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Review Article

Impervious Surfaces an Indicator of Hydrological Changes in Urban Watershed: A Review

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Abstract

In water scarce urban areas of the present world, groundwater management is a major environmental concern. Replenishment of water resources is a complex and slow process, which is catered mainly through the land surface from its contact on ground as a catchment area, infiltration inside, groundwater flow to groundwater recharge and its storage. Urbanization has been considered responsible for causing alterations in natural landscapes and hydrological cycle on a vast scale. Soil sealing by the construction of impervious surfaces not only impact the hydrology of that particular area but also hampers existing ecological balance of adjacent pervious area. However, not much knowledge has yet been gathered about impervious surfaces in relation to hydrological changes in the urban areas. Therefore, the current review investigates the effect of increasing impervious land area on various hydrologic components including rainfall, infiltration, surface runoff, evapotranspiration, groundwater recharge and its replenishment. The review highlights that the removal of natural vegetation and sealing of soils by building impervious surfaces impact the urban hydrology more significantly as it enhances the urban heat island effect and consequently increases the rainfall resulting in higher surface runoff volume and the stream peak flow rate leading to rising urban flood potential. It also adds to the lowering of groundwater replenishment, soil moisture and evapotranspiration, thereby disrupting the hydrological cycle.

Keywords: Urbanization; Impervious surfaces; Hydrological cycle; Evapotranspiration; Groundwater replenishment

Introduction

Before the advent of advanced technology, the land use type was primarily determined by the nature and type of the soils of a landscape. During last century, the relationship between soil nature and land use has been lost due to the urbanization [1-5]. The process of urbanization corresponds to the alterations in the natural landscapes by replacing the natural vegetation with impervious surfaces. Globally, more natural landscapes as well as agricultural land have been converted to the impervious area due to rising population and urbanization [4-6]. Urban impervious area covers nearly 0.6 million km2 i.e. 0.45% of global land other than Greenland and Antarctica and increasing incessantly day by day [2,3]. However, the land covered by impervious surface is small but poses larger concerned environmental issues. Urban sprawling alters the urban hydrological cycle in multiple ways. Soil sealing by the construction of impervious surfaces not only impact the hydrology of that particular area but also hampers the energy and gaseous exchange, ecological variables and correspondingly exerts pressure on adjacent non sealed or pervious areas [1]. Urbanization mainly results into increase in built-up area, development of road network, fragmentation of natural landscape, reduced drainage efficiency, larger storm water runoff generation, high flood frequency and channelization of water into streams and other surface water bodies, reduction in agricultural land and changing microclimate of the region [7-9].

Impervious surfaces influence the urban environment and generally considered as an indicator of urban watershed hydrology [5]. However, the amount and pattern of impervious surfaces changes occurring in space, which complicates the calculation and understanding of their related impacts on urban watershed. The imperviousness of any area can be defined by the extent and the degree to which they are linked with drainage system or stream channel. Measurement of total impervious area (TIA) is a generalized way to estimate the extent of impervious area which might reflect the degree of urbanization but unable to account for the connectedness of these surfaces with the receiving channel. According to [10], urban impervious surfaces can be broadly categorized into 3 types:

a. Effective impervious area (EIA): those impervious areas which are hydraulically connected to the receiving streams or drainage system e.g. parking lots, roads, streets and gutters that outfall into treatment system

b. Ineffective impervious surfaces: those impervious surfaces which are not hydraulically connected to the receiving system and runoff generated from these surfaces pass through the pervious area before entering the receiving stream e.g. rooftops first water fall over the roof top then it flows over a pervious area such as grassed area or to a bioswale/bioretention system

c. Remaining area under lawns, parks and gardens.

These 3 types of surfaces generally constitute total impervious area (TIA) of an urban watershed [10]. Due to urban sprawling, increased impervious surfaces become a key issue in the management of urban growth and hydrological dynamics. The effective impervious surfaces impacted the urban hydrology more significantly than the other two. In recent decades rapid urbanization led to increase in impervious area in the form of roads, parking spaces, increased roof top areas as well as housing areas which resulted in decrease in agricultural land, forested land, grasslands, wetlands and other open areas in which storm water easily percolates. Expansion of area under impervious surfaces is the key anthropogenic factor accountable for the changes in hydrological processes associated with the changing urban environment [7,11-15]. This review paper discusses at length the key hydrological impacts of impervious surfaces on urban watersheds.

Impact of Impervious Surfaces on Hydrological Cycle

The urban impervious surfaces influence the local hydrology of the watershed. The impact of impervious surfaces on hydrological process is complex in nature and intricate knowledge remains limited. A suave and unhindered natural hydrological system gets disturbed and turns complex, as existence of impervious surfaces influence the hydrological cycle by limiting the infiltration, generating more surface runoff, decreasing groundwater replenishment and its flow. Engineered water system in urban areas differentiates the urban water cycle from the natural hydrological boundaries, as it directly discharges to the receiving water bodies through pipes or underground drainage system, due to its hydraulic connectedness [9]. Most of the studies focus on the quantitative and qualitative impacts of impervious surfaces of an urban watershed [5,12,13,15,16]. However, there is a need to integrate these impacts with the assessment of material used in their built-up, topography, impact of infrastructure development on the natural to urban transformation rate; and water flow pathways from atmosphere to the ground in transitional state. The impacts of impervious surfaces on various components of hydrological cycle are discussed in sequel.

Impact on Rainfall

The high density of heat absorbing material in urban areas generate more heat in the lack of vegetation thus contributes to the temperature rise in that urban area, which is known as urban heat island (UHI) effect. This proliferates the rainfall in the downwind areas depending on the local microclimate of the area. The presence of aerosols in the atmosphere further subsidizes the thermal insulation and serves as condensation nuclei for cloud formation. This process profoundly influences the intensity and variability of rainfall not only at local scale but on regional level also. The precipitation system is divided into urban vegetation and other associated factors thereby, affecting the air mass circulation [14,17] hypothesized that impervious surfaces act as moisture convergence base required for the convective development and enhances cloud formation.

Impact on rainfall infiltration and Runoff Relationships

Rainfall runoff generation in a natural landscape counts on sundry factors like excess of Huttonian infiltration, saturation excess and other variable sources [18]. The amount of rainfall, its intensity and surface conditions of an area controls the water infiltration [15]. High intensity urban storms when fall on impervious surfaces impedes infiltration and generate high surface runoff [19] which generally infiltrates into the ground in natural landscapes. This leads to the generation of higher runoff volume as well as peak flow rate and results in consequent high frequency and magnitude of urban flooding [11,12]. The size, material used, connectedness of impervious surfaces also impacts the rainfall infiltration rate and runoff generation. Pitched rooftops made up of impervious material route the received rainfall into the drains or storage system, resulting in overall water balance loss. High density of buildings leads to the larger impervious areas which modifies the runoff from surface and near surface level [20]. The EIA's mainly route the runoff into nearby streams through surface or sub-surface drainage network which result in considerably higher peak discharge during the high intensity rainfall events [21]. Studied the rainfall runoff generation in urban watershed by employing hydrologic simulation program and found that there was a significant increase in urban runoff at a threshold percent impervious cover ranging from 20-25%.

Impact on evapotranspiration

Soil moisture content and vapor pressure are the main drivers of evapotranspiration process [22]. There are very limited discussions about the effects of impervious surfaces on the evapotranspiration, but the available studies signalized that the relationships between impervious cover and evapotranspiration is complex and inconsistent in nature [23]. It is a multiple counteracting process involving high atmospheric water demand due the urban heat island effect, low soil moisture content due to sealing of soil and enhanced water availability via urban landscape irrigation [23]. In a study conducted by [24] in Xiamen city (China), there has been a substantial increase (7 times) in impervious surface from the year 1989 to 2009 and the quantitative data showed that it was a responsible cause for significant rise of local temperature. In urban environment, soil sealing due to build up areas reduces the soil moisture and bare soil evapotranspiration and artificial urban slopes encourages fast flow of rainfall runoff and lowers its consequent loss as interception. Removal of natural vegetation (mostly evergreen and deciduous type of vegetation) reduces the leaf area index and root biomass and subsequently the evapotranspiration [25,26]. The urban heat island further exacerbates the reduction in evapotranspiration due the shift from perennial vegetation to the ones that are able to survive in water stressed conditions [27].

Impact on stream characteristics

Sealing of soils, removal of vegetation and routing stormwater directly to the streams or surface water bodies significantly impact the processes that regulates stream flow. The impervious surfaces affect the groundwater recharge and subsequently the groundwater discharge to the streams which resulted in drop in the steady state stream flow in urban watershed [6,28] and the frequency of floods become larger due to increased runoff volume and baseflow of streams generally lowers [29]. On the other hand, an important study conducted by [30] on Lower Cedar River drainage near Seattle (Washington) from 1991 to 1998, indicated that there was abrupt stream flow when the forest cover was reduced (17-37%) and increase (>46%) in impervious surfaces while the lowest stream flow was recorded in the presence of extensive forest cover (59-81%) and lower (<23%) impervious surfaces. The impervious surfaces reduce the lag time of the stream hydrograph due to lower roughness, infiltration, interception and high runoff [31,32]. These hydrologic alterations enhanced the frequency of large flow which subsequently accelerates erosion of stream channel cross section [33]. Furthermore, the high frequency and larger flood peaks enlarges the flood plains downstream [34].

Impact on groundwater recharge

Groundwater recharge can be categorized in four types

(a) Direct groundwater recharge,

(b) Indirect groundwater recharge

(c) Localized groundwater recharge and

(d) Artificial groundwater recharge [35].

Direct groundwater recharge is a diffuse mechanism taking place over a larger area by vertical percolation of rainfall in excess of soil moisture deficits and evapotranspiration [36] whereas indirect recharge includes percolation process and lateral water flow from the surface to the aquifer. In natural landscapes, direct and indirect groundwater recharge takes place; while in urbanized watershed localized as well as artificial groundwater recharge processes also occur. The localized groundwater recharge in urban watersheds takes place through fractures, depressions, leakages from pipes and distribution network and other associated systems whereas indirect recharge occur through infiltration basins, sinkholes, bioswales and rain gardens, unpaved edges of impervious surfaces and like detention systems [37]. The process of artificial recharge encompasses deliberate injection of water to the aquifer system. Impervious surfaces cover larger areas in urbanized watershed and affects the groundwater recharge as well as base flow due to high rate of rainfall runoff generation, very less infiltration and reduced soil moisture content [38,39]. Furthermore, the urban heat island effect increases the atmospheric water demand which may aggravate the problem of groundwater depletion through the process of evapotranspiration of the vegetation grown in urban landscape [13,16].

Conclusion

Impervious land surface area interacts closely with the urban hydrological environment and can impact it to a considerable extent. The removal of natural vegetation and sealing of soils by building impervious surfaces enhances the urban heat island effect and consequently increased the precipitation resulting high runoff and lowering evapotranspiration. High rate of runoff and lesser infiltration rate further lower the groundwater recharge and subsequently the baseflow. Construction of impervious surfaces and artificial drainage channels escalates the direct input of precipitation to the streams thereby circumventing the groundwater recharge and storage while leakage of water supply can increase the localized groundwater recharge. The high runoff velocity and lower groundwater level further changes the stream flow. The high flood frequency due to generation of more stormwater increases the sedimentation of streams as well as other water bodies and further alters the stream channel morphology. Overall, the impervious surfaces impart additional complexity to the urbanized hydrological setup and has potential negative effect on hydrology. Understanding these impacts is essential for planning, designing and operation of urban hydrological systems and future research may provide a comprehensive understanding of these impacts by combining hydrological measurements and process modelling in urbanized catchments for better groundwater management.

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