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Review of literature

2.1 Introduction

In the recent years, urbanisation has been a growing concern because, urban population is rapidly increasing day by day due to the migration of people from nearby areas to the urban areas in search of employment and better living conditions. Urbanisation increases the density of urban populations and is an important cause of the dramatic change of land use [42]. It has significant impact on the water environment. With urbanisation, the natural land uses such as forest, grassland etc. are changed by various common anthropogenic activities of an urban area which can generate a variety of pollutants. The anthropogenic activities associated with urbanisation are among the most significant sources of pollutant in an urban area [5]. Vehicular activities, industrial processes, commercial activities and construction and demolition activities etc. release a wide range of pollutants into the urban environment. These pollutants are transported by stormwater runoff to the receiving water bodies. Urban stormwater runoff transports a wide variety of pollutants which have a significant negative impact on the quality of receiving water [43-45]. The pollutant load associated with stormwater runoff can be significantly higher than that of secondary treated domestic sewage effluent [46, 47]. Various studies strongly suggested that urban stormwater runoff is highly polluting and a threat to the receiving water bodies [31, 48, 49].

2.2 Impacts of urbanisation on stormwater

Urbanisation produces various changes in the natural environment as it replaces the existing land use pattern. It transforms the natural areas to impervious surfaces such as buildings, roads, parking lots and other paved areas. Due to urbanisation, the percentage of impervious surface within the catchments greatly increase which reduce rainwater infiltration rate and increase stormwater runoff volume resulting in the reduction of ground water storage. Hence, urbanisation affects the hydrologic characteristics of the catchments.

Whilst, the various anthropogenic activities associated with urbanisation generate a range of pollutants such as nutrients, solids, heavy metals, organic matter etc. These pollutants are that accumulated on the catchments surfaces during dry days. Stormwater picks up these pollutants and transports them to the receiving water bodies, thereby resulting in high pollutant loads to the water bodies. Therefore, it has been considered as a major source of water quality deterioration in urban areas [28].

The rapid changes associated with urbanisation in a catchment area due to any type of activity have a direct impact on both the quantity and the quality characteristics of the water environment [6]. The impacts of urbanisation on the water environment can be categorised as hydrologic impacts and water quality impacts.

2.2.1 Hydrological impacts of urbanisation

Urbanisation has significant impact on the catchment hydrology. From the hydrologic point of view, urbanisation results in two important physical changes to a catchment which includes the increasing percentage of impervious surfaces such as roads, roof, parking lots etc. and conversion of natural drainage systems to artificial conveyance system. The increasing percentage of impervious surfaces can reduce the amount of water infiltration into the ground reducing ground water storage [50].

Solpuker and co-authors reported that the increased fraction of impervious surface area associated with urbanisation around the world has reduced the natural infiltration rate of stormwater into soil and increased stormwater runoff volume and peak flow rate [26]. Conversion of natural drainage systems to artificial conveyance system introduces uniform slopes, reduced roughness and flow channels [11]. According to various research studies [3, 51-53], the following are the main hydrologic changes that an urban catchment commonly exhibits -

- Increased runoff peak
- Increased runoff volume
- Reduced time to peak, and
- Reduced base flow

Increased runoff peak

There are two primary mechanisms which results in increased runoff peak flow with increasing urbanisation. Firstly, with urbanisation, pervious surfaces within a catchment transform to impervious surfaces due to the construction of buildings, roads, parking lots etc. with less surface roughness. Secondly, conversion of natural drainage channels to artificial channels associated with urbanisation introduces uniform slope and reduced roughness of flow channels. These two mechanisms combining together results in the increase in runoff volume, reduction of the time of runoff concentration and the time required for runoff to flow. This results in the increase in runoff peak [54]. Thus, the runoff peak increases with increasing urbanisation.

In an urbanised catchment, peak runoff flow can be increased up to 2-4 times in comparison to its natural state [55]. The magnitude of the increase in runoff peak in a catchment is closely related to the fraction of the catchment's impervious surface cover, type of drainage channel improvements and the vegetation present in the catchment [56]. With increased percentage of impervious surfaces, relatively larger volume of runoff is discharged within a shorter time interval, and hence peak runoff also increases [29]. The increased peak runoff flow can enhance flood risk, damage property and can lead to land degradation [57].

Increased runoff volume

Urbanisation leads to the increase in runoff volume [58-60]. Barron and his co-authors found that urbanisation is responsible for a 30-100% increase in the predicted volume of runoff [60]. Increased proportion of impervious surfaces due to urbanisation greatly reduces the amount of rain water to infiltrate into the soil and hence an increasing amount of rainfall becomes surface runoff which results in the increase in runoff volume [61]. Volume of runoff from an urban area can be 1.1 to 4.5 times greater in comparison to its rural condition [58].

Reduced time to peak flow

The time of peak flow also decreases as a result of urbanisation. Increased percentage of impervious surfaces results in uniform surface slope reduced surface roughness, reduced infiltration rate and depression of storage which in turn results in increased volume of runoff. However, natural channel improvements lead to an increase in runoff velocity. These phenomenon together results in the reduction to the time of peak flow. Urbanisation of a catchment leads to a significant reduction in the time of peak flow depending upon the amount of impervious surfaces and the degree of channel improvements in the catchment [55]. Espey and his co-author noted that in urbanised catchment, the trend of reduction in the time of peak flow is 30-40% [55]. However, it may vary from storm to storm [56].

Reduced base flow

Increasing proportion of impervious surface reduces water infiltration rate which results in the reduction of ground water recharge. The reduced ground water recharge reduces the base flow in the urban stream [62, 63].

2.2.2 Impacts of urbanisation on stormwater quality

Urbanisation not only impacts on the hydrology of catchment, but also has a significant influence on the degradation of stormwater quality including physical, chemical and microbiological qualities. The major problems in water quality arise due to urbanisation are rise in temperature, salinity, sedimentation, depletion of dissolved oxygen, introduction of toxic substances and biological impacts [61]. Rainfall and the resulting surface runoff transports pollutants from the air and land surface to the receiving water bodies, thereby changing the quality of the receiving water bodies from their natural state [46]. Various common anthropogenic activities in urban areas such as residential, commercial and industrial developments are the most important sources of pollutants [64]. They release a wide variety of pollutants to the catchment surfaces. The kinetic energy associated with rainfall and runoff detaches these pollutants from the catchment surfaces and transports them to the receiving water bodies [7], leading to the degradation of the quality of the receiving water.

Due to rapid urbanisation, the quality of stormwater runoff has been significantly deteriorated. In their study, Sonzogni and his associates reported that suspended solids and nutrients load originated from urban areas were 10 to 100 times higher than that of from an equivalent non-urbanised area [65]. Another study found that, in comparison to rural areas, there was 10 times increase in solids load and doubling of nutrients load from urban areas [66]. Some other researchers have also been reported the similar observations as above in relation to the increase in nutrients and other pollutants load [67, 68].

Catchment and rainfall characteristics play an important role in determining urban stormwater quality [11, 12, 69]. Among the catchment characteristics land uses have a significant influence on urban stormwater quality. Concentrations of pollutants in urban stormwater runoff are closely related to various types of land uses because human activities are different according to land uses [6]. Liu also noted that the quality of stormwater have variation with different urban land uses [11].

The urban land use areas have been classified into main roads (including parking lots and airports), roofs, residential areas, commercial areas, industrial areas, parks and lawns, open and undeveloped areas [70]. They further reported that, the quality of stormwater runoff generated from all of these areas were different.

Roads and parking lots release a variety of vehicular related pollutants such as hydrocarbons, oxides of nitrogen, sulphur and lead [71, 72]. Therefore, stormwater of roads and parking lots will be primarily contaminated with the aforementioned pollutants. According to a study conducted by Remler and Hutter, the residential areas often generate high quality stormwater [73]. However, some contaminant such as detergents, plants related nutritional materials and fertilizers, herbicides and insecticides are usually present in the stormwater runoff from residential areas [74]. Commercial land use areas produce relatively higher load of suspended solids [75].

The quality of stormwater runoff from an industrial area largely depends on the type of the industry, their management practices and other site specific conditions. In light industrial areas, stormwater quality is similar to that of commercial areas. However, in the heavy industrial areas, stormwater can be highly contaminated with various pollutants like heavy metals and organic compounds [10].

Rainfall characteristics like average rainfall intensity (ARI), rainfall duration (RD) and antecedent dry days (ADD) etc. have significant role in determining the quality of stormwater. Liu, in his study conducted in Gold Coast, Australia, found that

ARI have more important role in influencing stormwater quality than the ADD [11]. He further noted that stormwater quality resulting from high average intensity rainfall events is highly variable in comparison to low average intensity rainfall events. In another study, it was found that stormwater runoff resulting from a rainfall with intensity 75mm/hr have significantly higher concentrations of dissolved reactive phosphorous, particulate phosphorous and total phosphorous (TP) in comparison to a rainfall with intensity 25mm/hour [12]. The rainfall events of high average intensity can produce rain with higher kinetic energy than low average intensity rainfall events and can easily detach the pollutants attached to the catchments surface [76] resulting in relatively higher concentrations of pollutants in stormwater runoff.

2.3 Sources of stormwater pollution

Urban stormwater runoff is one of the most important non-point sources of pollutants to the receiving water bodies [6, 77, 78]. As stormwater runoff flows over the catchment surfaces, the pollutants accumulated are transported to the receiving water bodies through various physical and chemical processes [10]. There are a variety of sources which are responsible for the accumulation of pollutants on catchment surfaces of urbanised area.

As per the various reports, most of the authors suggested the following as major sources of pollutants which degrade the quality of stormwater of an urban catchment area [77, 79-82].

i. Transportation activities

ii. Industrial and Commercial activities

iii. Construction and demolition activities

iv. Vegetation input

v. Soil erosion

vi. Corrosion

vii. Spills

viii. Atmospheric fallout

(i) Transportation activities

Transportation activities are one of the major sources contributing to stormwater pollution in urban areas. Transportation activities mainly include street surfaces and motor vehicles. Bannerman and his co-authors have noted that street surfaces and vehicular traffic are the most important sources of urban water pollution [71]. According to literature [71, 77], the pollutants present on street surfaces can be originated from-

- Degradation of street surface
- Vehicle lubrication system losses
- Vehicle exhaust emission
- Load losses from vehicles
- Degradation of vehicle tyres and brake linings
- Atmospheric deposition and soil inputs

Street surfaces have a significant influence on urban stormwater quality because they constitute a high percentage of impervious surfaces and provide an efficient stormwater conveyance system to receiving water [22]. Moreover, the pollutants released from vehicles are mostly deposited on the street surfaces. Therefore, street surfaces exert a significant influence on the quality of urban stormwater runoff [71, 79, 83, 84]. The availability of pollutants on street surfaces is relatively higher in comparison to other impervious surfaces [79, 85, 86]. Runoff from road surfaces can contribute up to 80% of pollutant loadings to receiving water bodies [87]. Various road runoff contaminants and their sources as given by Ball and his associates are depicted in the Table 2.1.

Table 2.1 Contaminants in road runoff and their sources [86]

Contaminants	Primary sources
Particulates	Pavement wear, vehicles, maintenance activities
Nitrogen/ Phosphorous	Roadside fertilizer applications, atmosphere
Cd	Tyre wear, insecticide application
Cr	Metal plating, moving parts, brake lining wear
Cu	Metal plating, bearing and brush wear, engine parts, brake lining wear, fungicides, insecticides, pesticides
Fe	Automobile rust, highway structures, engine parts
Pb	Auto exhaust, tyre wear, lubricating oil and grease, bearing wear
Mn	Engine parts, automobile exhaust
Ni	Diesel fuel and petrol exhaust, lubricating oil, metal plating, brush wear, brake lining wear, asphalt paving
Zn	Tyre wear, motor oil, grease
Sulphate	Roadway surfaces, fuels
Petroleum Hydrocarbons	Spills, leakages of motor lubricants, anti-freeze and hydraulic fluids, asphalt surface leachate
PCBs	Background atmospheric deposition, PCB catalysts in synthetic tyres
PAHs	Asphalt surface leachate

Vehicular traffic generates solid, liquid and gaseous pollutants. Traffic is closely related to the introduction of thousands of toxic substances which adversely influence the human as well as other organism, leading to illnesses and mutagenic changes [88]. It is the primary contributors of particulates, heavy metals and hydrocarbons [48].

These pollutants are mainly originated from vehicle exhaust emissions, wear of vehicles tyres and brake linings and the loads of pollutants depend upon traffic volume, road characteristics such as traffic lights, road layout, pavement surface and driver habits [11].

Heavy metals are the important pollutants released from traffic activities. Among the various pollutants generated from vehicular traffic, heavy metals are of great concern because they are found at elevated concentrations that possibly threaten aquatic organisms and human health [89, 90]. The most commonly found heavy metals in stormwater runoff are Cd, Cr, Cu, Fe, Pb, Ni, and Zn and these are derived from traffic related activities [90-92]. Consumption of tyre wear is a source of Zn and Cd, use of brake wear generate Cr, Cu, Ni and Pb, engine wear and fluid leakages are the sources of Cr, Cu and Ni, vehicular component wear and detachment release Cr, Fe and Zn [93].

Accumulation of pollutants is directly related to the type of traffic related activities on the road [86]. However, traffic can be characterised by another factor such as land use [11]. Miguntanna noted that industrial and commercial land use can generate relatively higher pollutant loads and more different pollutant species in comparison to residential land use, which is due to the relatively more traffic activities in industrial and commercial land use areas than that of residential land use areas [94].

(ii) Industrial and commercial activities

Industrial and commercial activities have a significant influence on stormwater pollution. Various researchers have found that the industrial land use areas produce stormwater runoff with relatively higher pollutants load in comparison to other land uses [35, 79, 95]. The quality of stormwater runoff from an industrial area largely depends on the type of the industry, effectiveness of their management practices, particular industrial process and other site specific conditions. Pollutants in stormwater runoff from an industrial area may be leached from open stacks of raw materials, emissions from the industrial processes, finished products and process wastes. The primary pollutants released from industrial activities include suspended solids, heavy metals, hydrocarbons, nutrients and organic substances [96].

Heavy metals are one of the important pollutants released from industrial and commercial activities [71]. In commercial areas, the pollutants are primarily originated from gas filling stations, parking lots and shopping centres. However, the types and concentrations of pollutants in stormwater runoff from industrial and commercial activities also depend on some factors including traffic volume and degree of impervious surfaces [97].

(iii) Construction and demolition activities

Construction and demolition activities are an important non point source of pollution in urban areas [98]. These activities have a significant influence on urban stormwater quality [77]. The types and concentrations of pollutants released during construction are directly related to the on-going construction and maintenance activities and the extent of management at the site. Construction and demolition activities can produce a significant amount of solids and litter to the urban environment. The rates of solids runoff from construction sites are 10-20 times higher than that of agricultural lands and 1000-2000 times higher than for forested lands [99]. The quantity of solids exports from construction sites is more than 10 times higher in comparison to other land uses [66].

(iv) Vegetation input

Vegetation input is another source of pollutants that influence urban stormwater quality. It includes leaves, twigs, pollen, grass and bark which introduce nutrients and organic matter to stormwater runoff. It can be a significant source of nutrients in urban areas where canopy cover is high [22]. As per reports, there was an increasing level of phosphorous, nitrogen and organic matter in stormwater runoff flowing through fallen leaves and crop residues [100, 101]. Novotny and his co-authors noted that during the fall season, a mature tree can produce 15-25 kg of leaf residue with significant amount of nutrients [47]. Another study found increased concentration of total kjeldahl nitrogen (TKN) during pollen deposition periods [66]. However, Allison and his co-authors have questioned about the importance of leaf litter as a nutrients source, because in their study it was found that the contribution of nutrients from leaf litter was around two orders of magnitude smaller than the total nutrient loads measured in stormwater runoff samples [102].

(v) Soil erosion

Soil erosion is a primary source of suspended solids in urban stormwater runoff. It particularly includes the erosion of stream bank, pervious surfaces and material stockpiles at construction, demolition, industrial, commercial and waste disposal sites [47]. Factors such as soil type, topography, vegetation and climatic conditions have a significant impact on soil erosion [94]. Erosion from lawns and other open surfaces are low, whilst the erosion from construction sites is the largest source of solids in the urban stormwater runoff [103]. Due to the loss of protective vegetative cover on the ground of construction sites, soil erosion significantly increased which results in the increasing suspended solids load to stormwater runoff.

Hydrological changes due to urbanisation such as higher peak flows also have a significant influence on erosion. This particularly leads to increased stream bank erosion. It was found that due to the urban development, the annual sediment yield had increased by nearly 50% out of which about 20% was accountable for stream bank erosion [57].

(vi) Corrosion

Rainfall and particularly acid rain and aggressive gases can corrode roofs, gutters and other metal surfaces. Corrosion of metallic roofs is a significant source of stormwater pollution. Researchers have reported that heavy metal concentrations in runoff from galvanized roofs were higher in comparison to runoff from streets [71, 104]. Pitt and his associates also found a significantly higher concentration of heavy metals in roof runoff as compared to street runoff, which was attributed due to the corrosion of metals on roofs [81]. The rates of corrosion will depend on various factors such as availability of corrodible materials, the frequency and intensity of exposure to an aggressive environment, the drying-wetting frequency of the exposed surfaces, the material structures and maintenance practices [77].

(vii) Spills

Spills can degrade the physical, chemical as well as biological quality characteristics of stormwater. Pollutants generated from spillages vary with the nature of the spill. The major sources of spills are vehicular transport, building construction and industrial activities [79]. The vehicular activities such as lubricant leakages are the primary sources of spills on urban street surfaces [105]. However, stormwater quality degradation due to spills can be reduced by introducing proper maintenance and management practices.

(viii) Atmospheric fallout

Pollutants in atmospheric fallout include dust, dirt, sulphur dioxide and nitrous oxide. Industrial and vehicular emissions initially release pollutants to the atmosphere which in turn returns to surface with atmospheric deposition and thereby results in stormwater pollution. There is a significant contribution/influence of atmospheric sources to the mass of pollutants available on the ground surface for transport by surface runoff [106].

2.4 Primary stormwater pollutants

In urban areas, stormwater is being deteriorated due to the introduction of pollutants. Generally, a wide variety of pollutants release from natural as well as anthropogenic activities practiced in urban areas which are accumulated on urban impervious surfaces during the dry days. Stormwater runoff transports these pollutants to receiving water body and results in the degradation of receiving water quality. The degree of degradation depends on the nature of the pollutant species washed and pollutant loads. The loads and types of pollutants vary according to the anthropogenic activities practised in the different land use areas. Hence, a variety of pollutants are added to the stormwater runoff from the various anthropogenic activities associated the different urban land use areas. However, according to researchers [35, 99], the primary pollutants in urban stormwater responsible for the degradation of receiving water quality are-

(i) Suspended solids,
(ii) Organic carbon,
(iii) Nutrients,
(iv) Heavy metals and
(v) Hydrocarbons

(i) Suspended solids

Suspended solids exert significant influence in stormwater pollution, as the other pollutants such as heavy metals, nutrients, pathogens and hydrocarbon are transported in association with solid particles [7, 79, 106-108]. On volumetric basis, it is the largest non-point source pollutant in urban receiving water bodies [109]. It is one of the primary pollutants and basic indicators of urban stormwater pollution.

Suspended solids have both physical and chemical impacts on receiving water. In terms of physical impacts, suspended solids increases turbidity of water, reduces light penetration rate, inhibits photosynthesis leading to decrease in food supply to the aquatic organisms. The primary chemical impact of solids is the adsorption of other pollutants and their transportation to the receiving water bodies [11]. Increasing sediment loads may increase the transportation of various pollutants by acting as a mobile substrate on which pollutants can absorb, adsorb or adhere [110-112].

Solids can easily adsorb other pollutants such as heavy metals and hydrocarbons because of its electrostatic charges on the surface [113]. The adsorption capacity of a solid particle depends on its structure, size and chemical characteristics [114]. Because of their larger surface areas and electrostatic charges, the finer particles can easily suspend for a longer periods of time and transported by stormwater runoff to receiving water [115]. Therefore, it has been recognised as a significant transporter of pollutants [79].

Finer particles can adsorb relatively higher concentration of pollutants due to their greater surface area [116]. It was found that the finer fraction of particles had the highest phosphorous and nitrogen loads [94]. Significant portion of pollutants including nutrients, organic materials and heavy metals are attached to the finer fraction of solids [79]. The amount of Zn, Cu and Pb adsorbed to solid particles increased with the decreasing particle size [117]. Therefore, to remove the stormwater pollutants effectively, the stormwater treatment process should target to remove the finer fraction of particles.

In stormwater runoff, suspended solids may originate from different sources such as erosion of landscaped areas, flood water, construction and demolition activities, open areas that drain to the site, road surface erosion, irrigation activities, vehicles and maintenance activities [7]. In comparison to natural sources, the anthropogenic sources contribute relatively higher concentration of finer particles to the urban environment [118]. The nature and volume of suspended solids varies with the existing land use practices of a catchment [119]. The concentration of suspended solids in urban stormwater runoff also varies with other several factors such as rainfall duration and intensity [11, 120, 121]. In his study, Deletic found that the concentration of suspended solids decreases with increasing storm duration [120]. Some other researchers found a strong positive correlation between ARI and suspended solid concentration in stormwater runoff [11, 121].

(ii) Organic carbon

Organic carbons are oxygen demanding substances which are primarily decomposed by bacteria to carbon dioxide and water. The decomposition processes decrease/deplete the dissolved oxygen content of the water bodies, which is one of the most important indicators of water quality. Moreover, it can lead to undesirable odours, undermined water supplies and decrease the recreational value of waterways [122]. Depletion of oxygen can also affect the release of toxic chemicals and nutrients from the deposited solids in a water body [61]. Organic carbon can also play a significant role in the distribution of hydrocarbons by influencing their adsorption to solids and their transportation by stormwater runoff [13]. Parks and his co-author noted that organic carbon adsorbed to suspended solids increases their adsorption capacity to combine with hydrophobic organic chemicals and some heavy metals such as Pb and Zn [123]. Therefore, organic carbon can be considered as a good indicator of urban stormwater quality [48, 61].

The primary sources of organic carbon include vegetation debris, animal waste, street litter, vehicular activities and tyre wear [105]. Street surfaces are an important source of organic carbons to urban receiving water [79, 89, 104]. The concentration and loads of organic carbon is closely dependent on the catchment characteristics and the frequency of street cleaning practices [79]. Organic carbon concentration also varies with particle size of suspended solids and with land uses. The finer suspended solids particles contain more organic carbon in comparison to coarser particles [79]. Roger and his co-authors have also noted that, concentration of organic carbon is relatively high in particles smaller than 50μm as compared to other particle sizes [124]. This further confirms the need for the implementation of stormwater treatment facilities targeting to remove finer fraction of suspended solids from stormwater runoff. However, for all particle size ranges, Miguntanna found the highest organic carbon loads in the residential land use which was attributed to the presence of larger amount of vegetation in the surrounding area of the investigated residential road surfaces [94].

(iii) Nutrients

Nutrients include chemical compounds such as calcium, carbon, nitrogen, phosphorous, and potassium. Among these, nitrogen and phosphorous are the important nutrients that play the most vital role in the degradation of water quality [125,126]. In the environment, nitrogen and phosphorous can release from both the point and non-point sources. Releases of nitrogen and phosphorus from point-sources have declined dramatically since the 1970s, but releases from nonpoint-sources continue to pose a significant threat to water quality [127]. In urban areas, stormwater runoff is one of the most important non-point sources of nutrient pollution to the receiving water bodies.

Excessive level of nutrients in receiving water body results in eutrophication, which is a serious problem in urban areas. Eutrophication leads to algal blooms which results in lowering the dissolved oxygen level of the water body and blocking of sunlight to deeper water. Thus, it seriously affects the respiration of aquatic organisms, leading to a decrease in the diversity of aquatic animal and plant and also affects the use of water for drinking, swimming, fishing and boating [63]. According to a study carried out on the Neuse River basin in North Carolina, USA, high nitrogen level in the river has led to excessive algal blooms, lower level of dissolved oxygen and large fish kills [128]. Another study found that phosphorous is the key nutrient affecting the productivity of Great Lakes, USA [65].

The sources of nutrients in urban stormwater are fertilizer applications, plant matter, vehicular activities and atmospheric deposition [129]. Goonetilleke and Thomas remarked that the primary sources of nutrients in urban stormwater runoff are lawn fertilizer, animal waste, vegetation debris, vehicle exhausts, sewer overflows, power generation, industrial activities and atmospheric dry and wet deposition [22]. According to research literature, dry and wet precipitation, lawns and other soils within the catchment, fertilizers, leaf litter, organic decomposition processes, pets, and wildlife may derive nitrogen and phosphorus to the urban environment [130].

In stormwater runoff, nutrients can exist in both dissolved and particulate forms. As per various reports, in stormwater runoff, phosphorous is transported mainly in particulate form whereas nitrogen is transported primarily in dissolved form [131-133]. However, the finer fraction of particles (<150 mm) plays the most important role in the wash-off of both phosphorus and particulate nitrogen [133].

Nutrient transportation process and hence nutrient load in stormwater runoff is influenced by several factors such as soil type, rainfall and runoff characteristics, land use and anthropogenic activities in the catchment [22]. It was found that, park and residential land use have higher concentrations of total nutrients in comparison to other urban land uses [134]. Lawns can contribute more than 50% of the annual total phosphorous loads in a residential area [135]. Industrial wastewater and septic tanks are the major sources of nitrogen in stormwater runoff [125]. Atmospheric deposition is also an important source of nutrients in stormwater as it inputs both nitrogen and phosphorous to urban stormwater runoff. It supplies a larger proportion of nitrogen in urban runoff in comparison to phosphorous [136]. According to research literature, the finer fraction of solids is the most important for nutrient build-up and particulate nutrient wash-off process, because the nutrients are mostly associated with finer particles in both build-up and wash-off samples irrespective of land use types [94].

(iv) Heavy metals

Heavy metals are inorganic pollutants that are toxic to living organisms and some of them are lethal even at very low concentrations. Toxicity of heavy metals depends upon their type. The insoluble metals pass through the body without causing much harm whereas soluble metals have severe toxic effects. The heavy metals which can bioaccumlate and biomagnify in the food chain are the most toxic. When ingested, they combine with the body's biomolecules, like proteins and enzymes to form stable biotoxic compounds, thereby mutilating their structures and hindering them from the bioreactions of their functions [137]. Besides of their toxicity, heavy metals do not degrade in the environment.

As per various research reports, Cd, Cr, Cu, Fe, Pb, Ni, and Zn, Hg, As, Al are the most commonly found heavy metals in urban stormwater runoff [79, 116, 138]. The primary sources of some of these metals are presented in Table 2.2.

Urban stormwater runoff contain significant amount of heavy metals [80, 116, 138]. Heavy metals present in urban stormwater runoff have been of great concern because of their potential toxicity and non-biodegradable nature. The primary anthropogenic sources of heavy metals in urban stormwater runoff may be vehicular traffic, combustion of fossil fuels and industrial processes.

The other specific sources of heavy metals in urban area include corrosion of buildings and their fittings, atmospheric deposition, transport and various industrial activities and intentional and accidental spills [138]. Corrosion of roofing materials can also release heavy metals [71].

McPherson and his associates have pointed out that road surfaces, atmospheric deposition, roof runoff, industrial activities, soil erosion, contaminated sites, sewer overflows and illegal discharges are the major sources of heavy metals in an urban catchment [140].

Table 2.2 Sources of heavy metals in urban stormwater runoff [139]

Metals	Sources
Cd	Batteries, combustion of fossil fuel, corrosion of metals, pigments and paints, printing materials and graphics, plastics, tyre wears, metallurgical industries and medical uses.
Cu	Electronic wastes and metallurgical industries.
Ni	Batteries and metallurgical industries.
Pb	Combustion of fossil fuel, batteries, pigments and paints, metallurgical industries, printing graphics, and medical uses.
Zn	Tyre wears, combustion of fossil fuel, corrosion of metals, electronics, batteries, pigments and paints, printing graphics, metallurgical industries and medical uses.

All of these sources generate different heavy metals to stormwater runoff. The degree of traffic congestion and road surface roughness exert more significant impact on heavy metal build-up than traffic volume [141].

Concentration of heavy metals varies with different factors such as land use and particulate size. The accumulation and transportation of heavy metals is closely related to the physico-chemical properties of soil particles [142, 143]. Brezonic and his co-investigator from their study carried out in Minnesota, USA concluded that commercial and industrial land uses contributed a higher amount of heavy metals in comparison to residential land use [144]. In another study, it was found that industrial land use sites have the highest concentration of heavy metals than that of residential and commercial land uses [116].

Due to the higher adsorption capacity of finer solid particles, the heavy metals have relatively strong affinity to finer particles [145]. Sartor and Boyd found that significant portion of heavy metals is attached to the finer fraction of solids [79]. The amount of Zn, Cu and Pb adsorbed to suspended solid particles increased with the decreasing particle size [117]. Therefore, to effectively minimize the associated heavy metal loads, the stormwater treatment facilities should target for reducing the finer fraction of particulates.

(v) Hydrocarbons

Hydrocarbons are the organic compounds, which contains carbon and hydrogen. Urban stormwater transports a wide variety of hydrocarbon compounds to the receiving water bodies [146]. Increased amount of hydrocarbon is toxic to receiving water bodies. It is harmful to aquatic life and can affect the use of water for drinking and recreational purposes. Hydrocarbon compounds can generated from both natural and anthropogenic sources [147]. The primary natural sources of hydrocarbons include anaerobic degradation of organic materials and forest fires whilst the primary anthropogenic sources include roads, parking lots, vehicle service stations and petroleum storage facilities [94]. Latimer and his co-authors have noted that the leakage of crankcase oil associated with vehicular traffic is the major source of hydrocarbons, whereas street dust, soil and atmospheric depositions are the minor sources [148].

Among the hydrocarbon compounds, the total petroleum hydrocarbons and particularly polycyclic aromatic hydrocarbon (PAHs) are the main types of hydrocarbons that influence the deterioration of water quality [94]. PAHs are originated from both natural and anthropogenic sources [147], but the contribution of anthropogenic sources is much higher in comparison to natural sources [149]. Van Metre and his co-authors have noted that the concentration of PAHs in stormwater increases with the increasing use of automobiles [147]. Tyre wear, crankcase oil and fuel exhaust are the specific vehicular sources of PAHs [150]. The primary source of petroleum hydrocarbons is used up crankcase oil [148].

In urban stormwater runoff, hydrocarbons are associated to suspended solids. Due to their strong affinity to fine particles, hydrocarbon compounds are primarily transported with the association of finer fraction of suspended solid particles. About 88-96% of the total hydrocarbons discharged to stormwater runoff are particulate hydrocarbons [151]. Therefore, from stormwter runoff, hydrocarbons could be effectively reduced by implementing stormwater treatment facilities that can reduce suspended solids, particularly finer fraction of suspended solid particles.

2.5 Factors affecting stormwater quality

Both catchment and rainfall characteristics have a significant influential role in urban stormwater quality. Catchment characteristics such as land use and urban form, percentage of impervious area, urban area location etc. play a significant role in pollutant generation *i.e.*, pollutant build-up process, whereas the rainfall characteristics such as duration and intensity of rainfall primarily influence the pollutant detachment and transportation *i.e.*, pollutant wash-off process. Number of ADD is another important factor which influences the pollutant build-up process.

2.5.1 Catchment characteristics

Some of the important catchment characteristics and their influential role in stormwater quality are discussed below:

(i) Land use

Land use is one of the most important factors in influencing the stormwater quality [6]. In urbanised catchments, land uses are typically classified as residential, commercial and industrial land use. The anthropogenic activities associated with these land uses are different from each other, and hence can produce different types of pollutants. The frequency of the anthropogenic activities also varies with the land uses which results in the variation of pollutant loads. Thus, land use exerts a significant influence on pollutant build-up.

As per available literature, the accumulated solid load is relatively higher in industrial land use areas in comparison to residential and commercial land use areas [152]. Industrial land uses can also produce more fine particles as compared to other land uses [94]. Concentration of total phosphorous increases with the increasing level of urbanisation and industrialisation [68]. In literature, it was found that the total organic carbon load is relatively higher in residential land use as compared to commercial and industrial land uses which could be due to the presence of increasing amount of vegetation in the residential land use [94]. Therefore, it is important to further investigate the relationship between land use and stormwater quality.

(ii) Urban form

Urban form refers to the physical layout and design of the urban area such as road layout, urban design features and spatial distribution of urban areas [6]. It is one of the important factors affecting the quality of stormwater. Liu and his co-authors have noted that urban form has a significant role in stormwater quality as it influence the pollutant generation, build-up and wash-off process [153]. Stormwater runoff generated from more uniform urban forms has relatively less variation in its quality [11]. Goonetilleke and his co-authors noted that stormwater runoff produced from different urban forms have very little similarity in terms of their quality even for the catchments with same fraction of impervious surface area [6]. Another study also found that the stormwater quality of two catchment with same impervious area fraction and land use were significantly different [153]. These differences in the quality of stormwater were attributed due to the significant differences in the spatial distribution of the impervious surface areas and catchments management practices [6, 153].

According to literature, the most important source of stormwater pollution in urban areas is the road surfaces [71]. Hence, road layout of an urban catchment can also play an important role in determining urban stormwater quality.

(iii) Fraction of impervious area

The fractions of impervious area have a significant influence on both the quality as well as the quantity of stormwater runoff. Increased fraction of impervious surfaces results in uniform surface slope and reduced surface roughness. This in turn results in the reduction of infiltration rate, depression of storage and increase in the volume as well as velocity of runoff. Therefore, due to the increasing volume and velocity of runoff, pollutants from the impervious surfaces can be easily detached and transported by stormwater runoff to the receiving water bodies. Greater fraction impervious area commonly results in the higher peak flows, reduction of infiltration rate and groundwater recharge and increase in pollutant loads to receiving water [154]. The fraction of impervious area has a strong correlation with phosphorous concentration in urban stormwater runoff [155]. Dietz and his co-author have noted that both the concentration of TN and TP significantly increased with the increasing fraction of impervious surface area [156].

(iv) Urban area location

It primarily refers to the distance of the urban areas from the catchment outlet. Urban area location influences the pollutant transportation process of stormwater runoff to the catchment outlet. The stormwater runoff process including the starting time of runoff from pervious surfaces, velocity of flow and pollutant loads and hence the quality of stormwater can vary with urban area location [157]. If pervious surface area location is close to the catchment outlet or drainage system then the quality of stormwater runoff could be diluted with impervious surface runoff. However, if the pervious surface area location is far away from the catchment outlet then due to the long travel distance, the pervious surface runoff may not reach to the catchment outlet or may be delayed significantly [11]. Unfortunately, the impact of urban area location on the quality of stormwater runoff is still not clear [158] due to the limitation of research undertaken in this field.

2.5.2 Rainfall characteristics

Rainfall characteristics, such as RD and ARI have a significant influence in the deterioration of stormwater quality [11, 13]. Zhang and his co-authors have noted that the ARI, RD as well as the ADD played important role in the pollutant wash-off process [159]. The ARI and RD have more significant influence in the wash-off of pollutants when the pollutants are predominantly in particulate phase [160]. The rainfall events with high ARI can easily detach the pollutants from the catchments surface [76] contributing to relatively higher pollutant loads in stormwater runoff.

Egodawatta and his co-authors found a strong positive correlation between ARI and suspended solid concentration in stormwater runoff from a mixed urban catchment [121]. Liu found that ARI is positively related to TN, TP, TOC and TSS [11]. It was also found that the peak rainfall intensity and RD have significant relationship with the wash-off of TSS and total Pb [160].

The RD also influences the quality of urban stormwater runoff. It has a negative relationship with stormwater quality. Liu found that the concentrations of TN, TSS and TOC in stormwater runoff decreases with increasing RD. He remarked that the reason of this reduction was the dilution of stormwater with increasing RD [11].

The treatment efficiency of stormwater in terms of pollutant types and load largely depend upon the appropriate selection of rainfall events [41]. Unfortunately, the natural rainfall events have been primarily classified on basis of hydrologic criteria [161]. There is only limited knowledge regarding the classification of rainfall events in terms of stormwater quality. Therefore, for appropriate classification and hence to improve stormwater quality treatment efficiently, it is very important to clearly understand the role of rainfall characteristics on stormwater quality.

2.6 Stormwater management

Management and treatment in of urban stormwater is a widely recognized problem throughout the world [162]. Urbanisation has an adverse impact on both the quantity and quality of stormwater runoff. The management of quantity impacts are relatively straight forward, but the management of quality impacts are far more complex [6], which is due to the fact that the quality of stormwater runoff is influenced by a variety of factors [40]. However, some of the most common approaches for stormwater treatment and management practiced in different countries include best management practices (BMPs) [163], water sensitive urban design, low impact development, sustainable urban drainage systems [164] and innovative stormwater management [165]. Here in the present study, different types of BMPs are considered for extensive study. The objectives of BMPs are to prevent or reduce the transportation of pollutants from land surface to the receiving water [166] and to reduce the volume of stormwater runoff.

The most widely used BMPs in stormwater management can be classified into structural and non-structural techniques.

2.6.1 Structural best management practices

Structural techniques include three main categories:

(i) Infiltration

(ii) Filtration and

(iii) Detention

(i) Infiltration

In infiltration technique, a portion of stormwater runoff is allowed to infiltrate into soil [167]. This process removes pollutants through filtering the stormwater runoff by soil and replenishes the groundwater [168]. Infiltration practices are most effective in reducing stormwater pollution as they retain first flush of stormwater runoff. The effectiveness of infiltration devices depend upon the site conditions such as infiltration rate at the site, vertical distance between the infiltration device invert and the seasonal high groundwater table and the lateral distance from the adjacent water resources [169]. To avoid groundwater contamination, infiltration devices should be placed at a distance of minimum 30 meter away from the domestic water sources [170]. Some of the important infiltration devices are infiltration tranches, infiltration basins and porous pavements.

(ii) Filtration

In filtration technique, stormwater drainage is allowed to pass through a contained filtration medium and the treated water is returned to the drainage network [171]. The pollutant removal efficiency of filtration devices depend upon the used filter media. The removal efficiencies of sand filtration for suspended solids, nutrients and heavy metals are in the range of 50-93% [172]. Some of the important filtration devices include filter strips, bio-retention areas, grassed swales (or biofilters) and media filters.

Filter strips are the vegetative sections of land which are designed to accept runoff as overland sheet flow [167]. They are often used for the pre-treatment of stormwater runoff for other downstream BMPs. Their efficiency in removing sediment depends on the drainage area, slope and rainfall duration [173]. Filter strips cannot treat high velocity flows [167].

Grassed swales are the vegetated channels in which pollutants are removed from stormwater by filtration through grass and infiltration through soil [174] and by settling. They can effectively remove coarse sediments and associated pollutants but poor in the removal of dissolved pollutants [175].

In media filters, pollutants are removed from the first flush of stormwater runoff. Sand filters are among the most widely used media filters. They provide significantly good amount of particulate removal and moderate removal of bacteria and dissolved metals.

Bio-retention is one of the most popular stormwater treatment measures because it can reduce stormwater runoff volume as well as can effectively improve the quality of stormwater runoff [176, 177]. Bio-retention systems can remove significant amount of nutrients and heavy metals from stormwater runoff [178-180]. The pollution removal performance of bio-retention basin is highly variable and dependent upon various factors such as inflow pollution concentrations, filter media, construction methods and environmental factors [181].

(iii) Detention

Detention basins are the most widely used stormwater BMPs. They provide detention for stormwater runoff and thus reduce the runoff peak to the pre-developmental stage [167]. They can also remove pollutants from stormwater runoff. In detention basins, the rate of pollutant-load-reduction depends on its volume [182]. The most commonly used detention basins include dry ponds, wet ponds and constructed wetlands.

Dry pond consists of a reservoir, an inlet, an outlet and in some cases, a spillway to pass high flows [167]. In comparison to other detention facilities, dry ponds are less expensive, easier to construct and have relatively less impact on the environment [183]. They are moderate in removal of particulate pollutants but poor in removing soluble pollutants and bacteria.

The basic components of wet ponds are a permanent pool of water, a shallow littoral zone with aquatic plants and the storage capacity to provide detention for a required volume of runoff [184]. Wet ponds can control both storm water quantity and quality [185]. They reduce downstream flooding problems and also reduce pollutant loadings to the receiving water. Their efficiencies of removing both the particulate as well as soluble pollutants are moderate to high.

Constructed wetlands are typically shallow and extensively vegetated water body with different zones [186]. They are very effective in removing pollutants from stormwater runoff.

2.6.2 Non-structural best management practices

Some of the important non-structural source control practices include:

- Public information programs
- Lawn and fertilizer management
- Control of pesticide use
- Street sweeping
- Erosion and sediment source control on construction sites

Urban stormwater problem is mainly arising due to the anthropogenic activities of the individuals. Many people do not know that some of their common activities can result in stormwater pollution. They do not realize that yard, debris, trash and hazardous materials thrown into the ditches will contribute to flood problems and pollute surface water [184]. Therefore, it is very essential to undertake public information program to provide information to the individuals about the sources of pollutants and also to provide specific information about storing, using and disposing of materials which may pollute stormwater.

To reduce nutrient pollution, it is very essential to control the use of fertilizers. This can be implemented through public information program, by making the public aware about the problems associated with the overuse of fertilizers [184]. Pesticide pollution can be reduced to a great extent by using less toxic, mobile and less persistent pesticides. Public information programs on the handling and use of pesticide will help to reduce pesticide pollution to the receiving water body [184].

Street surfaces are one of the major sources of stormwater pollution. Due to both the natural and anthropogenic activities associated with urbanisation, a variety of pollutants are accumulated on the urban street surfaces. These pollutants can be removed by street sweeping. The pollutants accumulated on the street surfaces can be removed to some extent by street sweeping during dry days before precipitation washes them into sewers [187].

Soil erosion is the major cause of diffuse pollution and sediment is the most visible pollutant [188]. Various pollutants enter to the stormwater attaching with soil particles. Erosion and sediment source control on construction sites provide protection of the receiving water bodies [184], by reducing the entrance of sediments as well as other associated pollutants.

2.7 Summary

The current states of knowledge on the impact of urbanisation on the water environment, the role of rainfall and catchment characteristics in determining urban stormwater runoff quality and the stormwater management by implementing BMPs are included in this chapter.

The impacts of urbanisation on the water environment include hydrologic impact and water quality impact. Due to urbanisation, impervious surface area fraction of a catchment increases which reduces water infiltration rate of the surface and introduce more uniform surface slopes. This in turn results in a range of hydrologic changes to catchment including increased runoff volume, increased runoff peak flow and reduced time to peak. On the other hand, various anthropogenic activities associated with urbanisation generate a range of pollutants including solids, nutrients, heavy metals, and other toxicants. Stormwater runoff picks up and transports these pollutants to the receiving water and thus degrades the quality of the receiving water.

The primary pollutants found in urban stormwater runoff which degrade the receiving water quality are suspended solids, organic carbon, nutrients, heavy metals and hydrocarbons. These pollutants are mainly originated from transportation activities, industrial activities, commercial activities, construction and demolition activities, vegetation, soil erosion, corrosion, spills and atmospheric fall out.

Both rainfall and catchment characteristics have significant role in determining stormwater quality as they influence the pollutant build-up and wash-off process. Catchment characteristics such as land use and land cover influence the pollutant build-up process. Pollutant wash-off process is influenced by both catchment and rainfall characteristics. The efficiency of stormwater quality treatment and largely depend upon the appropriate selection of rainfall events. However, there is only limited knowledge regarding the classification of rainfall events in terms of stormwater quality. Therefore, for appropriate classification and hence to improve stormwater quality treatment efficiently, it is very important to clearly understand the role of rainfall characteristics on stormwater quality.

Urban stormwater management in terms of both quantity and quality is a challenging task before the stormwater authorities throughout the world. The management of stormwater runoff quantity impacts are relatively straight forward, but the management of quality impacts are very complex. However, for the treatment and management of stormwater, different approaches can be followed. The BMPs are among the most common approaches which are used for the treatment and management of stormwater.

BMPs can be classified into structural and non-structural techniques. Structural BMPs are the engineered facilities which can be implemented to control the quantity and quality of urban stormwater runoff. The structural BMPs are mainly categorised as infiltration, filtration and detention techniques. However, non-structural BMPs include a variety of programmes or practices which can result in the behavioural changes of people in such a way that they avoid or reduce stormwater pollution. Some of the important non-structural BMPs are public information programmes, lawn and fertilizer management, control of pesticide use, erosion and sediment control at construction sites and street sweeping etc.