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Summary and conclusion

According to various reports, urban stormwater throughout the world has been highly polluted with the introduction of various pollutants such as nutrients, suspended solids, heavy metals and other toxicants. This has been severely affected the quality of receiving water. The increasing trend of urbanisation is the main cause of stormwater pollution. Pollutants in stormwater are mainly sourced from the anthropogenic activities associating with the urbanisation. Some of these pollutants are biodegradable and some are non-biodegradable. Non-degradable pollutants are very toxic because, they are bio-accumulated through food chain causing long term impact on human health.

Researchers also reported that, the process of stormwater pollution is affected by a wide range of factors. Both the rainfall and catchment characteristics are among the factors which have significant role in stormwater pollution. 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.

Management of urban stormwater runoff is very widely recognized problem. The management of stormwater quantity is relatively straightforward. However, the management of stormwater quality is very complex task, as the deterioration of stormwater runoff quality is influenced by a wide range of factors.

The detailed analysis of the role of land use and rainfall characteristics on urban stormwater quality is presented in the thesis. The review of stormwater management practices are also presented in the thesis.

8.1 Rainfall characteristics and stormwater quality

The study was conducted in a residential catchment so that no variability in stormwater pollutant concentration (*i.e.,* stormwater quality) can arrive due to catchment characteristics and hence only the influence of rainfall characteristics on stormwater quality should be understood.

The present study confirms 3 types of rainfall events in the area under study. On the basis of average rainfall intensity (ARI) and rainfall duration (RD), these events can be classified as Type-I rainfall which was characterized by high average intensity-short duration, Type-II rainfall, characterized by high average intensity-long duration and Type-III rainfall by low average intensity-long duration.

The nature of pollutant generated by different rainfall types was also found different. Therefore, for stormwater quality treatment rainfall type should be select on the basis of treatment objectives. For example, if the treatment objective is to remove

OG or TSS then Type-I rainfall event should be selected but if the treatment objective is to remove PO_4^{3-} then Type-II rainfall event should be selected.

Low average intensity rainfall events have relatively lower variability of pollutants than high average intensity rainfall events and hence the prediction of treatment performance would be much easier if low average intensity rainfall event is selected for stormwater quality treatment design.

Through PCA, the investigated rainfall characteristics and stormwater pollutants were classified into three principal components (PCs). PC1 has the highest eigen value of 2.823 and has strong positive loadings on ARI, PO_4^{3-}, K^+, OG and TSS and hence explained maximum variation in the original dataset among the three PCs. The PC2 has strong negative loading on RD and strong positive loading on NO_3^-. The PC3 has significant positive loadings only on ADD. Thus from the PCA, it is clear that ARI has more influential role in stormwater pollution in comparison to the other investigated rainfall characteristics *i.e.*, RD and ADD.

The duration of rainfall has negative correlation with almost all of the pollutants *i.e.,* with the increasing duration of rainfall, the concentrations of pollutants in stormwater decreases, which is due to the dilution effect of stormwater with increasing RD.

Both the ARI and antecedent dry days (ADD) have positive correlation with pollutant parameters which confirms that high average intensity rainfall event with long ADD would generate relatively high pollutant load and thus results in highly polluted stormwater runoff.

The ARI has a more significant positive relationship with pollutants than that of ADD. Therefore, it can be concluded that ARI play more significant role in

determining stormwater quality than ADD. This further implies that pollutant wash-off ability has more influential role in stormwater pollution rather than pollutant build-up characteristics.

With the increasing RD, concentration of NO_3^-, K^+, OG and TSS decreases but PO_4^{3-} concentration increases indicating the PO_4^{3-} has different wash-off process from other four selected pollutant parameters. Thus the results of the present study found that the wash-off characteristic varied with different pollutants.

8.2 Pollutants in the stormwater of different land uses

For identifying the role of land use on urban stormwater quality, stormwater of four different land uses namely residential, commercial, heavy traffic and industrial was analysed for some selected stormwater quality parameters. The present study confirmed significant variations in concentration of pollutants with the different land uses.

8.2.1 Stormwater of residential and commercial land use

In the stormwater of residential and commercial land uses, the concentrations of all the analysed pollutants were found lower in comparison to the other two land uses. In the residential land use, the concentrations of PO_4^{3-}, Cd, Cu, Ni and Pb were higher than that of commercial land uses. On the other hand, it was documented that compared to the residential land use, commercial land use have higher loads of NO_3^-, TSS, OG, Co, Cr, Fe and Zn.

8.2.2 Stormwater of industrial land use

The loads of PO_4^{3-} and NO_3^-, TSS, Cu and Fe were found higher in the industrial land use area in comparison to three other land uses indicating that the stormwater of this is highly polluted with the aforementioned pollutants. The presence of heavy numbers of tree canopy in the industrial area may be the possible cause of higher loads of PO_4^{3-} and NO_3^- in this area.

The surrounding of the industrial site is hilly area, the roads have greater slope. Therefore, the flow force of stormwater runoff from these road surfaces is higher, which can lead to higher rate of road surface erosion and hence contribute to higher concentration of TSS. The higher amount of plant decomposition materials might be another significant cause of higher TSS in this area.

Sources of Cu in the industrial area may be combustion of fuel, corrosion of roof, gutter and vehicular traffic related activities which are commonly practised at this area. On the contrary, the potential/possible sources of iron are paints, tires, different materials which are made of iron, surface erosion, brake ware of equipments and vehicles and other vehicular sources in this area.

8.2.3 Stormwater of heavy traffic zone

Compared to other land uses, concentration of OG, Cd, Co, Cr, Ni, Pb and Zn were found higher in heavy traffic area. In the present study, ISBT was found most heavy traffic area among the rest of the areas investigated where a large number of vehicles are gathered at a regular manner. Therefore, OG, Cd, Co, Cr, Ni, Pb and Zn in this area may originate from vehicular sources like used crankcase oil.

Thus the results of the present study again stresses that, the anthropogenic activities practiced are the main sources of pollutants in stormwater of the area. The anthropogenic activities vary with the pattern of land use of an area. Therefore, the loads and species of pollutants in stormwater also vary with land use pattern of the area. Hence, the land use pattern of an area significantly influences the quality of stormwater. In comparison to residential and commercial areas, industrial and heavy traffic areas produce higher pollutant loads causing heavy stormwater pollution than the first two areas. Therefore, stormwater of these two land use areas should be managed specially.

8.3 Results of the correlation study

From the correlation study, it was found that the nutrients (PO_4^{3-} and NO_3^-) have weak to moderately strong (R^2= 0.2571 to 0.5322) relationship with TSS. The relationship was relatively stronger in residential and industrial land use areas. Therefore, it can be concluded that most of the nutrients in these two land uses are particulates. Except from the industrial land uses, OG showed strong correlation (R^2>0.50) with TSS at all other land uses.

The correlation coefficient between heavy metals and TSS ranged from 0.2066 to 0.7824, which suggests a weak to moderately strong correlation between them. The heavy metals in the residential and the heavy traffic areas have relatively strong relationship with TSS. Hence, the heavy metal load in stormwater from residential and heavy traffic areas can be effectively reduced by removing TSS. However, in all land use areas, TSS showed positive relationship with all other parameters chosen. Therefore, TSS can be regarded as a primary stormwater pollutant and hence by

reducing TSS from stormwater, the other pollutant concentration in stormwater can also be reduced to some extent.

8.4 Variability of stormwater pollutants

The variability in the stormwater pollutants within the same land use were analysed by using CV. The analysis confirmed that, except for TSS in industrial and heavy traffic area, all other parameters have higher CV values (>30%). Thus, the present study further confirms the high variations of the pollutants even within the same land use. This implies that, the quality of stormwater is not only influenced with land uses but also with the site specific characteristics.

In the residential land use area, Fe shows the highest CV value (>100%) and Ni shows the highest CV values (>100%) for the commercial, industrial and heavy traffic areas. Therefore, the variability of these two pollutants within the same land use is relatively higher than that of other and thus mostly influenced by the existing site specific characteristics.

8.5 Stormwater management

One of the most common solutions of stormwater treatment and management is BMPs. For effective management of stormwater runoff, it is essential to implement both the structural as well as non-structural BMPs together. Only a single BMP is not suitable for implanting in all site conditions. Different BMPs are suitable for different site conditions. Therefore for a specific site, an appropriate BMP should be selected on the basis of the site conditions such as soil type of the site, depth of water table,

slope, drainage area, developmental conditions at the site and land use etc. The cost-effectiveness and maintenance requirement should also be considered. The pollutant removal efficiency for different pollutants also varies with BMPs. Therefore, for selecting appropriate BMP, it is also essential to consider the pollutants of concern for the specific site.

8.5.1 Infiltration

In case of small drainage areas, infiltration BMPs are appropriate for implementation. They are suitable on highly permeable soils, where the seasonal high water table is sufficiently below the ground. They can effectively remove pollutants from stormwater runoff. The construction cost of infiltration BMPs is low to moderate, but they require high maintenance.

Infiltration trenches can remove up to 89% of TSS, 82-84% of nutrients, 89-90% of organic matter, 100% of hydrocarbon and 89-93% of heavy metals. However, they are not suitable for implementing in urban and industrial areas. The pollutant removal efficiency of infiltration basins is relatively less than infiltration trenches. About 85% of TSS, 85% of TP and 30% of NO_3^- can be removed by an appropriately designed infiltration basin. They can be implemented at residential and commercial areas and are also applicable at industrial areas with some specific consideration to their design. Permeable pavement can remove 95% of suspended solids, 71% of TP, 62% of Zn, 42% of Cu, 50% of Pb, 33% of Cd and 99% of the oil. They are not applicable in the areas where the wheel loads and traffic volume is high.

8.5.2 Filtration

Filtration BMPs are suitable for the management and treatment of stormwater of the small drainage areas. Through the infiltration BMPs, pre-treatment of stormwater runoff is generally carried out and. Their maintenance requirements are relatively lower than infiltration BMPs.

Vegetated filter strips can effectively reduce suspended solids and particulate pollutants from stormwater runoff, but they are less effective in reducing dissolved pollutants. They can remove 56-95% of TSS, 70-95% of metals, 25-65% of nutrients and BOD. Filter strips are suitable for the treatment of stormwater runoff from roads and highways, small parking lots and low to medium density residential areas, but are not appropriate for industrial areas and highly urbanised areas.

By implanting grassed swale, the coarse sediments and associated pollutants can be reduced effectively from stromwater runoff. However, they cannot reduce the dissolved pollutants effectively. They can be installed at office campus, multi-family residential areas, commercial areas, industrial areas, parking lots, residential parkways and highways, but not at too flat or too steep areas.

Sand filters can significantly reduce particulates. However, their removal efficiency for bacteria and dissolved metals are moderate. They are not suitable for large watersheds. Their construction cost and maintenance requirements are relatively higher.

Bio-retention systems can effectively improve the quality of stormwater. They can remove 73% of TSS, 77% of TP and 70% of TN, 90% of total Zn, more than 85% of Pb and 46-86% of Cu. They are suitable for commercial, high-density urban and

single-family residential areas and also suited in many ultra-urban areas. Their construction cost and maintenance requirements are low to moderate.

8.5.3 Detention

Detention BMPs are the best option for the treatment of stormwater runoff from large watershed. Dry ponds provide moderate removal of particulate pollutants, but have little or no capability in removing soluble pollutants and bacteria. They are applicable only in the low developmental areas. The pollutant removal efficiency of wet ponds is moderate to high for both particulate as well as soluble pollutants. About 50-90% of TSS, 30-90% TP, 40-80% of soluble nutrient, 70-80% of Pb, 40-50% of Zn and 20-40% of BOD can be reduced from stormwater runoff by wet pond treatment. They are suitable for both low and highly developed areas if the watershed area is larger than 5 hectares. Constructed wetlands can remove more than 90% of TSS, 70-98% of COD, 79% of TN and 77% of TP from stormwater runoff. However, they are not applicable in urban and suburban areas where land costs are high. Their construction cost is very high in comparison to other BMPs. The maintenance requirements of constructed wetlands are moderate to high.

8.6 Utility of the findings of the present study

The present study identified the problems of stormwater pollution in Guwahati and its suburbs. The possible reason of this is the change of land uses associated with the increasing trend of urbanisation in the area.

The study confirmed the higher level of pollutants in stormwater of industrial and heavy traffic areas. The Governmental organisations and NGOs may now take decision for further studies on the stormwater of industrial and heavy traffic areas throughout the country. This would be helpful in understanding the problems of urban stormwater throughout the country and implementing effective stormwater quality treatment and management approaches in the affected areas.

The study classified the rainfall events into three types which were on the basis of RD and ARI. For the effective management and treatment of stormwater, selection of rainfall type is an important criterion for meeting the treatment objectives. Therefore, it might be helpful for decision makers who are involved in the treatment and management of stormwater.

8.7 Recommendations

The present research study has provided an in-depth understanding regarding the role of rainfall characteristics and land use on stormwater quality and about the effectiveness of stormwater BMPs in improving stormwater quality. Besides these, the outcome of the study provided guidance for the enhancement of the stormwater quality treatment design. However, for the complete understanding of the stormwater pollution process, a number of other areas should be considered for further detailed investigation. Some of the important areas are discussed below.

a) In the present research study, the role of rainfall characteristics on stormwater quality is investigated for a mixed (residential, commercial and istitutional) landuse. Therefore, to enhance the knowledge and to

confirm the conclusion, the concerned authorities may plan for some further investigations on the role of rainfall characteristics on stormwater quality for the other urban land uses including commercial and industrial.

b) This study investigated the role of land use on stormwater quality. However, other catchment characteristics such as urban form, the fraction of impervious surface and urban area location exert significant influence on stormwater quality. Therefore, it is very essential to investigate the role of these catchment characteristics on stormwater quality.

c) In the present study, the pollutants investigated were NO_3^-, PO_4^{3-}, OG, TSS and heavy metals. But, the other pollutants including organic carbons and pathogens also affect the quality of stormwater. Therefore, a thorough study may be proposed to further investigate the build-up and wash-off process of these pollutants.

d) A number of stormwater BMPs were reviewed and their overall effectiveness was assessed from the existing literature. It was found that no one single BMP is suitable for all situations. Some BMPs are effective in improving stormwater quality but cannot be implemented in urban areas, some are expensive to construct and maintain. Therefore, further investigation is needed for the modification of design of the different BMPs so that they can be implemented in effective manner for the management of stormwater quality