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Integrating Satellite Image Classification and Sustainable Strategies for Urban Stormwater Management using Artificial Intelligence

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Abstract

Urban stormwater management is a critical environmental and infrastructural challenge, complicated by the proliferation of impervious surfaces in growing cities. Traditional strategies focused on rapid water conveyance are insufficient to address the resulting issues such as flooding, erosion, and water pollution. This paper presents an innovative approach to urban stormwater management utilizing satellite image classification and Artificial Intelligence. This research proposes novel categorization of urban areas based on surface permeability, land use and regulation ease. As part of this work, an annotated urban landscape dataset is created to train a deep learning model that classifies urban landscapes into discrete categories amenable to sustainable practices and policy intervention. Stormwater runoff estimates are estimated for the landscape, followed by an impact assessment of sustainable and green infrastructure. This integrated approach highlights the potential of combining advanced image classification techniques using deep learning with sustainable urban stormwater management practice to inform urban planning and policy for a resilient city.

Introduction

Houston, we have a problem. One that is decades in the making (Erdman, 2021). The urban footprint of impervious surfaces in Houston has grown bigger than the land area of New York City (Smiley & Hakkenberg, 2020). This is not just a Houston problem; it is true in cities across the globe. Urbanization introduces extensive impermeable surfaces such as parking lots, pavements *etc.* which dramatically reduces the natural infiltration of rainwater into the ground. Consequently, urban areas experience increased surface runoff, leading to flooding, erosion, water pollution alongside overloading of stormwater infrastructure (Shuster et al., 2005; Arnold & Gibbons, 1996). The traditional stormwater infrastructure, which primarily focuses on rapid water conveyance through drains and sewers, is evidently not sufficient to address these complex challenges.

Stormwater management in urban areas has significant implications for water quality, flood control, and urban sustainability. The introduction of impermeable surfaces alters the natural hydrological cycle, significantly reducing the percolation of water into the soil, which replenishes groundwater and supports healthy ecosystems (Dietz, 2007). Instead, the water, now unable to penetrate these surfaces, accumulates rapidly, transporting pollutants from urban surfaces into water bodies and leading to degraded water quality (Walsh et al., 2005). More importantly, the increased volume and speed of runoff exacerbates the risk of flooding, especially in areas with inadequate stormwater infrastructure (Fletcher et al., 2013).

In response to these challenges, ‘Slow Water Movement’ advocates for sustainable water management through the utilization of natural hydrological processes. This approach involves implementing green infrastructure to restore ecosystems, recharge groundwater, and reduce flood risks (Geis, 2023). Green technologies like sustainable urban drainage systems (SUDS), low-impact development (LID) practices aim to, in general, improve the permeability of urban surfaces and mimic natural hydrological processes thereby increasing infiltration, storage, evapotranspiration, and the quality of stormwater runoff (Fletcher et al., 2015; EPA, 2000). Green and adaptable infrastructure has become increasingly important because of climate oscillations (S. Fletcher et al., 2023) which are exasperated by climate change.

The potential of satellite imaging in this context is particularly promising. Satellite images offer a comprehensive and detailed view of urban landscapes, enabling the identification and classification of various surface types across large areas with high efficiency and low cost (Weng, 2012). By applying deep learning image classification techniques, researchers can map the extent of impermeable surfaces in urban areas, assess their impact on stormwater runoff, and identify opportunities (Xian & Crane, 2006). However, there is limited research that delves into types and distribution of impervious surfaces which are relevant to stormwater management.

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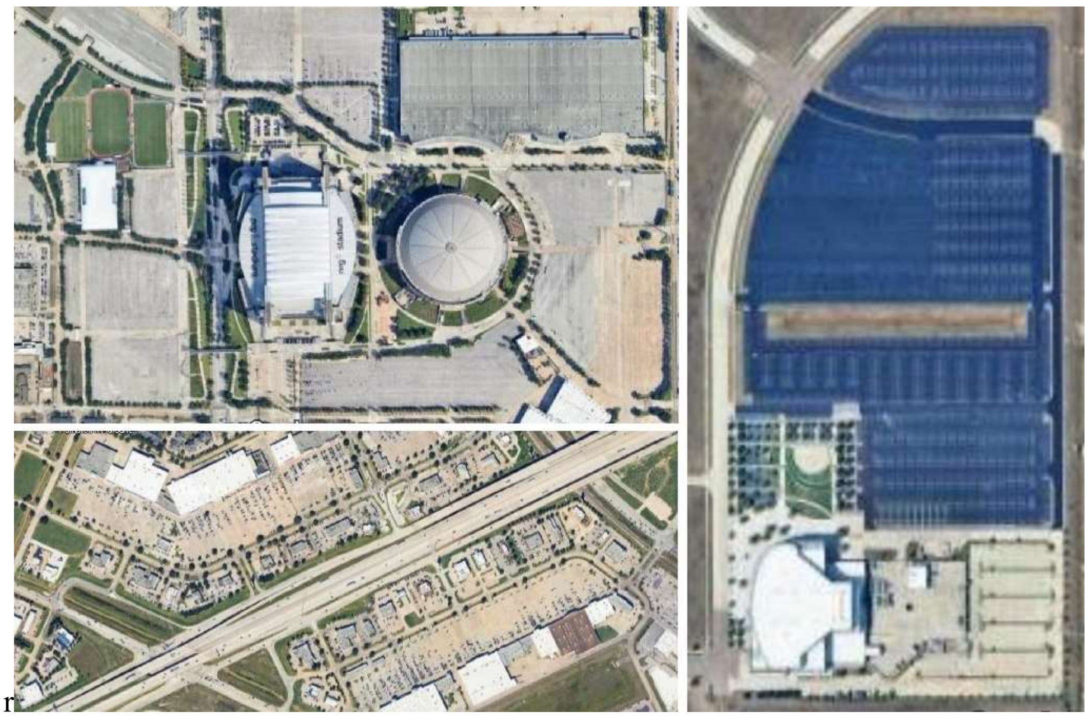

Figure 1 – Concrete City – Examples of Impervious Surfaces in Houston

This research paper makes novel contributions to urban stormwater management by 1) Proposing categorization of urban surfaces which is relevant to stormwater management – based on - land use, permeability and ease of regulation 2) Creating an annotated urban landscape dataset to facilitate categorization of urban surfaces by training a semantic segmentation model 3) Providing a storm water raimpact assessment of green interventions on stormwater runoffs.

Literature Review

Urbanization significantly alters the natural hydrology of the land. A study by Gregory et al. (2006) demonstrates that urban soil compaction significantly reduces infiltration rates, increasing stormwater runoff. Construction activities can decrease infiltration by 70-99 percent, necessitating larger stormwater conveyance networks to manage increased runoff. According to a study published by USGS, the increase in basin development factor for a region in Houston (north of Buffalo Bayou) resulted in corresponding increase in magnitude of stormwater runoff, ranging from about 40 percent (for direct runoff) to 235 percent (for peak yield). (Liscum, 2001)

The management of stormwater in urban environments has traditionally focused on the rapid conveyance of runoff away from built-up areas to prevent flooding. Conventional stormwater systems, comprising of gutters, drains, and underground sewers, aim to quickly channel water from impermeable surfaces to nearby waterway. However, these systems often overlook the ecological impacts, such as reduced groundwater recharge and increased pollutant loads in receiving waters (Makepeace et al., 1995).

To estimate runoffs from precipitation, Curve Number (CN), a hydrological parameter, is used in the Soil Conservation Service (SCS) runoff estimation method. In drainage basins without runoff measurements, the CN method can be employed to estimate the depth of direct runoff using rainfall depth and an index that characterizes runoff response. Various regions have further tailored this method to meet local requirements (Singh et al., 2018). A study investigating the impact of land use changes on flood intensity in the *Khiavchai* Watershed using hydrological modeling concluded that a 25% increase in CN values results in peak flood discharges rising to 6.3 times, highlighting the necessity for strategic watershed management and flood control measures. (Kazemi et al., 2024)

In response to the above challenges, Sustainable Urban Drainage Systems (SUDS), Green Infrastructure (GI), and Low-Impact Development (LID) practices have been developed. These approaches seek to manage runoff volume and improve water quality by mimicking natural hydrological processes through infiltration, biofiltration, and storage (Dietz, 2007; EPA, 2000). Examples include rain gardens, permeable pavements, green roofs, and constructed wetlands, which have been shown to effectively reduce runoff and pollutant loads (Tsihrintzis & Hamid, 1997; Zhang & Chui, 2018). For instance, extensive monitoring substantiated the effectiveness of a bio-infiltration rain garden in mitigating stormwater runoff impacts and partially restoring watershed natural hydrology (McGauley et al., 2023).

In addition, the application of satellite image classification in urban planning has grown significantly with advances in remote sensing technology. These methods enable the detailed mapping and monitoring of land use and land cover changes over time, providing valuable data for urban and environmental planning (Weng, 2012; Xian & Crane, 2006). For instance, high-resolution satellite imagery has been used to accurately identify and quantify impermeable surfaces in urban areas, offering insights into the spatial distribution of potential runoff sources (Weng, 2012; Herold, Couclelis, & Clarke, 2005). Studies have also applied machine learning algorithms to satellite images for enhanced classification accuracy, enabling the differentiation between various types of urban land use (Lu & Weng, 2007; Myint et al., 2011).

While significant progress has been made in both stormwater management practices and the use of satellite imagery for urban analysis, several gaps remain in the current body of research. Firstly, there is need for more relevant categorization of satellite images based on both permeability distribution and land use. This can inform urban planners about the current hydrology and potential impact of stormwater management practices. Secondly, there is a need for integrated approaches that combine detailed spatial analysis derived from satellite imaging with sustainable stormwater management strategies and urban policy development. Most studies have treated these as separate domains, with limited research exploring how satellite data can directly inform and evaluate the design and implementation of green infrastructure. We strongly believe that without tools and framework that can help the planners assess the current urban surface distribution, policy makers visualize the effect of sustainable interventions, the true potential of green infrastructure cannot be realized. This research aims to fill this critical gap.

Methodology

Urban Surface Categorization

This research proposes twelve surface categories (classes) which are important for stormwater management. These classes are selected to cover a wide range of surface types found in urban environments and facilitate accurate and detailed analysis of stormwater runoff characteristics. The classes are chosen based on the following criteria:

1. Land use (residential, commercial, or public use)
2. Permeability (pavements, land, compacted soils etc.)
3. Relevance to sustainable interventions and/or regulations

Surface Category	CN Range	Permeability	Ease of Regulation
Golf Course	39-69	high	medium
Pavement (Residential)	85-98	low	low
Pavement (City)	89-98	low	high
Land (Grassland)	58-71	medium	low
Land (Urban)	70-94	low	medium
Stream	0-5	high	high
Lake	0-2	high	high
Yard	49-85	medium	low
Parking Lot	95-98	low	high
Commercial Rooftop	95-98	low	medium
Residential Rooftop	85-95	low	low
Roads	95-98	low	high

Table 1 – Proposed Surface Categories for Urban Landscape Relevant to Urban Stromwater Management

Dataset Collection

As part of this study, a new dataset is created to facilitate identification of urban surface categories (Table 1) - Semantic Segmentation Database for Stormwater Management in Urban Landscapes. To ensure broad applicability, satellite images were acquired from Google Maps, providing detailed views of the selected metropolitan area. The criteria for selecting the urban area included geographical location, urban density, availability of ancillary data, and environmental and socioeconomic diversity. These factors ensured that the selected area is both representative of common urban landscapes and relevant to the research objectives. After annotating the images, masks are generated, where each pixel is assigned, a label corresponding to the annotated region.

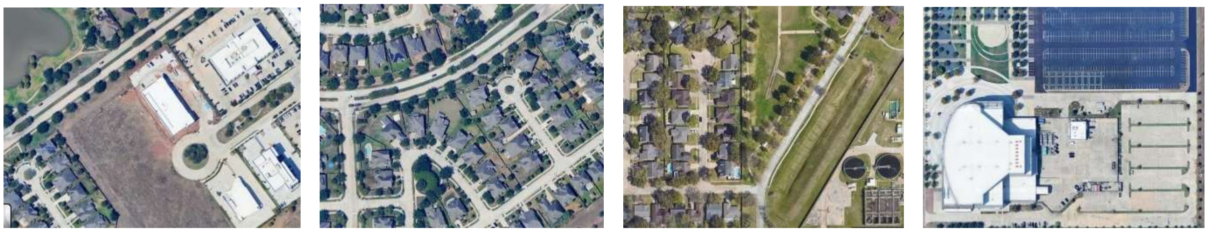

Figure 2: Sample Images from Semantic Segmentation Database for Stormwater Management in Urban Landscapes

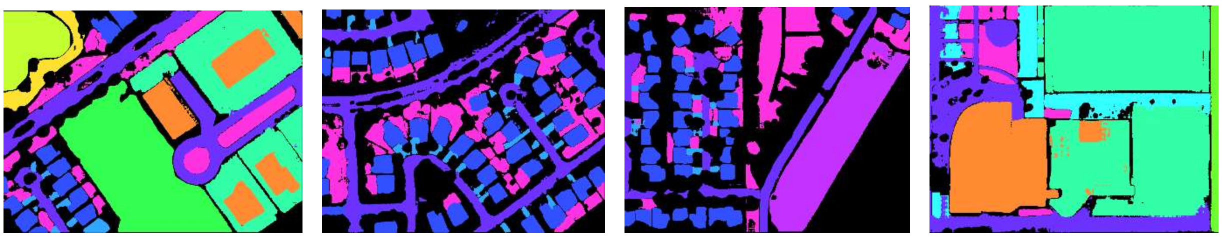

Figure 3: Sample Masks from Semantic Segmentation Database for Stormwater Management in Urban Landscapes

The masks serve as the ground truth for training a semantic segmentation model. Once the annotation and mask creation process were complete, the annotated images and corresponding masks were exported to a format suitable for training the machine learning model.

Semantic Segmentation

This work leverages semantic segmentation model using a U-Net architecture to classify satellite images into the proposed categories. The model is trained on the dataset created as part of this study, and the performance is evaluated. Semantic segmentation involves classifying each pixel in an image into one of twelve predefined categories. (Figure 3)

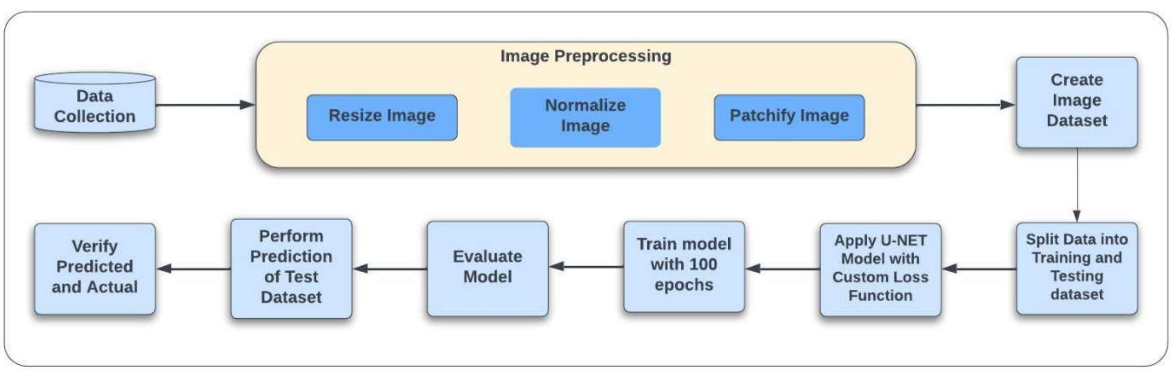

Figure 4: Semantic Segmentation Prediction Model Training Workflow

The model is trained using a combination of two loss functions: Dice loss and Focal loss. The Dice loss is a measure of the overlap between the predicted segmentation mask and the ground truth mask, and it is commonly used for image segmentation tasks. The Focal loss is a variant of the cross-entropy loss that is used to handle class imbalance problems. The model is evaluated using several metrics, including accuracy, IoU (Intersection over Union), and Mean IoU. The IoU, also known as the Jaccard Index, is a common metric for evaluating the accuracy of an object detector on a particular dataset. It measures the overlap between the predicted bounding box and the ground truth bounding box.

Area estimations

Once the model is trained, it is used to perform segmentation of urban landscapes. The area of a surface category is proportional to the frequency of the pixels corresponding to each surface type in the segmented image.

$$a_i = \frac{n_i}{\sum_0^n n_k}$$

$where$

$a_i \ = \ area\ for\ a\ category/class\ i$

$n_i \ = \ number\ of\ predicted\ pixles\ for\ category/class\ i$

Initial Curve Number calculations

The Curve Number (CN) is a hydrological parameter used in the Soil Conservation Service (SCS) runoff estimation method, used to estimate stormwater runoff from precipitation. The higher the curve number, the more impervious is the surface and greater the runoff.

An impervious area is considered connected if runoff from it flows directly into the drainage system or if runoff from it occurs as shallow concentrated flow that runs over a pervious area and then into a drainage system. (Chen, 1982)

If all the impervious area is directly connected to the drainage system, then

$$CN_c = \ CN_p + (\frac{P_{mp}}{100})(98 - \ CN_p)$$

$where$

$$\begin{aligned} CN_c \ &= \ composite\ runoff\ curve\ number \\ CN_p \ &= \ previous\ runoff\ curve\ number \\ P_{mp} \ &= percent\ imperviousness \end{aligned}$$

We propose the following methodology for estimating the initial curve number and runoff volumes. Since our method of classification of urban surfaces into distinct categories ensures distinct and uniform curve number, this method is reliable.

1) Calculate the fractional area for each category of surface (a_i)
2) Estimate the curve numbers for the predicted area based on hydrology of the local environment. The curve numbers are given in this paper for guidance only. Change in soil type, compaction, vegetation, moisture *etc.* have significant impact on the estimated curve numbers

3) The composite curve number can be calculated as a weighted average of the initial values of curve numbers of the categories

$$CN_c = \sum_{0}^{n} CN_i . a_i$$

$where$

$CN_c \ = \ composite\ runoff\ curve\ number$
$CN_i \ = \ Intial\ runoff\ curve\ number\ for\ category\ i$
$a_i \ = fractional\ area\ of\ category\ i$

Stormwater Management Strategies

Stormwater management involves controlling and utilizing rainwater runoff to minimize environmental impact and enhance water quality. Effective strategies help mitigate flooding, reduce pollution, and recharge groundwater. Here is a brief review of sustainable stormwater management strategies:

- **Rain Gardens** are shallow, vegetated basins that capture and infiltrate runoff from rooftops, driveways, and other impervious surfaces, reducing runoff volume and peak flow rates. A well-designed rain garden can result in a reduction of the curve number from average of 94 to 76 (McGauley et al., 2023). An example of their application is seen in the city of Portland, Oregon, where the "Clean River Rewards" program incentivizes homeowners to install rain gardens.

Surface Category	Initial CN*	Sustainable Stormwater Management Techniques	Effective CN*
Golf Course	74	Rain Gardens, Bioswales, Permeable Pavements	61
Pavement (Residential)	98	Permeable Pavements, Bioretention Areas	85
Pavement (City)	98	Green Streets, Permeable Pavements	85
Land (Grassland)	61	Native Landscaping, Soil Amendments	58
Land (Urban)	81	Rain Gardens, Tree Canopy	70
Stream	10	Riparian Buffers, Constructed Wetlands	0
Lake	10	Constructed Wetlands, Vegetated Swales	0
Yard	70	Rain Gardens, Native Landscaping, Soil Amendment	60
Parking Lot	98	Permeable Pavements, Bioretention areas, Tree Canopy	85
Commercial Rooftop	98	Green Roofs, Blue Roofs, Rainwater Harvesting Systems	85
Residential Rooftop	98	Green Roofs, Rain Barrels	85
Roads	98	Permeable Pavements, Bioretention Cells	85

* *As a sample indicative number. The curve numbers varies significantly with soil type, structure, compaction etc.*

Table 2 – Proposed Urban Surface Categories with Corresponding Sustainable Stormwater Management Strategies

- **Bioswales and buffer strips** are landscaped features designed to slow and filter stormwater runoff. Swales, shallow grassy channels that convey water slowly across landscapes, and buffer strips, vegetated areas that filter runoff, can be integrated into backyard designs to enhance stormwater management. A bioswale with a riprap lined forebay was constructed along State Highway NC 211 in Bolivia, North Carolina, and monitored for 12 months. Out of 39 monitored rain events, 37 exfiltrated into the underlying soils, preventing significant overflow or underdrain volume (Purvis et al., 2019).

- **Permeable Pavements** allow water to infiltrate, reducing runoff and promoting groundwater recharge. It is one of the primary methods used in parking lots (Brattebo & Booth, 2003) to allow stormwater to infiltrate through the surface into the ground below. Materials such as pervious concrete, porous asphalt, and interlocking pavers are designed to have void spaces through which water can pass. The EPA highlights the use of permeable pavements at the Edison Environmental Center in New Jersey, where they have been successfully implemented in parking areas to reduce runoff and promote groundwater recharge.
- **Bioretention Areas** are similar to rain gardens but are more advanced in their design. They incorporate an underdrain, overflow inlet, gravel bed, and engineered soils to enhance infiltration and manage stormwater effectively. They are a great addition to commercial parking lots.
- **Native Landscaping** uses native plants to improve soil structure and increase infiltration. They can increase the permeability of land while providing habitat for wildlife. Native plants and trees are adapted to local conditions and typically require less water and maintenance than non-native species. Their deep root systems enhance soil infiltration, reducing runoff. A study by Hurd et al. (2006) emphasizes the benefits of native landscaping in increasing biodiversity and managing stormwater through increased infiltration.
- **Soil Amendments** improve stormwater management by enhancing soil structure, which increases water infiltration and reduces runoff (EPA, n.d.). They can also boost the soil's ability to retain moisture, thereby decreasing the volume of stormwater that needs to be managed (Brown et al., 2017). Additionally, soil amendments can enhance the soil's capacity to filter pollutants, improving water quality in urban areas (University of Minnesota Extension, n.d.).
- **Tree Planting** intercepts rainfall, reduces runoff, and provides shade. Tree planting initiatives increase canopy cover in parks, grasslands, and vacant lots, enhancing stormwater interception and soil infiltration. The Million Trees NYC initiative, which planted one million new trees across the city, significantly increased green space and its capacity to manage stormwater through increased evapotranspiration and soil absorption (Pataki et al., 2011).
- **Riparian Buffers** help stormwater management by acting as natural filters, trapping sediments, nutrients, and pollutants before they reach water bodies (Mayer et al., 2007). These vegetated areas also enhance infiltration and reduce surface runoff, thereby mitigating flooding and erosion (Naiman & Decamps, 1997). Additionally, riparian buffers provide habitat for wildlife, promoting biodiversity while maintaining the ecological integrity of aquatic systems (Wenger, 1999).
- **Constructed Wetlands** are engineered wetlands to treat and store stormwater. Constructed wetlands in parks and grasslands mimic the functions of natural wetlands, providing habitat for wildlife while filtering and storing urban runoff. The Tijuana River National Estuarine Research Reserve in California utilizes constructed wetlands to treat stormwater from surrounding urban areas, demonstrating the dual benefits of water quality improvement and habitat restoration (Mitsch & Gosselink, 2007).
- **Rainwater Harvesting Systems** capture and store rainwater for non-potable uses. Rainwater harvesting systems capture and store rainwater for reuse, reducing the volume of stormwater runoff from commercial rooftops. The Bangkok International Airport in Thailand, for instance, incorporates

an extensive rainwater harvesting system that collects water from its vast roof area for non-potable uses, significantly contributing to the airport's water efficiency and sustainability goals (Ghisi, 2006).

- **Green Roofs** are a widely adopted solution for managing stormwater on commercial buildings. These systems support vegetation on rooftops to absorb rainwater, delay runoff, and facilitate evapotranspiration. An example of their effectiveness can be seen in the Ford Motor Company's River Rouge Plant in Dearborn, Michigan, which features one of the largest green roofs in the world. This installation has been shown to retain millions of gallons of stormwater annually while improving energy efficiency (Getter and Rowe, 2006).
- **Rain Barrels** collect and store rainwater from downspouts. Rain barrels and cisterns are systems used to collect and store rainwater from rooftops for later use in irrigation or other non-potable applications. This technique reduces the amount of stormwater runoff and conserves municipal water supplies. The City of Seattle has implemented a rain barrel distribution program, demonstrating the practical application of rainwater harvesting in residential settings and its benefits for stormwater management. (Seattle Public Utilities, 2012)
- **Blue Roofs**, designed to detain stormwater temporarily, are another technique utilized in commercial settings. These roofs use controlled flow drain systems to hold water during heavy rainfall events and then release it slowly, reducing peak flow to the drainage system. The New York City Department of Environmental Protection has piloted blue roof installations on its buildings as part of its comprehensive approach to stormwater management, demonstrating a practical application of this technology in urban settings (Carter and Jackson, 2007).

Implementing the strategies listed above can reduce the effective curve number of a watershed, reduce stormwater runoff, decrease the occurrence and intensity of flood events and restore the urban landscape closer to its natural hydrology.

Results

A preliminary stormwater management workflow is proposed. The process begins with preprocessing satellite or aerial images to enhance, denoise and normalize. These images are then divided into smaller, manageable patches.

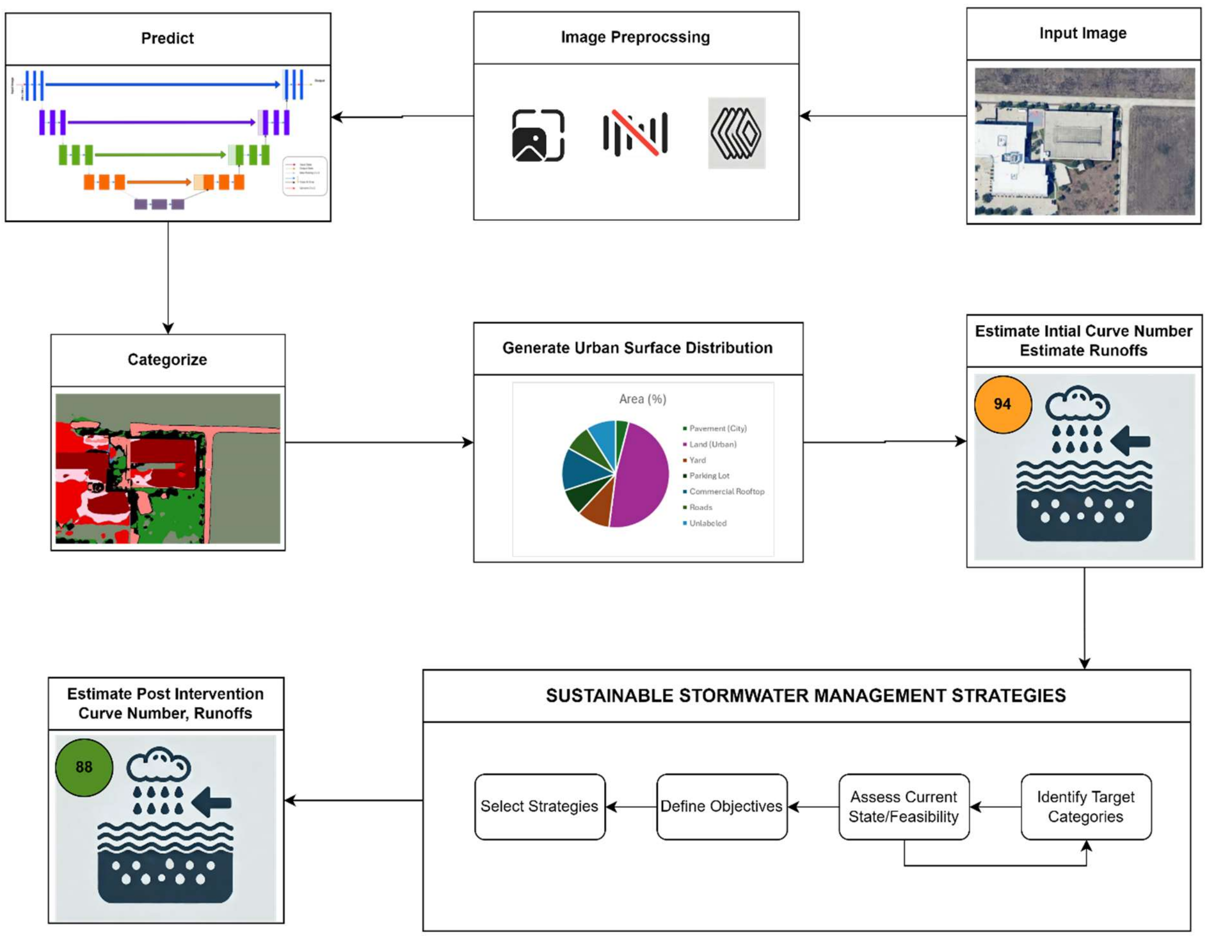

Figure 5 - Workflow for a Proposed Stormwater Management Assistant

The pre-trained deep learning model is loaded to classify each patch, and the predicted patches are blended back into a single coherent image.

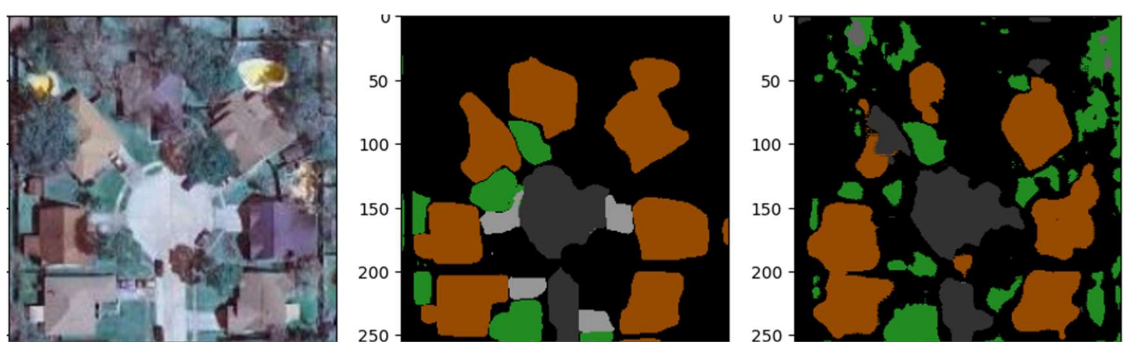

Figure 6 – Actual, Annotated & Predicted Image Patch (in order)

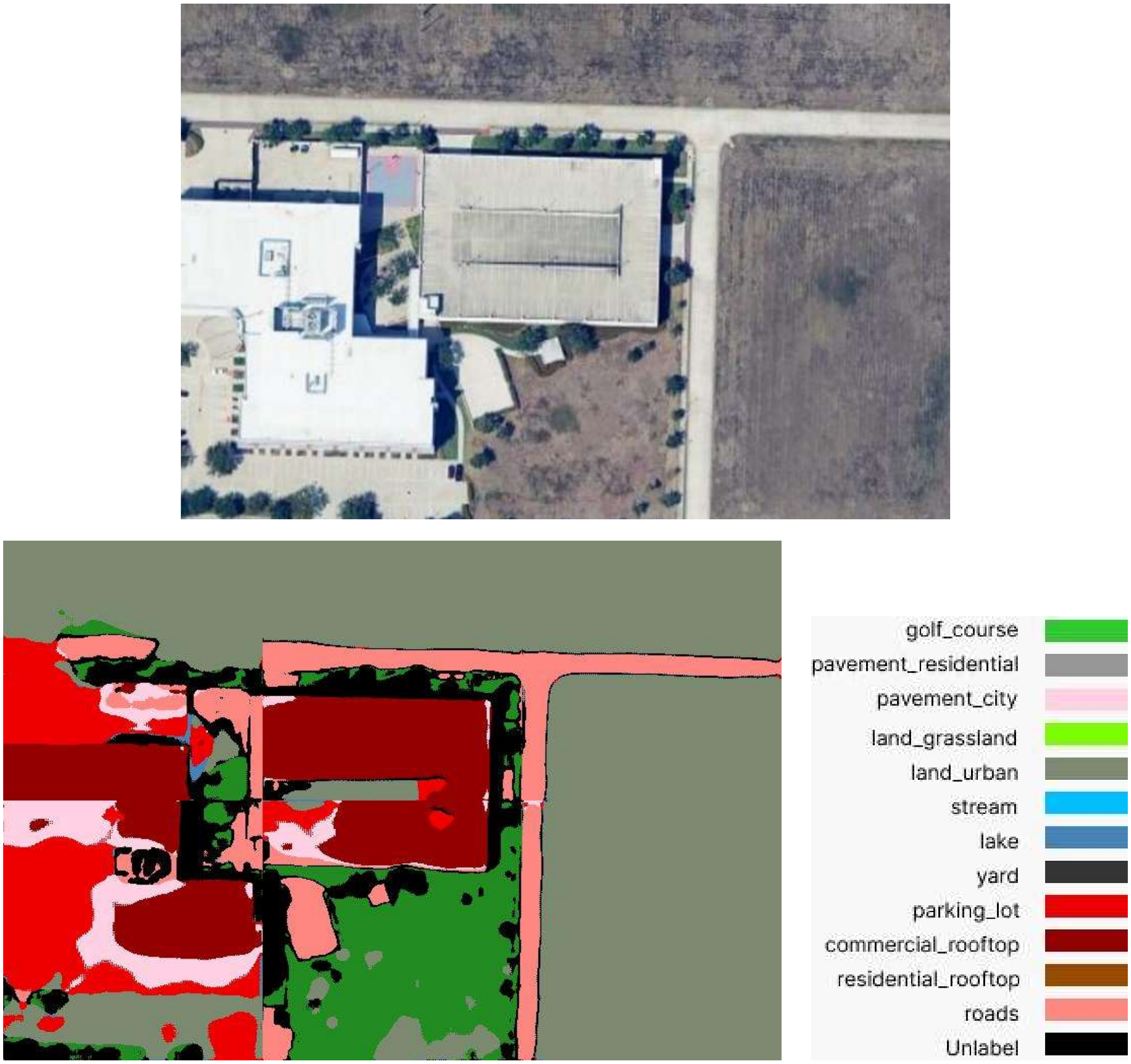

Figure 7 – An Urban Landscape and Its Blended Prediction

The area covered by each land cover category is calculated, followed by determining the weighted initial Curve Number (CN) to estimate runoff potential.

Urban Surface Category	Curve Number	Area (%)
Golf Course	55	0
Pavement (Residential)	98	0
Pavement (City)	98	4
Land (Grassland)	61	0
Land (Urban)	79	48
Stream	0	0
Lake	0	0
Yard	74	10
Parking Lot	98	8
Commercial Rooftop	98	13
Residential Rooftop	98	0
Roads	98	8
Unlabeled	-	9

Table 3 – Estimated Distribution of Proposed Urban Surface Categories in an Urban Landscape

Landscape improvements, such as green roofs or permeable pavements, are then formulated. Finally, the Curve Number is recalculated to calculate effective Curve Number (CN) post interventions, providing a comprehensive approach to optimizing stormwater management in urban areas.

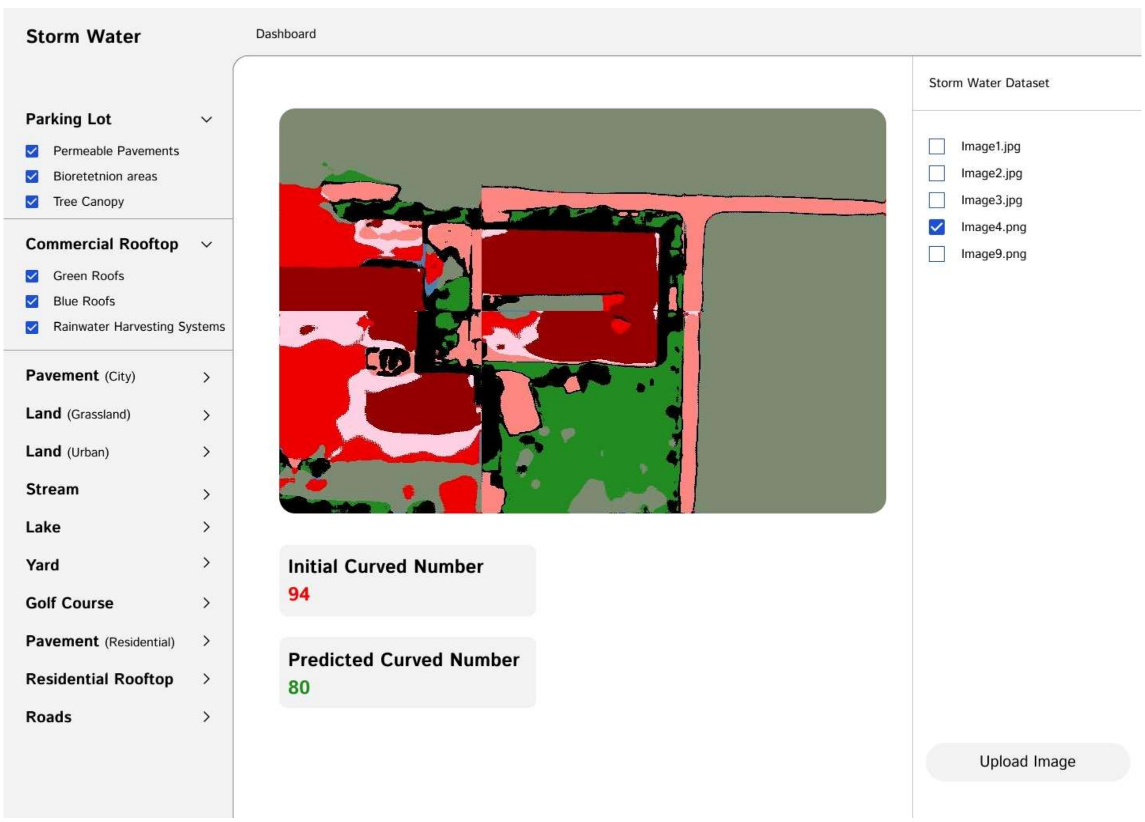

Figure 8 – A Proposed Storm Water Management Assistant

Effective Curve Number

One of the primary objectives of this research is to assist city officials and urban planners in evaluating and visualizing the impact of stormwater management strategies and policies. The segmented image of the urban landscape predicted by the proposed model not only offers an understanding of the stormwater characteristics of the current landscape, but also enables the selection of appropriate stormwater management strategies and assessment of their impact on the runoffs.

To calculate the predicted curve number for a proposed mitigation strategy, following method is suggested

1) Estimate the post intervention Curve Number for the various urban surface categories
2) Plug in the predicted Curve Numbers in the equation below

$$CN_c = \sum_{0}^{n} CN_{\boldsymbol{ip}}.\, a_i$$

$$CN_{ip} \ = \ estimated\ runoff\ curve\ number\ for\ category\ i\ post\ treatment$$

Discussion

Implications for Stormwater Management

By identifying and categorizing surfaces such as residential rooftops, commercial parking lots, paved roads *etc.* this research provides a nuanced understanding of how different urban surfaces contribute to stormwater runoff. The categorization leads to targeted strategies for increasing the infiltration and storage of stormwater and reducing runoff volumes and peak flow rates.

The implementation of these strategies would lead to a measurable reduction in burden on urban drainage systems, mitigating the risk of flooding and improving water quality before they enter waterways. Moreover, enhancing the permeability of urban surfaces contributes to groundwater recharge, an essential process for maintaining the balance of urban water cycles and ensuring the sustainability of water resources.

Challenges and Limitations

One of the primary challenges encountered in this research was the variability in the quality and resolution of satellite images across different urban areas. This variability can affect the accuracy of surface classification, particularly in densely built-up areas where distinguishing between different surface types is more complex. Additionally, the dynamic nature of urban environments, with ongoing construction and development, means that the dataset requires regular updating to remain accurate and relevant.

Future research should focus on integrating higher-resolution satellite imagery, incorporating temporal data, and expanding datasets to include socioeconomic and regulatory information. Interdisciplinary research that combines hydrological modeling, urban planning, and social science is essential to developing integrated strategies for managing stormwater in urban areas.

Conclusion

The integration of satellite image classification into development of sustainable urban stormwater management practices and policy interventions represents a significant opportunity in addressing the multifaceted challenges posed by urbanization. This research has demonstrated that using computer vision to categorize urban surfaces based on permeability, land use and ease of regulation can provide invaluable insights into the dynamics of stormwater runoff. By creating an annotated dataset and applying deep learning models, this study has enabled identification of opportunities and impact assessment of green infrastructure. The application of this integrated approach can inform policy interventions and urban planning, leading to more resilient and sustainable cities.

By leveraging the proposed dataset, deep learning model and stormwater management framework, planners and policymakers can make informed decisions to enhance long term sustainability and resiliency of urban environments. The implementation of targeted stormwater management strategies based on detailed spatial analysis promises to improve urban water cycles, reduce flood risks, and ensure the long-term sustainability of water resources.

References

Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association*, 62(2), 243-258.

Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research*, 37(18), 4369-4376.

Brown, S., McIvor, K., & Hodges Snyder, K. (2017). Soil Health and Stormwater Management: A Review. *Journal of Environmental Quality*, 46(5), 1024-1036.

Chen, C.-L. (1982). Infiltration formulas by curve number procedure. *Journal of the Hydraulics Division*, 110(3), 347. https://doi.org/10.1061/(ASCE)0733-9429(1984)110:3(347)

Dietz, M. E. (2007). Low impact development practices: A review of current research and recommendations for future directions. *Water, Air, & Soil Pollution*, 186(1-4)

Erdman, J. (2021, September 13). Recent Years Show Why Houston Is Likely America's Rainfall Flooding Capital. The Weather Channel.

Environmental Protection Agency (EPA). (2000). Low Impact Development (LID): A Literature Review. EPA-841-B-00-005.

EPA. (n.d.). Green Infrastructure: Soil Amendments. Retrieved from EPA.

Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, 51, 261-279.

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525-542.

Getter, K. L., & Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. *HortScience*, 41(5), 1276-1285.

Gies, E. (2023). *Water Always Wins: Thriving in an Age of Drought and Deluge*. University of Chicago Press.

Gregory, J. H., Dukes, M. D., Jones, P. H., & Miller, G. L. (2006). Effect of urban soil compaction on infiltration rate. *Journal of Soil and Water Conservation*, 61(3), 117.

Herold, M., Couclelis, H., & Clarke, K. C. (2005). The role of spatial metrics in the analysis and modeling of urban land use change. *Computers, Environment and Urban Systems*, 29(4), 369-399.

Hurd, B., Shaw, D., & Hatch, U. (2006). Public attitudes toward water management and drought in the United States. *Water Resources Research*, 42, W03407.

Kevin T. Smiley, Christopher R. Hakkenberg, "Race and affluence shape spatio-temporal urbanization trends in Greater Houston, 1997 to 2016," *Land Use Policy*, Volume 99, 2020, 105093, ISSN 0264-8377, https://doi.org/10.1016/j.landusepol.2020.105093. Available at: ScienceDirect.

Liscum, F. (2001). Effects of Urban Development on Stormwater Runoff Characteristics for the Houston, Texas, Metropolitan Area. U.S. Geological Survey Water-Resources Investigations Report 01–4071. In cooperation with the Harris County Flood Control District and the City of Houston, Austin, Texas.

Lu, D., & Weng, Q. (2007). A survey of image classification methods and techniques for improving classification performance. *International Journal of Remote Sensing*, 28(5), 823-870.

Makepeace, D. K., Smith, D. W., & Stanley, S. J. (1995). Urban stormwater quality: Summary of contaminant data. *Critical Reviews in Environmental Science and Technology*, 25(2), 93–139. https://doi.org/10.1080/10643389509388476

Mayer, P. M., Reynolds, S. K., McCutchen, M. D., & Canfield, T. J. (2007). Meta-Analysis of Nitrogen Removal in Riparian Buffers. *Journal of Environmental Quality*, 36(4), 1172-1180.

McGauley, M. W., Amur, A., Shakya, M., & Wadzuk, B. M. (2023). A Complete Water Balance of a Rain Garden. *Water Resources Research*, Published 12 December 2023. https://doi.org/10.1029/2023WR035155

Myint, S. W., Gober, P., Brazel, A., Grossman-Clarke, S., & Weng, Q. (2011). Per-pixel vs. object-based classification of urban land cover extraction using high spatial resolution imagery. *Remote Sensing of Environment*, 115(5), 1145-1161.

Naiman, R. J., & Decamps, H. (1997). The Ecology of Interfaces: Riparian Zones. *Annual Review of Ecology and Systematics*, 28(1), 621-658.

Purvis RA, Winston RJ, Hunt WF, Lipscomb B, Narayanaswamy K, McDaniel A, Lauffer MS, Libes S. Evaluating the Hydrologic Benefits of a Bioswale in Brunswick County, North Carolina (NC), USA. *Water*. 2019; 11(6):1291. https://doi.org/10.3390/w11061291

Raoof, M., Kazemi, J., Mostafazadeh, R., Hoseini, Y., & Mirzaei, S. (2024). Effect of curve number changes on flood hydrograph in a rapid response watershed (Case study: Ardabil Khiavchai Watershed). *Volume 4, Issue 1*, 248-261.

S. Fletcher*, M. Zaniolo*, M. Zhang*, M. Lickley. 2023. “Climate oscillation impacts on water supply augmentation planning.” Proceedings of the National Academy of Sciences. 120 (0).

Seattle Public Utilities. (2012). "Natural Drainage Systems." Seattle Public Utilities.

Shuster, W. D., Bonta, J., Thurston, H., Warnemuende, E., & Smith, D. R. (2005). Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal*, 2(4), 263-275.

Singh, Gurdeep & Leh, Mansoor & SINGH, P. K. (2018). Determination of curve number and estimation of runoff using experimental rainfall and runoff data. *Journal of Spatial Hydrology*, 2017, 13(1), Article 2.

Tsihrintzis, V. A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: A review. *Water Resources Management*, 11(2), 137-164.

University of Minnesota Extension. (n.d.). Amending Soils for Stormwater Management. Retrieved from University of Minnesota Extension.