change in watershed hydrology. Thus, the urbanization not only affects the site hydrology and geomorphology, but aquatic ecosystems as well. Schueler [191] proposed that percent catchment impervious surface classifies stream drainages into one of three aquatic ecosystem management categories: 'stressed' at 1–10% impervious cover; 'impacted' at 11–25% impervious cover; and 'degraded' at 26–100 percent impervious cover. Also, Klein [192] proposed a preliminary estimate of 10% total imperviousness as a threshold for the effects on aquatic ecosystems, which are severely affected when watershed imperviousness develops to 30%.

6. Conclusions

Although the anthropogenic and geomorphological impacts play an important role in greater runoff generation in urban catchments, the meteorological and climatologic changes have resulted in great concern in terms of rainfall-runoff behavior and urban runoff. The precipitation intensity and duration along with spatial-temporal variability, urban heat island, temperature, and evapotranspiration have significantly impacted the urban runoff generation. The timing and magnitude of runoff can greatly be affected by climate change which in turn affects the water resources management in the future. The combination of urbanization and climate change has significantly intensified the process of urban runoff generation. The increase in urban temperature will enhance evapotranspiration process and this will adversely affect the potential increase of precipitation in urban areas.

The effect of urbanization on the precipitation intensity and patterns is indispensable. It will change the hydrological response of a catchment to precipitation and this in turn will affect the runoff volume, peak flow, and flood risk. Similarly, climate change strongly affects the hydrological cycle even more significantly than other effective factors, and therefore leading to more severe surface runoff generation.

Based on this review study, some gaps identified which need further exploration as follow.

1. Since several studies have proved that urbanization and climate change have strong effects on surface runoff generation, it is advisable to investigate these two factors more carefully in further research. Whenever possible, climate change and urbanization can be coupled to investigate the impacts of both on the rainfall-runoff behaviors.
2. Spatial variability is of high importance in urban catchments which affects the physical processes. Therefore, there should be research directed towards this issue to figure out the spatial-temporal distribution of precipitation in urban catchments more accurately.
3. The data used in urban hydrological modelling is usually derived from hydrological stations or collected manually; both cases lack accuracy in hydrological modelling. Remote sensing is a much more accurate source in spatial data for modelling purposes. Thus, the future studies can probably couple the remote sensing information and site inspection data to come up with better and more accurate results in urban rainfall-runoff modelling.
4. Although depression storage and land slope both have great effects on urban runoff, they have not been well considered in urban modelling. It is suggested that future studies consider these two variables in urban hydrological modelling to achieve more accurate results of surface runoff.
5. There are many uncertainties in urban rainfall-runoff modelling which result in the inaccuracy of research in this field. To have more sustainable modelling and achieve precise results, these uncertainties should be considered in further studies.

There are several measures to mitigate and control the excess surface runoff in urban catchments to reduce the resultant adverse effects on both human and ecosystems. The most known ones are best management practices, shortly known as (BMPs) and low impact development, shortly known as (LID). They are usually denominated as LID-BMPs measures for controlling the urban stormwater runoff quantity and quality. As there are different types of LID-BMPs, they should be carefully selected based on the urban development planning and quantity or quality control purposes. The LID-BMPs have been well proved in many studies to be beneficial in mitigating and controlling the urban runoff quantity and quality.

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