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GIS-Based Ecosystem Service Analysis of Green Infrastructure

Tolessa Deksissa

Water Resources Research Institute, College of Agriculture, Urban Sustainability and Environmental Sciences,

University of the District of Columbia, Washington, DC

ABSTRACT: To restore and sustain urban stream or river water quality, many cities have been devoting to a green infrastructure, and federal agencies have started collaborating to help the community invest in green roof, roadside rain gardens and increased tree canopies. The objective ofthis study is toanalyze the ecosystem benefit of the green stromwaterinfrastructurethat applies to managing stormwaterquantity and quality.Using an ArcGIS-based modelling tool, we quantitatively analyzedthe ecosystem service of green roofs. The results show that constructing green roofs on the rooftops of 2% of the impervious areas or building can reduce up to 166% and 32% storm water runoff in Rock Creek and Anacostia River sub-watersheds in Washington DC, respectively. This can save up to $21.4 million in building storage tanks to store total runoff volume. Improving green roof and tree canopy areas can significantly reduce the negative impact of urban storm water runoff and therebyimprove urban-stream water quality.

KEYWORDS: Best management practices, Green roof,Low impact development, Stormwater management,Water quality

I. INTRODUCTION

Many historical cities have used the conventional stormwater management design which is often defined as a grey infrastructure. The focus of the grey infrastructure has been oncapturing and conveyingstromwaterin hard piped networks that empty into the underground deep tunnel or a combined sewer system or a stream or river. The drawback of this approach is that as the percentage of impervious area increases due to land development, the runoff volume increases or exceeds the capacity of existing grey infrastructure. This causes often flooding, sewer backup or frequent contamination of urban streams or rives.

The District of Columbia (DC) is one of the densely populated cities in the nation in which the development activities have resulted in the decline of pervious land covers. When impervious area increases, the runoff volume increases during significant rain. This is problem is the combined sewer systems. In DC, One third of the city depends ona combined sewer system developed before 1900. This old sewer system cannot handle the current volume of urban runoff mixed with raw sewerage. In the combined sewer overflows region, a mixture of storm water runoff with raw sewerage is directly discharged into the river during as low as a half inch of rain. This resulted in frequent contaminations of most waterways, including Anacostia River, Rock Creek, and Potomac River.

Consequently, most parts of DC water ways do not meet the designated water use of class A or primary contact of water quality standards. To meet the designated water use, the District made significant progress in applyinggreen infrastructures. In 2000, DC Water proposed a long term control plan, which includes urban tree canopies and green surface areas[1].In 2012, the District made infrastructure agreement with the District of Columbia Water and Sewer Authority (DC Water) and the U.S. Environmental Protection Agency (EPA) [2]. Recently, the District developed sustainable DC plan. According to Sustainable DC Plan [3], by the year 2032, the District stated to ensure that 100% of the city’s waterways will be fishable and swimmable.

To meet this ambitious goal,like any other cities in US, the District is devoting to implement green infrastructure[4]. Many cities are now trying to apply green infrastructure for its various benefits. In contrast to grey infrastructure, which considers water as a wastewater, the green infrastructure considers water as resource. Green infrastructure can be used as a tool for building resilience to climate change impacts including heavy rainfall and heat

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island effect. Maintaining green infrastructure is much more inexpensive as compared to maintaining and replacing aging grey infrastructure systems.

Regardless of those benefits, qualitative and quantitative analysis is required. Before making an investment on the green infrastructure, quantitative analysis of the benefit and effectiveness of the strategy is crucial. Many studies demonstrated that quantifying ecosystem service interms of monetary value helps promote sustainable growth as well as protect the environment [5-10]. The costs of ecological service can be estimated on the basis of cost associated with the absence of those ecological services. For example, DC now recognizes that the existing natural and modified ecosystems within and outside of existing boundaries are providing benefits that if lost would result in costs to the DC residents and surroundings. This can be done by linking dollar values with the ecological service of green infrastructures to attain EPA's water quality goal [11].

Furthermore, quantitative assessment of ecosystem service can serve as a tool to encourage landowners to invest in green infrastructures, such as planting trees or maintain green surfaces. Quantifying ecosystem service requires spatially explicit values of service across landscapes that might inform land-use and management decisions. GIS-based tool can be applied as a tool to assess the effectiveness of ecosystem service of the green infrastructure or the stormwater management benefit. Green roof is one of the most popular types green infrastructure in improving storm water quantity and quality [12-13]. The objective of this study is to evaluate the ecosystem service of green infrastructure or green roof in managing stormwater quantity and quality.

II. MATERIALS AND METHOD

Geographic Information System (GIS) or spatial modeling approach was applied to quantify ecosystem services. This quantification method requires collection of data pertaining to both green andgray infrastructures. The green infrastructures include areas covered with trees, shrubs, green roofs and grass, whereas gray infrastructures include areas covered by buildings, roads, sidewalks, and parking lots. Based the orthophotography of 2010 with 16 cm resolution, we digitized the green infrastructures and conducted the quantitative assessment of the storm water benefit of the green infrastructure in both Anacostia River and Rock Creek watersheds. Thisanalytic method relies on the principle that improved green infrastructure reduces surface runoff by increasing infiltration of storm water and thereby reduces combine sewer overflows[14]. In the previous cover, 50% of water infiltrates into the ground and only 5% produce surface runoff; whereas in impervious cover, about 55% of the rain water goes to surface runoff and only 15% could go to shallow or deep infiltration (Fig 1).

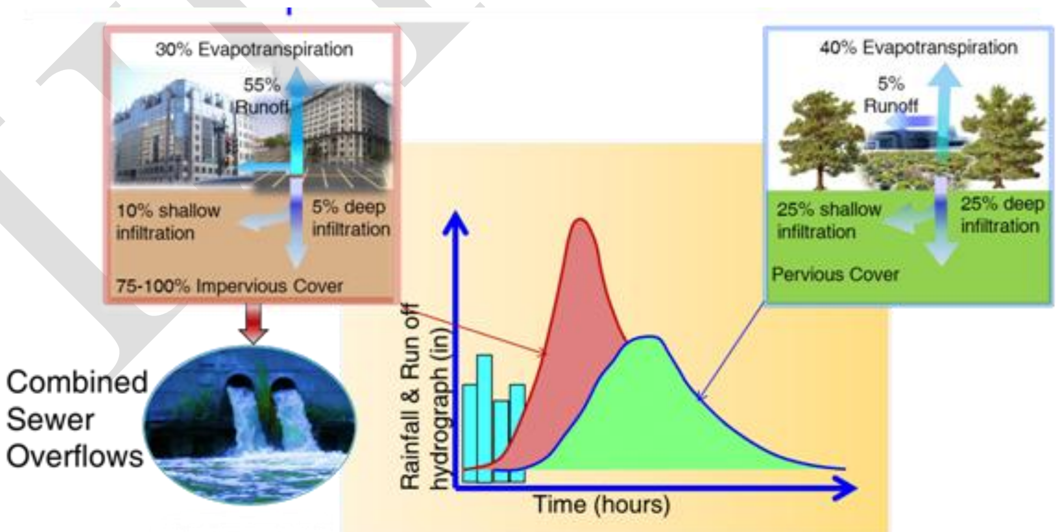

Fig.1. Conceptual representation of the effect of green infrastructure on surface runoff

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III. STUDY SITE

To conduct ecosystem service analysis of green infrastructure in DC, we considered Rock Creek and Anacostia River watershed. The Anacostia River is relatively a slow moving water body that is significantly affected by the tide. In contrary, Rock Creek is a free-flowing stream and unaffected by the tide for the majority of its length. Based on ArcGIS and land cover map of 2006(Fig. 2), about 40% of the land cover in the Rock Creek park is impervious surface, including roads, buildings and other pavements, whereas about 60% of the area is covered by pervious layer, including tree canopies, grass/shrubs and bare earth.

The urban ecosystem analysiswas conducted using CITYgreen® software inArcGIS[15]. The CITYgreen® software uses the raster data land cover classification from the high-resolution imagery for the analysis. In this software three sub-models are integrated, such as stormwater runoff and water quality model, both were developed by U.S. Natural Resource Conservation (NRC), and urban forest effects model developed by the USDA.

Forest Service for assessing air pollution model [15] is integrated with the water quality model. Air quality model is not the scope of this study, but the water quality model estimates the change in the concentration of the pollutants in a runoff during a typical storm event given the change in the land cover from existing trees to a no tree condition. This model estimates the event mean concentrations of nitrogen, phosphorus, suspended solids, zinc, lead, cadmium, chromium, chemical oxygen demand (COD), and biological oxygen demand (BOD). Pollutant values are expressed as a percentage of change, which depends on the areal coverage of the green infrastructure.

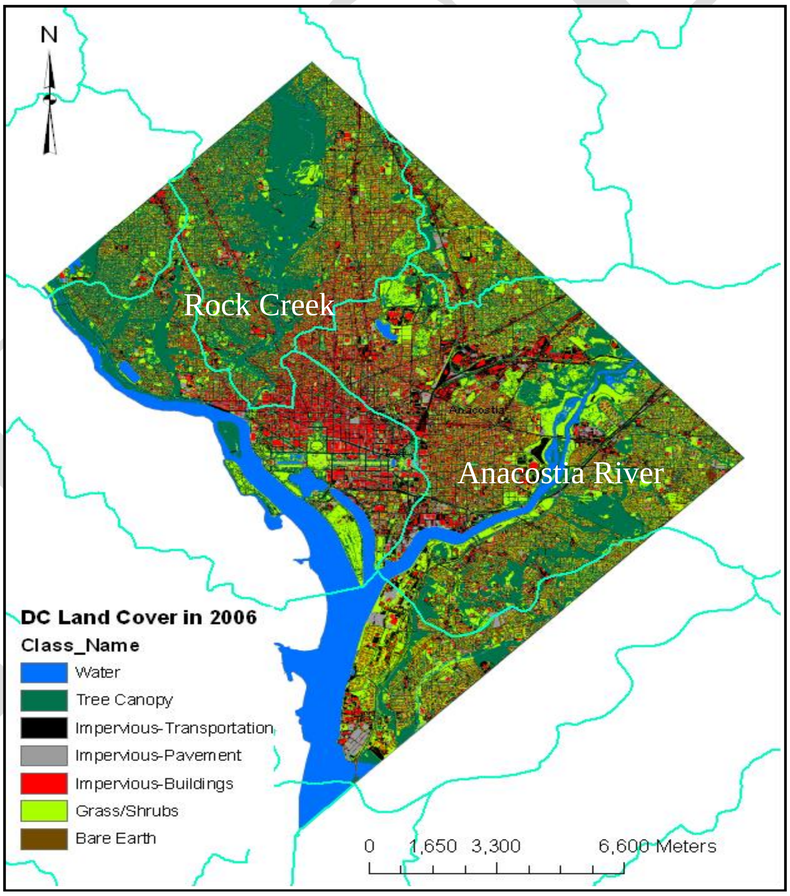

Fig.2.DC Land cover in 2006

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IV. EXPERIMENTAL RESULTS

4.1. EXISTING CONDITION

Before scenario or "if what" analysis using GIS-Map of 2006, we analysed the percentage of existing land coverand associated ecosystem service for both Rock Creek and Anacostia River in DC (Fig. 3). In the Rock Creek sub-watershed, the impervious surface area is 32.3%, which includes buildings, driveways, surrounding lots and paved area. The other 67.7% of the Creek is pervious, including grass and trees. Based on the model input for two yearsof 24-hr rainfall and runoff of 3.25 inches and an estimated curve number of 88, the predicted additional volume of storm water we need to storeto prevent combine sewer overflows is 32,632,100 ft^3. If we need to build a storage tank, based on construction cost of $2.00 per cubic feet, total estimated storm water value is $65,264,200.00. The cross ponding change in percentage of water quality is more than 90% in cadmium, chromium and chemical oxygen demand and more than 80% in phosphorus.

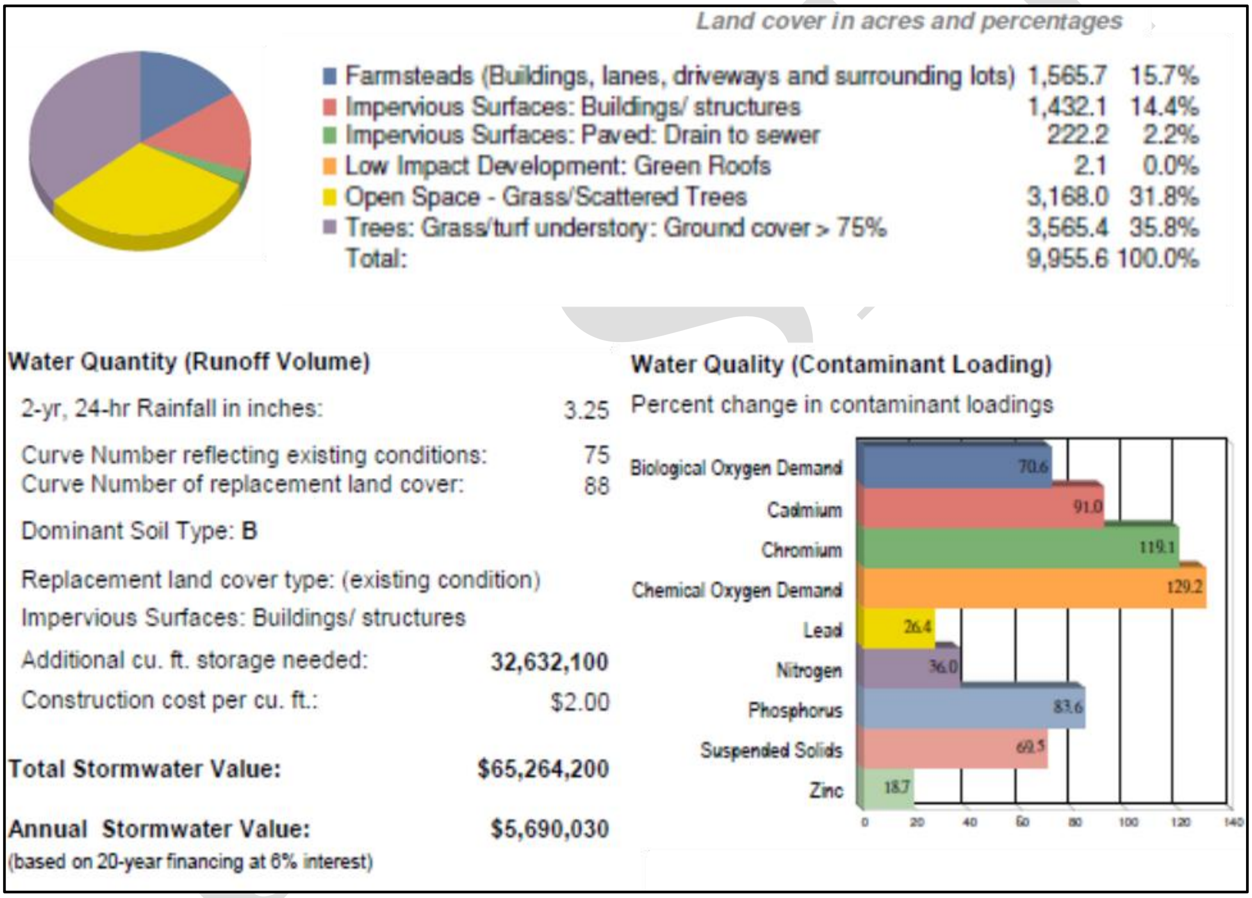

Fig. 3.Effect of existing green infrastructure on runoff volume and water quality in Rock Creek watershed of DC.

In the Anacostia River subwatershed, the percentage area of impervious are is 44.2%, which includes buildings, driveways, pavement and parking lots (Fig 4). The other 55.8% is pervious cover, which includes green roofs, grass, trees, shrubs and bare soil. Based on the model input for two years of 24-hr rainfall and runoff of 3.25 inches andthe estimated curve number of 88, total storm water needs to be stored to prevent combine sewer overflow is 35,130,627 ft^3. If a storage tank is needed, based construction cost of $2 per cubic feet, the total stormwater value is $70,261,254.00.

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The percent change in water quality or contamination loading is more than 90% in chemical oxygen demand, more than 80% in chromium.

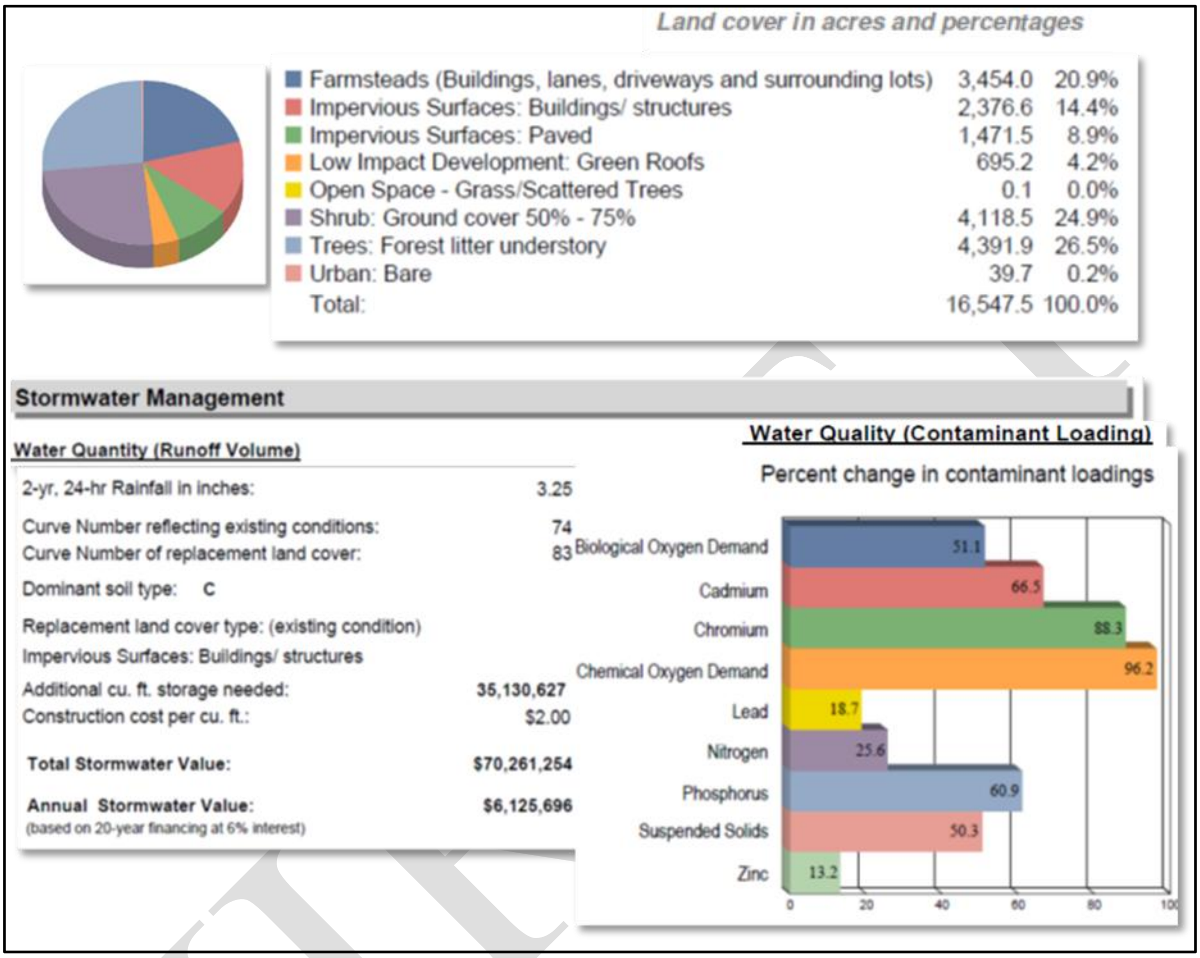

Fig.4Effect of existing green infrastructure on runoff volume and water quality inthe Anacostia River watershed, DC

4.2. SCENARIO ANALYSIS

Based on the established GIS-Based model, the effect of change in percentage of green roof and tree canopies was assessed. The current trend shows that the district wants to increase the percentage of green infrastructure to 2%. The scenario analysis in both watersheds was conducted by changing the percentage of land cover of the impervious building into green roofs. In the Rock Creek watershed, when a 2% of the impervious building area is covered by green roofs, it reduces about 8.2 million $ft^3$of storm water runoff (Fig5). Thischange can save about $16.4 million total storm water value if a storage tank has to be built.

In the Anacostia Watershed, when 2% of the impervious building area is covered by green roofs, it reduces about 2 million ft^3 storm water storage and saving about $23 million total storm water value if a storage tank has to be built.

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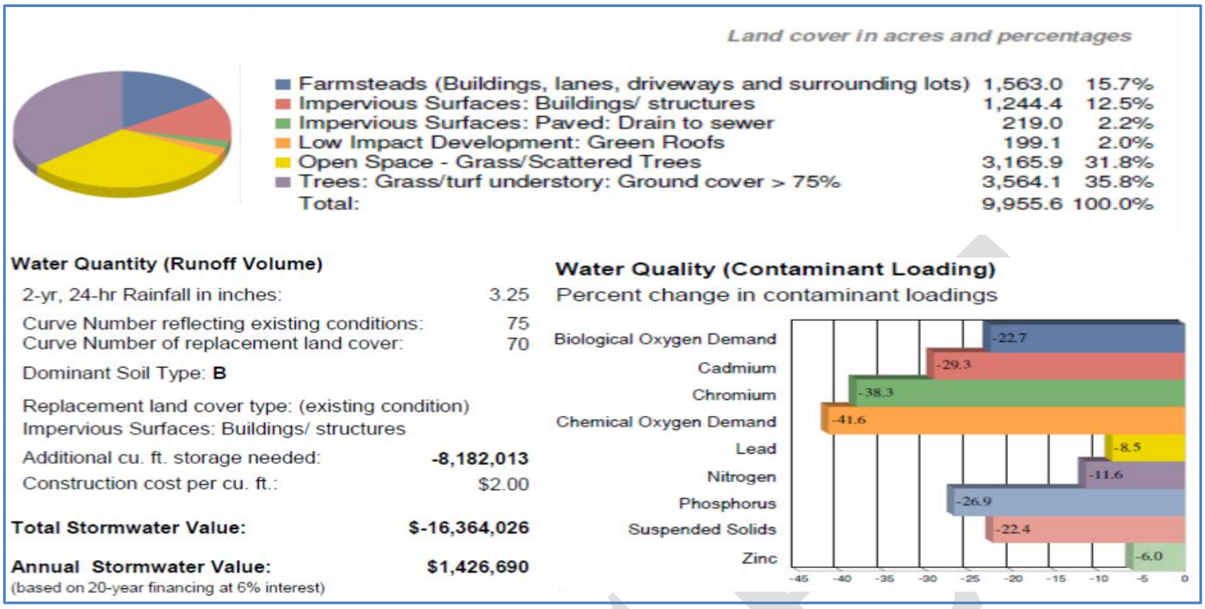

Fig.5.Effect of 2% increase of green roof area on storm water storage, water quality contaminant load reduction in Rock Creek.

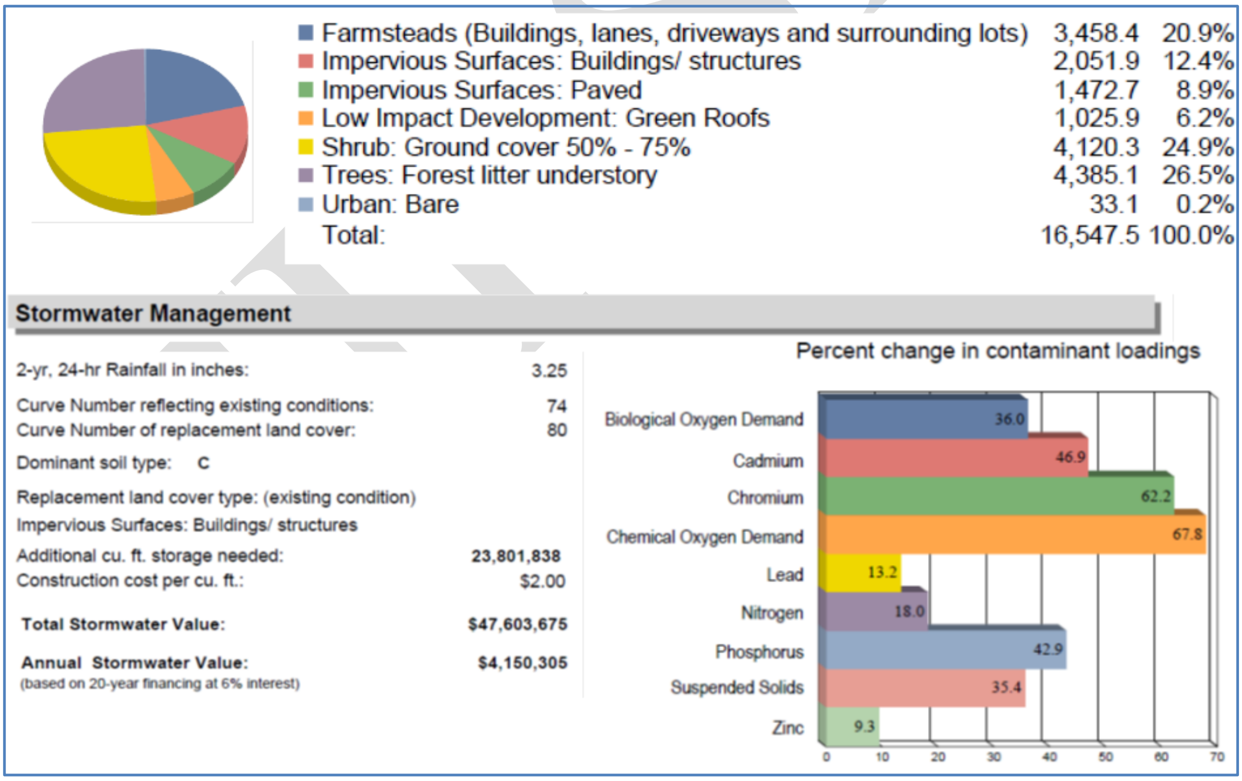

Fig. 8.Effect of 2% increase of Green roof area on storm water runoff and water quality in Anacostia River watershed in DC.

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V. CONCLUSION

Based on the scenario analysis, one can conclude that increase of green roofs area by 2% can reduce peak flow rate. This is logical as green roof is mainly designed to slow down and reduce the peak flow rate of runoff during storm events.

The overall study of this project shows the usefulness of integrating the GIS based quantitative ecosystem service analysis in the decision making process for sustainable water resources management. The results of the proposed GIS based ecosystem services analysis have the following benefits:

- Quantify the stormwater, water quality ecosystem service of the existing green infrastructure of the District of Columbia.
- Calculate the effects of future land cover change before those changes are made.
- Analyze the changed of green area of the city over time, by comparing land cover maps from earlier periods, such as 10 or 20 years ago, depending on the available data.
- Assist environmental managers as a tool for mitigating carbon emission and reduce its effect on climate.
- Community awareness of ecological and economic value of green infrastructure creates incentives for the landowner to consider planting trees and urban gardening.
- Quantify the costs of parts of the green area if lost to the residence.
- Can be used to educate future scientists, including school children, and thereby improve the wellbeing of our community.

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