The Potential of Green Infrastructure and Artificial Intelligence in Urban Stormwater Management

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Urban stormwater management presents critical challenges, exacerbated by climate change and rapid urbanization. Traditional grey infrastructure, while effective at water removal, often neglects environmental sustainability. Green infrastructure, such as rain gardens and permeable pavements, provides eco-friendly alternatives but faces scalability and maintenance challenges. The integration of artificial intelligence (AI) with green and grey infrastructures offers a novel, adaptive approach to mitigate flooding, optimize resources, and enhance urban resilience. By combining green infrastructures ecological benefits with AI's real-time adaptability, this paper proposes a novel framework for urban stormwater management that is resilient, scalable, and adaptive to climate change. While extensive research exists on green infrastructure and AI independently, their integration remains under explored in stormwater management. This review explores the synergistic roles of AI and green infrastructure through case studies and real-world applications, highlighting the transformative potential of predictive modeling, real-time management, and climate-adaptive designs. Future research should focus on cost-effective hybrid models to address urban sustainability challenges and ensure long-term adaptability to climate uncertainties.

Introduction

Urban stormwater runoff poses significant risks, including flooding, environmental degradation, and infrastructure damage. Traditional stormwater systems, predominantly grey infrastructure such as pipes and channels, focus on rapid water removal but often neglect environmental impacts. Green infrastructure such as rain gardens, permeable pavements, and green roofs provides sustainable alternatives by mimicking natural hydrology. However, these solutions face significant challenges related to scalability, maintenance, and cost, limiting their widespread adoption in urban areas.

This review identifies a criticalgap: the lack of integration between AIs predictive power and the scalability challenges of green infrastructure in urban stormwater systems. Current stormwater management approaches often treat green infrastructure and artificial intelligence (AI) as distinct innovations, missing the opportunity to combine their strengths. By leveraging AIs capacity for dynamic, data-driven decision-making, green infrastructure can be optimized to deliver enhanced performance and adaptability in real-world urban settings.

To contextualize these solutions, it is essential to understand the limitations of current frameworks like the National Pollutant Discharge Elimination System (NPDES). While NPDES regulates point source pollution, it inadequately addresses nonpoint source runoff, a significant contributor to urban flooding. Additionally, aging stormwater systems, many nearing or exceeding their 50-100 year lifespans, are ill-equipped to handle the increasing frequency and intensity of storm events driven by climate change. These gaps underscore the urgent need for innovative approaches that address both sustainability and resilience.

Artificial intelligence offers transformative potential for addressing these challenges. Through tools like the EPAs Stormwater Management Model (SWMM) and advanced machine learning algorithms, AI can optimize infrastructure design, predict flooding scenarios, and manage stormwater in real time. When integrated with green infrastructure, AI can enhance system efficiency, scalability, and adaptability, creating hybrid approaches capable of mitigating urban flooding while addressing long-term sustainability goals. This review synthesizes innovations in green infrastructure and AI applications, emphasizing their integration as a pathway to creating resilient, sustainable urban environments. By bridging the gap between these complementary solutions, this work aims to provide actionable insights for advancing urban stormwater management in the face of climate change.

Methods

This literature review draws on 20 peer-reviewed articles and government reports published after 2000 to ensure relevance and rigor. Sources were identified using databases such as ScienceDirect, PubMed, and Google Scholar, with keywords including stormwater infrastructure, green infrastructure, AI stormwater management, and hybrid stormwater models. Inclusion criteria prioritized studies offering novel insights, robust methodologies, and a focus on urban environments. Articles were evaluated for quality based on citation frequency, methodological rigor, and relevance to key themes, such as flood mitigation, sustainability, and adaptability to climate change.

Methodology Justification

The decision to limit this review to 20 peer-reviewed articles was guided by the goal of focusing on high-quality, relevant studies published after 2000, ensuring that the findings reflect the most recent advancements in urban stormwater management. Articles were selected based on rigorous inclusion criteria, including citation frequency, methodological robustness, and relevance to key themes such as AI integration and green infrastructure innovations. While this review focuses on high-impact studies, the reliance on peer-reviewed literature may omit perspectives found in grey literature, such as government reports or technical white papers. Expanding future reviews to include such sources could provide additional insights into emerging challenges and opportunities in stormwater management.

Results and Discussions

Our literature review found various cases of green infrastructure and AI used to improve current stormwater infrastructure. The following sections first define these critical terms, then discuss key cases for each innovation.

Green Infrastructure

Green infrastructure reduces stormwater runoff by mimicking natural hydrology, offering an eco-friendly alternative to traditional grey systems. In New York City, rain gardens absorb millions of gallons of stormwater annually, demonstrating their efficacy in densely populated areas. Cincinnatis rain gardens, strategically placed at the base of sloped terrain, detained nearly 50% of inflow and delayed overflow by 5.5 hours during heavy rain events, highlighting their adaptability to unique topographies. However, challenges such as scalability and maintenance hinder their widespread implementation, particularly in urban areas with limited space. These challenges could be mitigated by integrating artificial intelligence (AI) solutions to optimize placement and predict maintenance schedules, ensuring consistent performance even in resource-constrained settings. Other solutions include permeable pavements and rain barrels. Permeable pavements in North Carolina achieved infiltration rates of 8.6 cm/hr with maintenance, significantly reducing runoff volumes. Despite their effectiveness, high costs and ongoing maintenance requirements limit their scalability. AI-based cost-optimization algorithms could identify priority areas for instal-

Fig. 1 Photos depicting various forms of green infrastructure, including rain gardens, green roofs, permeable pavement, infiltration trenches, landscape water bodies, and grassed swales [1].

lation and recommend efficient maintenance routines, reducing costs and improving long-term performance. Rain barrels, though cost-effective, are limited by contamination risks from roof debris, requiring proper maintenance to ensure usability. Real-time AI sensors could monitor water quality and provide early warnings about contamination, enabling proactive interventions to improve usability and safety.

Cost and Scalability of Green Infrastructure

The cost and scalability of green infrastructure remain critical considerations in urban stormwater management. Rain barrels, for instance, are low-cost solutions that provide decentralized water management, but their utility is constrained by maintenance needs and contamination risks. Comparatively, permeable pavements offer significant runoff reduction and filtration benefits; however, their high initial costs and technical expertise requirements can hinder widespread adoption in resource-constrained settings. AI-based systems could enhance scalability by identifying cost-sharing opportunities, predicting long-term maintenance needs, and simulating the effectiveness of materials to reduce upfront costs.

Future Potential of AI-Enhanced Green Infrastructure

Integrating AI with green infrastructure presents significant opportunities to improve performance, scalability, and resilience. For example:

- **Rain Gardens:** AI-powered real-time sensors could monitor inflow levels and predict maintenance schedules, preventing system overload during heavy rainfall. Predictive algorithms could analyze hydrological data to identify optimal locations for rain garden placement, maximizing efficiency in densely populated urban environments.

- **Permeable Pavements:** AI simulations could evaluate material performance under varying environmental conditions, helping urban planners make data-driven decisions about installation and maintenance.
- **Rain Barrels:** Smart systems could monitor water quality and optimize usage, transforming simple collection systems into efficient, automated management tools.

Urban planners should prioritize hybrid models that integrate green infrastructure with existing systems to balance ecological benefits and financial feasibility. Future research should explore cost-sharing mechanisms, such as public-private partnerships, and the development of low-maintenance materials to improve scalability. By addressing these factors, cities can enhance the accessibility and effectiveness of sustainable stormwater solutions. Analysis of New York City rain gardens revealed that out of the 52.5 inches of rainfall the city received between 1990 and 2015, 130-143 million gallons of stormwater were absorbed by community stormwater gardens[2]. Topography plays a large role in rain garden effectiveness, highlighted by the construction of a Cincinnati rain garden at the bottom of a sloped hill directly in the path of runoff. The garden detained roughly half of all water inflow, preventing 90% of rain events from producing runoff that flowed into a combined sewer system (CSS) that typically overflowed during heavy rain. The 10% of events that did produce enough runoff to flow into the CSS were delayed in flow by an average of 5.5 hours, demonstrating the rain garden's strengths in completely neutralizing or mitigating stormwater runoff through natural forms of ground infiltration rather than dumping[3].

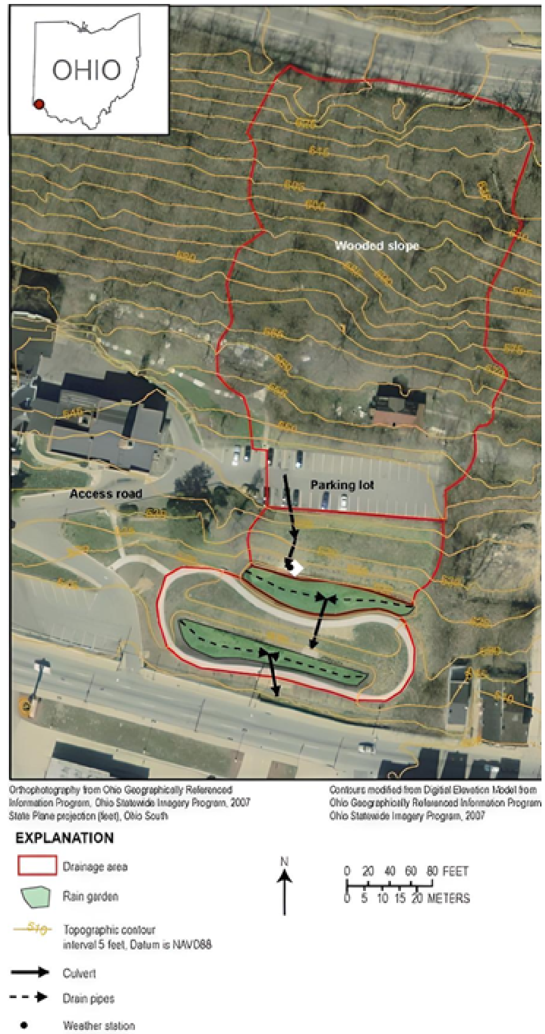

Fig. 2 Figure depicting the St. Francis, Cincinnati green infrastructure network, including rain garden, drainage area, and conveyance infrastructure[3].

A more manageable and easily implemented form of green infrastructure is the rain barrel, which can be purchased from local retailers or provided by local governments. Typically attached to residential drainage systems like rain gutters, rain barrels passively collect rainwater to be used at a later date for activities that require water[4]. Rutgers University tested the water quality of twelve rain barrels linked to the same roof, discovering that while the water is not safe to drink due to unsafe E. coli contamination, the water is safe to use for agriculture based on minimal zinc, lead, and coliform values. Contamination could result from the cleanliness of the tested roof and/or animal activity[5].

While rain barrels and gardens are smaller projects, permeable pavement can be installed at a variety of sizes depending on the allotted space. Permeable pavement, an alternative to traditional pavement, is designed to contain small pores that allow runoff to seep through and infiltrate into the ground underneath the pavement, reducing runoff volume and filtering existing contamination[6]. Researchers studied 40 permeable pavement sites across North Carolina, Virginia, Maryland, and Delaware to determine the form of permeable pavement with the greatest infiltration rate. Permeable interlocking concrete and porous concrete demonstrated moderate infiltration while concrete grid pavers demonstrated the most infiltration at ∼4.9 cm/hr without maintenance and ∼8.6 cm/hr with maintenance, respectively[7].

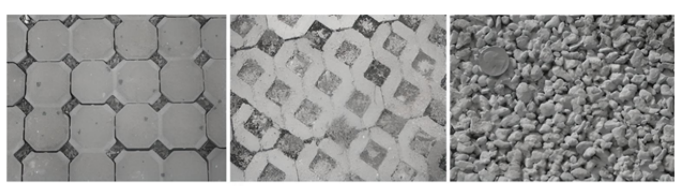

Fig. 3 Photos that showcase the forms of permeable pavement used in the study. (a) Permeable interlocking concrete pavers, (b) concrete grid pavers, (c) porous concrete[7].

Introduction to AI Stormwater Management

The use of AI has become increasingly popular today; while originally used in an industry application, automation, decision-making, and predictions make AI useful for simplifying stormwater issues[8]. AI developments seek to minimize the amount of retrofitting existing infrastructure by designing adaptable systems. Instead of redesigning an entire system, AI applications would react to and survive continual changes. Because altering a location's respective watershed shifts the outcome of stormwater management, a more long-term solution like AI application ensures shifts in hydrology are compensated for by adaptive AI infrastructure[9].

Artificial Intelligence in Stormwater Management

AI Modeling

AI models, such as EPA-SWMM, simulate stormwater behavior to inform infrastructure design and management. For instance, modeling of the Bronx River watershed demonstrated a 28% reduction in runoff through low-impact developments. Advanced algorithms like the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) optimize pump operations, achieving a 71% improvement in efficiency at the Yu-Cheng pumping station in Taipei. Comparatively, deep neural networks (DNNs) excel in real-time management by balancing short- and long-term mitigation strategies, though they require extensive computational resources.

When integrated with green infrastructure, AI modeling becomes even more powerful. For example, predictive algorithms could assess hydrological and climatic data to optimize the placement and design of rain gardens or permeable pavements, maximizing their effectiveness in stormwater management. Additionally, AI models like the Coupled Model Intercomparison Project (CMIP5) can predict extreme weather patterns, supporting the adaptive placement of green infrastructure to address climate change impacts.

Real-Time Management

AI-based real-time systems enhance stormwater management by dynamically responding to environmental conditions. In Ann Arbor, Michigan, wireless sensors and control valves were used to reduce runoff flow to below 0.15 m^3/s, demonstrating superior performance compared to static infrastructure. This technology could also be applied to green roofs, where sensors might monitor water retention and release in real-time, optimizing their performance during heavy rainfall. Digital twins, which create virtual simulations of physical systems using real-time data, offer additional opportunities for integrating AI with green infrastructure. These tools can predict system behaviors under various scenarios, enabling urban planners to test the resilience of hybrid systems combining green infrastructure and traditional drainage before implementation.

Table 1 Comparison of AI and Green Infrastructure Features in Stormwater Management

Feature	Artificial Intelligence (AI)	Green Infrastructure (GI)
Primary Function	Predictive modeling, real-time management, and optimization	Stormwater absorption, filtration, and ecological benefits
Scalability	Highly scalable with sufficient computational resources	Limited by space, costs, and maintenance needs
Cost	High upfront investment for sensors, models, and training	Variable, with rain barrels being low-cost and pavements higher
Adaptability	Dynamic, capable of adjusting to real-time data and weather changes	Static unless coupled with AI for adaptive maintenance
Maintenance	Requires regular data updates and computational resource upgrades	Manual maintenance needed for systems like rain gardens
Data Dependency	Requires extensive datasets for effective modeling	Performance depends on location-specific factors (e.g., soil, topography)
Climate Resilience	Predicts and mitigates extreme weather impacts	Absorbs and manages runoff, reducing urban heat islands
Implementation Challenges	High technical expertise, integration with existing systems	Space constraints, maintenance complexity
Key Advantage	Optimizes design and real-time management for efficiency	Provides direct ecological and hydrological benefits

Hybrid Systems: The Intersection of Green and AI Solutions

Hybrid systems that integrate green infrastructure, grey infrastructure, and AI technologies represent a transformative approach to urban stormwater management. By combining these elements, cities can leverage the ecological benefits of green infrastructure with the structural reliability of grey systems and the adaptability of AI-driven management.

Case Study Examples

- **Green Roofs and Digital Twins:** In a proposed hybrid system, digital twins could simulate the performance of green roofs under various weather conditions, informing adjustments to maximize water retention and reduce urban heat island effects. AI-driven models could monitor and predict system performance, ensuring optimal functionality over time.

- **Rain Gardens and Adaptive AI Systems:** AI algorithms could assess hydrological data to dynamically allocate resources for rain garden maintenance and expansion, ensuring these systems operate effectively even in areas with limited space.
- **Permeable Pavements and Predictive Models:** By integrating AI-based predictive models, urban planners could prioritize the installation of permeable pavements in areas with the greatest impact potential, balancing runoff reduction with cost constraints.

Addressing Climate Change

The hybridization of green infrastructure and AI is especially critical in the context of climate change. AI-driven tools such as climate models can predict the frequency and intensity of extreme weather events, enabling urban planners to proactively adapt infrastructure systems. For instance, AI-guided simulations of green-grey-AI systems can model flood scenarios and recommend design modifications to enhance resilience.

Challenges and Opportunities

Challenges to Integration

Despite their transformative potential, the integration of artificial intelligence (AI) and green infrastructure in stormwater management faces several barriers:

- Technical Challenges: Interoperability between AI systems and green infrastructure remains a significant hurdle. Current systems often lack standardized protocols for integrating AI-driven tools with physical infrastructure like rain gardens or permeable pavements. Additionally, many AI solutions require extensive datasets for effective operation, which may be difficult to obtain in regions with limited monitoring or sensor networks.
- Financial Barriers: Both AI technologies and green infrastructure entail high upfront costs. AI implementation often requires investments in computational resources, sensors, and skilled personnel. Similarly, green infrastructure installations like permeable pavements or green roofs can be prohibitively expensive, particularly in resource-constrained settings. Balancing cost-effectiveness with sustainability goals is a persistent challenge for urban planners.
- Maintenance and Scalability: Green infrastructure solutions, while effective, require regular maintenance to ensure long-term functionality. Integrating AI to address these issues adds complexity, as maintaining the digital and physical components of hybrid systems can strain available resources.

Opportunities for Integration

Despite these challenges, significant opportunities exist to harness the synergy between AI and green infrastructure:

- Emerging Technologies: Advances in machine learning, digital twins, and real-time data analytics offer unprecedented potential for adaptive management. For instance, digital twins can simulate the performance of hybrid systems under varying environmental conditions, allowing planners to refine designs before implementation. Machine learning models can analyze vast datasets to predict flooding events and recommend targeted interventions, enhancing the efficiency of green infrastructure.
- Public-Private Partnerships: Collaborative funding models can address financial barriers, enabling cities to share the costs of hybrid system implementation with private stakeholders. These partnerships can also support the deployment of advanced AI systems, bridging the gap between technological innovation and practical application.
- Climate Resilience: Integrating AI with green infrastructure creates adaptive systems capable of responding to climate uncertainties. AI-driven climate models can predict the frequency and intensity of extreme weather events, enabling proactive infrastructure planning. For example, predictive algorithms can identify optimal locations for rain gardens and permeable pavements to mitigate flood risks while maximizing ecological benefits.

Future Trends

Emerging trends indicate a promising future for hybrid AI-green infrastructure systems:

1. Climate-Resilient AI Algorithms: New machine learning models tailored for extreme weather scenarios are driving the development of adaptive stormwater solutions. These models can incorporate variables like rainfall intensity, urban heat island effects, and soil permeability to optimize infrastructure performance.
2. Integration into Urban Planning: As cities increasingly prioritize sustainability, green infrastructure supported by AI technologies is becoming a core component of urban planning frameworks. Real-time management systems, enabled by wireless sensors and predictive analytics, are poised to replace static, outdated stormwater systems.

3. Scalable Solutions: Advances in AI and materials science are creating scalable, low-maintenance solutions for green infrastructure. For instance, AI can optimize resource allocation for maintenance, ensuring cost-effective and efficient operation over time.

Climate Adaptation Framework

Addressing the impacts of climate change requires innovative solutions that combine technological advancements with sustainable practices. Integrating artificial intelligence (AI) with green infrastructure presents a transformative framework for enhancing urban resilience. This section explores predictive modeling for extreme weather, strategies for scaling hybrid systems, and policy recommendations for integrating AI-green infrastructure solutions into urban planning.

Predictive Modeling for Extreme Weather

The increasing frequency and intensity of extreme weather events demand precise tools for prediction and planning. AI-powered models, such as the Change Factor Approach (CFA), enable urban planners to simulate future climate scenarios and assess their potential impacts on stormwater infrastructure. By incorporating variables like precipitation patterns, temperature changes, and soil permeability, these models provide actionable insights for adaptive infrastructure design.

For instance, AI-driven climate models like the Coupled Model Intercomparison Project (CMIP5) can downscale global climate data to forecast localized weather conditions. These predictions inform the placement and design of green infrastructure, such as rain gardens and permeable pavements, to maximize flood mitigation and stormwater retention under future conditions. Additionally, predictive analytics can guide the allocation of resources for maintenance, ensuring that green infrastructure remains functional during extreme weather events.

Long-Term Scalability

Adapting to climate change requires scalable solutions that balance ecological benefits with cost-effectiveness. Hybrid systems that integrate green infrastructure with AI technologies offer a promising pathway for achieving this balance. Strategies for long-term scalability include:

- Modular Green Infrastructure Design: Employing modular systems, such as rain garden networks or distributed rain barrels, allows cities to expand infrastructure incrementally as funding and resources become available. AI-driven optimization models can identify high-priority areas for initial implementation and recommend phased expansions based on urban growth and climate projections.
- AI-Assisted Maintenance Scheduling: Green infrastructure requires regular maintenance to remain effective, particularly in urban environments where space and resources are limited. AI-powered tools can analyze sensor data to predict maintenance needs, reducing downtime and ensuring consistent performance over time.
- Resilient Materials and Techniques: Advances in materials science, guided by AI simulations, are enabling the development of low-maintenance, climate-resilient infrastructure components. For example, permeable pavements enhanced with AI-optimized materials can withstand extreme temperatures and heavy rainfall, reducing long-term costs.

Case studies of cities like Copenhagen and Singapore highlight the potential for scaling hybrid systems. Copenhagen's cloudburst management plan integrates green infrastructure with AI-powered predictive tools to handle extreme rainfall, while Singapore employs real-time AI systems to manage stormwater across its urban landscape.

Policy Integration

Effective policy frameworks are critical for leveraging the full potential of AI-green infrastructure models. Recommendations for city planners include:

- Incentivizing Public-Private Partnerships: Collaborative funding models can reduce financial barriers, enabling municipalities to implement hybrid systems. Public-private partnerships can also facilitate the sharing of data and technological resources, accelerating the deployment of AI solutions.
- Incorporating Hybrid Systems into Building Codes: Updating zoning laws and building codes to require or incentivize hybrid stormwater systems ensures that new developments contribute to urban climate resilience. For example, mandates for green roofs equipped with AI-based energy models can reduce urban heat island effects while managing stormwater.
- Standardizing Data Collection and Sharing: Establishing protocols for data collection and sharing enables the effective use of AI in stormwater management. Centralized data repositories, maintained by government agencies, provide a foundation for training machine learning models and improving predictive accuracy.

These policy measures, coupled with community engagement and education, create an enabling environment for the widespread adoption of AI-green infrastructure systems. By embedding these solutions into urban planning processes, cities can build resilience to the challenges posed by a changing climate.

AI Modeling Discussion

Applying accurate AI modeling to stormwater management requires adding extensive hardware and software to existing or newly constructed infrastructure. Various forms of hardware and software, including Internet of Things, AI and Big Data Analytics, Digital Platforms, Social Sensing, Semantic Model Approach, and Energy Benchmarking Approach, among other, collect data that can then be applied to predictive and adaptive models. AI models analyze collected data and derive realistic digital simulations that increase in accuracy with additional data. Various modeling tools exist for stormwater management. Hydrologic and hydraulic modeling analyzes the movement of water through drainage systems by acquiring data on rush, evaporation, infiltration, runoff, and pipe dimensions[10]. Water quality modeling focuses on runoff pollutants to predict the contamination of runoff and the appropriate reaction[11]. Floodplain and green infrastructure modeling coincide together through the creation of digital floodplain recreations, which predict how water moves along the watershed and help with grey and green infrastructure placement[10]. Climate change modeling serves as a way to eliminate climate change variations in stormwater management, predicting changing weather patterns and shifts in the environment[12]. These models can be incredibly expensive and complex but can provide highly useful data.

AI models can also be used in the creation of treatment plans, expediting this process. Through generative design, urban planners can expedite a projects initiation phase while mapping out the projects ecological outcome, maximizing sustainability, resilience, and treatment capacity. Asia Development Bank demonstrated the power of the Transcend Design Generator, developing more than 10 wastewater treatment plans under a timeframe of 8-12 weeks as opposed to the traditional 8-10 months[13]. AI modeling combined with geographic data can move beyond simple planning and into complex digital simulations that assess key stormwater data. Stormwater Management Models (SWMMs), specifically EPA-SWMM and Personal Computer Stormwater Management Model (PCSWMM), popularized forms of digital modeling, have been designed for stormwater management[10]. Created by the U.S. government, EPA-SWMM is a public simulator often used in research to model and predict the effects of stormwater in urban environments[14]. EPA-SWMM can model various infrastructures including both typical gray infrastructures, and less common green infrastructures like vegetable swales and infiltration tunnels[15]. Using EPA-SWMM5, researchers modeled the Bronx River watershed and simulated the effects of various green infrastructures/low-impact developments (LID) on stormwater peak flow rate and return periods. Simulated LID implementations decreased watershed runoff corresponding to return periods of 2, 5, 10, 25, and 50 years by 28% (ranging from 47 for S1 to 13 for S4), 22% (ranging from 45 for S1to 7% for S4), 19% (ranging from 42 for S1 to 2% for S4), 18% (ranging from 40 for S1 to 5% for S4), and 14% (ranging from 27 for S1 to 4% for S4), respectively, relative to no LID scenarios[16].

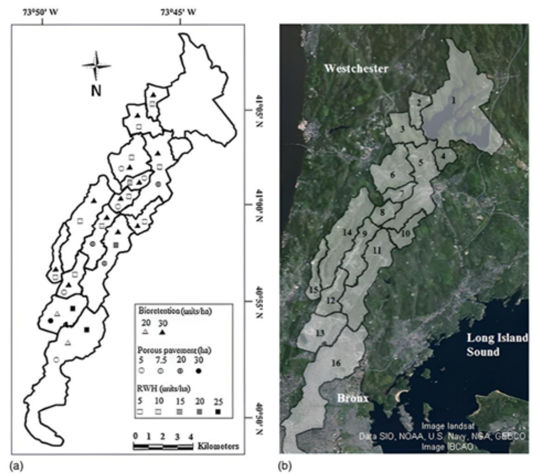

Fig. 4 Map depicting the locations or LID developments along Long Island modeled on the subwatershed and aerial imaging[16].

To address the variable effects of location-specific infrastructure, location-specific AI such as the Virginia Runoff Reduction Method (VRRM) and the Delaware Urban Runoff Management Model (DURMM) have been developed to simulate specific areas with greater accuracy. VRMM was created to record and react to stormwater runoff and contaminant loads from development areas, suggesting land use options to effectively control stormwater runoff pollution. DURMM applies a water-centric approach to modeling, analyzing the quantity and quality of runoff water based on environmental factors such as existing infrastructure, soil types, and land use. Much like VRMM, DURMM estimates runoff and contaminate levels in simulated stormwater. DURMM combines modeling with a spreadsheet system that produces estimations in stormwater based on current conditions filled into the spreadsheet (DURMM v2.5, 2020). The variety of AI-based modeling tools creates the opportunity to plan future infrastructure rather than randomly retrofitting existing structures. As more data is collected, models become more expansive and complicated, becoming extremely useful when modeling real-life scenarios that test the limits and possibilities of stormwater runoff and stormwater infrastructure[10].

AI-Based Real-time Management

Real-time management through AI involves creating dynamic stormwater infrastructure, replacing less reactive, static infrastructure. Through the application of smart technologies, gathered data can be applied to a digital twin simulation, digitally simulating an area of interest. Digital twins gather sensor data and process information through a feedback loop, generating a real-time, nearly identical depiction of a physical area. Data from the physical system is presented in the digital twin, optimizing the manipulation of real-time data that can then be used to create informed decisions controlled by humans or the AI system.[17].

Virginian stormwater management officials sought to adopt a digital twin-based approach to stormwater to reduce the amount of combined sewer overflows they experience after large rain events. They inputted weather data, tunnel inflow volume, the peak value of the inflow rate, and the duration of the rain events, receiving outputs of overflow volume from the outfall and the peak flow rate from the outfall. From modeling these situations, an AI model could be trained to react and activate stormwater pumps, discharging cleaner stormwater from a plant rather than directly into waterways[18].

Additionally, detention facilities in Taipei utilized an experimental nondominated genetic sorting algorithm II (NGSA-II) combined with a two-tier sorting process to optimize the operation of urban drainage pumps. A model of the Yu-Cheng pumping station and 17 storm/typhoon events were applied to the NGSA-II program where complex calculations based on storm data and the pumping station capabilities from 13 events were completed by the AI, creating an optimal operation model that was then tested against the remaining four events. Of all of the findings, the greatest takeaway was that the pumping station experienced improvements of up to 71%. Reactive activations of the Yu-Cheng pumping stations infrastructure calculated through NGSA-II greatly improved the efficiency and reliability of stormwater mitigation practices, emphasizing AI's capacity to assist in real-time management[8].

Later studies in Ann Arbor, Michigan attempted to address the full complexities of urban stormwater through a Deep Neural Network that was able to predict and adapt to rain events through AI-controlled rain valves. The watershed was retrofitted with wireless sensors and control valves that fed data to the deep neural network. Reinforced learning trains the deep neural network in effective stormwater mitigation, assigning reward and punishment values for forms of effective and ineffective storm management respectively. The AI then takes a summation of total reward values and attempts to maximize future reward values through machine learning. The reinforced learning system has the unique ability to balance both short and long-term rewards, allowing the system to differentiate point values for short and long-term mitigation. The Deep Neural Network can then understand the summation of its total reward over long periods, leading to a system that both predicts future events and reacts to said events to the maximum extent. To test the limits of the AI system, researchers first tested the program's ability to control one detention basin, later moving on to the control of multiple basins simultaneously.

Furthermore, researchers sought to understand the effects of specific guidance on the AI systems ability to mitigate stormwater, testing the system multiple times with differing and more

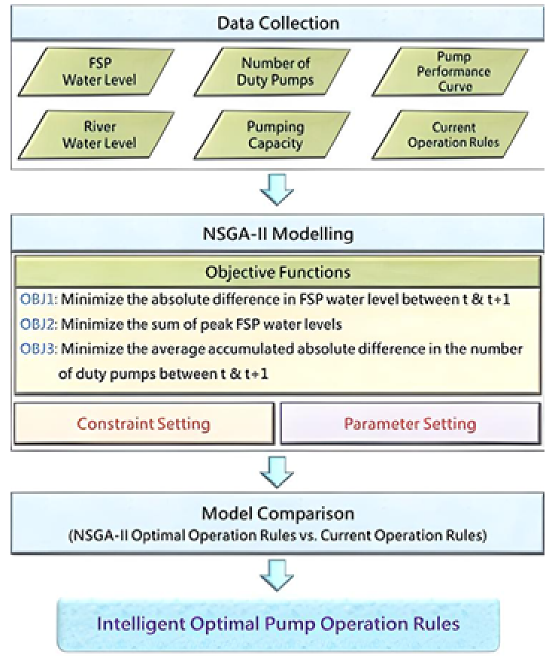

Fig. 5 Chart depicting the research framework behind the NGSA-II program. The system collects data, calculates based on data and objective functions, and compares results to current operation rules[8].

specific criteria for the reward and punishment system. Results from the single basin experiment demonstrate the system was capable of mitigating runoff flow to below 0.15 m/s and that systems given more specific restrictions to the reinforced learning system were more effective in their control of the stormwater. A batch-normalized neural network was then applied to the multiple basin system, replacing the ineffective single basin system as its reward system was unable to converge a stable reward under the more complicated system.

The multiple basin system, though unable to formulate a consistently high reward return, was still seen to be more capable than the uncontrolled system, particularly during intense rainfall events[19]. Results from the experiment suggest that larger systems require the application of more complex sensor and AI systems, but future research and technological developments may improve large system real-time management.

Change Resistant AI and Green Infrastructure Solutions

The combination of AI and green infrastructure creates a systematic approach that maximizes the ability of stormwater infrastructure, developing infrastructure systems resistant to major environmental changes and extreme weather events. A change factor approach (CFA) represents climate change utilizing variables that represent statistics like precipitation. Zahmatkesh et al suggests the application of CFA for rainfall projects that can then be applied to Coupled Model Intercomparison Project

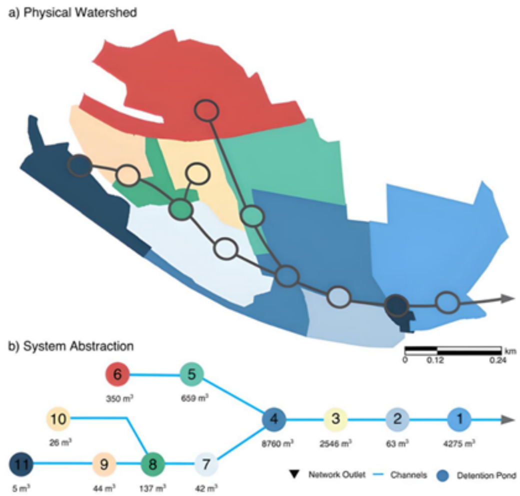

Fig. 6 Diagram depicting the 11 catchment basins controlled by the AI system with corresponding colors between the basin and the catchment that contributed water to said basin. The basins are labeled with the average volume experienced by the pond during a 25-year 6-hour storm event[19].

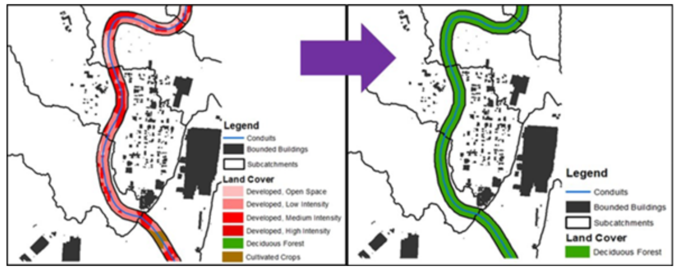

Fig. 7 Diagram depicting the land changes made in the PCSWMM simulation, converting the developed riparian into a 150ft deciduous forest riparian[20].

Phase 5 (CMIP5), which provides downscale data that can then be used to model the effects of climate change on urban hydrology. The CFA will find extreme precipitation projections, and consequently estimate the possible range of runoff variations under future uncertain climate change impacts. Monthly climate factors (CFs) are used to select extreme precipitation conditions which then go towards calculating daily and hourly CFs. These CFs are then applied to the Change Factor Approach algorithm to complete calculations that predict future weather conditions near the Bronx River watershed. This model, when applied to stormwater planning and green infrastructure placement, effectively reduced total runoff by roughly 15%[16]. Modeling using PCSWMM of the Blue River Watershed and protective green infrastructure suggests that LIDs increase the resistance of surrounding infrastructure, protecting important transportation infrastructure from the full extent of climate change-related weather events. The addition of a 150ft riparian and the strategic placement of green infrastructure along the riparian (such that at least 25% of stormwater moved through the green infrastructure) reduced the peak inflow, total volume of inflow, and flood extent of 1, 5, and 10-year events effectively. Flood extents were reduced by roughly 8% for the smaller events, however, larger 100-year events saw minimal changes in flooding. Results of the experiment indicated that green infrastructure was capable of mitigating increasingly common 1, 5, and 10-year events produced by climate change. Green infrastructure combined with additional forms of management will increase the strength of protective measures, ensuring crucial infrastructure will remain undamaged by future climate change[20].

Conclusion

Urban stormwater presents significant risks to both the environment and human lives. As traditional stormwater infrastructure reaches the end of its lifecycle, the challenges of flooding and environmental degradation will intensify. Urban development must evolve to address these issues, prioritizing sustainable practices that limit impermeable surfaces and maintain ecological balance. Modern stormwater management, through the integration of green infrastructure and artificial intelligence (AI), offers a transformative approach that not only mitigates flood risks but also enhances urban resilience.

Green infrastructure, by mimicking natural hydrology, sustains the watershed while promoting environmentally conscious urban growth. Meanwhile, AI applications simplify the complexities of stormwater management, from planning to real-time operation. By simulating stormwater behavior and optimizing infrastructure design, AI enhances the efficiency and adaptability of green infrastructure. Real-time AI systems further enable dynamic responses to stormwater challenges, outperforming static, human-reliant methods and paving the way for smarter, more resilient cities.

The integration of green infrastructure and AI represents a novel and significant advancement in stormwater management. This hybrid approach not only addresses immediate needs but also builds long-term resilience to the impacts of climate change. AI-powered solutions, trained to predict and adapt to environmental changes, offer enduring tools for managing stormwater sustainably and efficiently.

Looking forward, further exploration into AI's role in optimizing green infrastructure under dynamic climatic conditions is critical for sustainable urban development. Future research should focus on expanding hybrid models, refining predictive capabilities, and addressing challenges such as scalability and cost. As these innovations gain traction, the combined potential of green infrastructure and AI will redefine urban stormwater management, leading to more resilient, sustainable, and climate-adaptive cities.

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