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FIVE-DIMENSIONAL ASSESSMENT MODEL FOR OPERATION AND MAINTENANCE OF STORMWATER CONTROL MEASURES – TOOL FOR STRATEGIC PLANNING AND CRISIS MANAGEMENT

M. Askar[1], Ph.D., assoc. prof., and M. Islam[2], Ph.D., assoc. prof.
[1] Southern Utah Univ., Eng. & Tech. Dept., USA e-mail: mohamedaskar@suu.edu;
[2] Colorado State Univ.-Pueblo, C.Eng. Dept., USA, e-mail: md.islam@csupueblo.edu

Abstract. *Most stormwater infrastructures are aging and deteriorating in the United States. The American Society of Civil Engineers (ASCE) announced in its 2021 Report Card for America's Infrastructure that stormwater infrastructure has received a 'D' grade. The primary study objective is to help decision-makers deal effectively with the control measures of the limited-budgeted, ambiguous and inconsistently applied operation and maintenance of stormwater infrastructures. A five-dimensional assessment model for operation and maintenance of stormwater control measures (5D-SAM) was developed, including location, quality, time/quantity, cost, and environmental aspects. The model is very effective in helping decision-makers identify the current stormwater infrastructure conditions, predict the future state, manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner. It helps determine whether a distressed stormwater system is beneficial to be demolished or it would be cost-effective to either repair, rehabilitate or retrofit. Moreover, the model can be utilized for fast and accurate assessment and better resource allocation for strategic planning of stormwater infrastructures.*

Key words: *assessment model, operation and maintenance, stormwater control measures, stormwater infrastructures*

Introduction and Problem Statement. United States' stormwater infrastructure is rated the lowest grade by the 2021 Report Card for America's Infrastructure (ASCE, 2021). This grade considered different aspects, such as capacity, condition, operations/maintenance, public safety, funding and resilience. The country has over 3.5 million miles of storm sewers with an overall age that exceeded or reached the end of their useful lives. Numerous of these systems have not been maintained to extend their lifespan. The paper also found that the majority of the stormwater lines in the U.S. are currently undersized to control the stormwater flow.

In urban areas, impervious surfaces such as roadways and roofs stop precipitation and melted snow from naturally running into the ground. Rather than water soaking rapidly into storm and sewer systems and drainage ditches, it can cause infrastructure damage, flooding, erosion, turbidity, combined storm and sewage overflow, and contaminated streams (U.S. EPA, 2022).

Flooding is the natural hazard with the most significant social and economic impact in the U.S. These impacts are becoming more critical over time. Catastrophic flooding caused billions of dollars in infrastructure damage, harmfully affected millions of people, and damaged economic welfare. Prominent urban flood cases between 2004 and 2014 cost an average of $9 billion in direct damage and contributed to 71 deaths annually. These figures do not contain the cumulative costs of common small floods, similar to those of infrequent severe floods (NASEM, 2019).

Stormwater infrastructure capacity can impact the hydrologic cycle by detaining or retaining stormwater runoff. Detention reduces peak discharge that increases runoff travel time or rate-controlled storage facilities. Increasing residence time may improve water quality by providing time for other treatment processes, such as sedimentation. The permanent capture of stormwater runoff by infiltration or evapotranspiration reduces the total runoff volume (The WE&RF, 2017).

The Municipal Water Infrastructure Council (MWIC), Green Infrastructure (GI) task committee of the Environmental and Water Resources Institute of the American Society of Civil Engineers (EWRI-ASCE) recognized a necessity for better tracking of operation and maintenance activities for stormwater infrastructures. To meet this requirement, the MWIC GI task committee developed a preliminary suggested list of the operation and maintenance parameters in 2018. These parameters form the foundation of a recommended database to store collected data. The main benefits are to provide recommendations for standardized operation and maintenance activity by local governments and a framework to develop a national cost database (WRF, 2018).

ASCE (2021) recommends specific ways federal funding can help create a stormwater-management network that accommodates changing weather patterns and increased flooding. Among other solutions, the report card authors suggest:

- developing a new federal-level stormwater funding program along with the existing ones,
- establishing a grant program to support training in the stormwater sector,
- extending eligibility for existing water-infrastructure grants to stormwater infrastructure
- promoting new stormwater utilities, and
- updating standards for stormwater infrastructure in response to climate change.

Unfortunately, there is not enough study in the literature on stormwater infrastructure sustainability and improvements considering multi-factors. Semanedi-Davies et al. (2008) studied the potential impacts of climate change and continued urbanization on stormwater flows to a suburban stream. They concluded that city growth and projected increases in heavy rainfalls, both together and alone, are set to raise peak flow volumes and increase flood risk. Conversely, the installation of a sustainable urban drainage system has a positive effect on the urban environment and can largely allay the adverse impacts of changing roads. Cherqui et al. (2013) conducted a survey on performance indicators related to urban drainage systems such as economic aspects, other environmental and sanitary, social aspects, lifespan and long-term effectiveness. Indeed, the performance of sustainable drainage systems should not be limited to pollution and hydrology. Petrucci and Tassin (2011) proposed an empirical approach to quantify the hydrographs' attenuation in sewers to evaluate attenuation's consequences for the scale transfer between the parcel and the catchment in urban settings. A sensitivity analysis on different pipes' and hydrographs' characteristics concluded that the peak attenuation's driving factors differ consistent with the distance from the outlet. The above studies are not comprehensive and do not discuss the multi-dimensions of stormwater assessment.

Research Objectives. A study is thus needed to evaluate the different aspects of stormwater infrastructure conditions. The research objective is to develop a theoretical Five-Dimensional Stormwater Assessment Model (5D-SAM) to analyze and help hydrologic engineers and planners choose the best feasible option with the limited-budgeted, ambiguous and inconsistently applied operation and maintenance of stormwater infrastructures. The paper imparts the rehabilitation of a stormwater system as a feasibility study for applying the proposed 5D-SAM. It presents the outline of the design system for the stormwater system retrofitting based on the performance-based design to satisfy an adequate required level concerning all required performance items, including structural safety and serviceability. The model helps decision-makers identify the current stormwater infrastructure conditions, predict the future state, manage the quantity and raise the quality of stormwater runoff in the most cost-effective manner. It helps determine whether a distressed stormwater system should be demolished or whether it will be cost-effective to either repair, rehabilitate or retrofit it. Moreover, the model can be used in a crisis for fast and accurate assessment and better resource allocation for strategic planning.

Research Scope and Limitations. The research focuses on developing the 5D-SAM model theoretical framework. A model testing and an ArcGIS database of the stormwater infrastructures will be implemented later in several cities in Utah, USA, to validate the proposed model's success.

Methodology. An appropriate rehabilitation method was selected among various alternatives and the performances of the retrofitted stormwater system by the selected method are verified with required performances after retrofitting until the end of service life. The concept is to convert any criteria in measurable values to the same scale. Steps in numerical analysis techniques and the evolution of precise simulation methods are considered. The Five-Dimensional Stormwater Assessment Model (5D-SAM) consists of ten modules to help the operation and maintenance assessment process (Askar, M. et al., 2022).

Stormwater Five-Dimensions:

The stormwater's five dimensions consist of location (X, Y, Z), quality/functionality, time, cost, and environmental/social aspects, as shown in Figure 1.

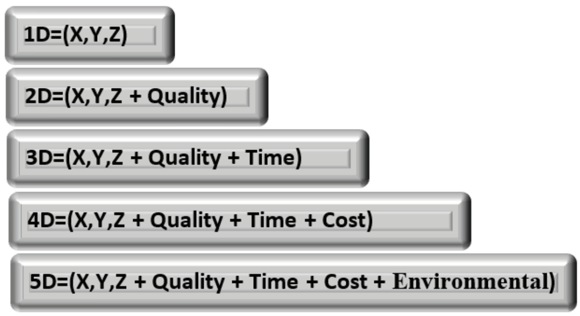

Fig. 1. Stormwater Five Dimension Model

Conceptual Design of the Five-Dimensional Stormwater Assessment Model

Any asset consists of several components with the same conditions at the design stage. However, after years of usage, the conditions of the components change and are not the same anymore. The primary idea of the stormwater assessment model is that the assessment is a result of a combination of different aspects, such as condition, functionality, time, cost, and environment. Furthermore, the stormwater infrastructure's repair cost depends on its components' condition. Two approaches were taken into consideration to achieve the research objectives (Figure 2):

1. The condition approach results from the stormwater's physical condition and structure load/capacity relations, and
2. The cost approach includes the Current Replacement Value (CRV) and Total Repair Cost (TRC).

Model Design and Analysis. Stormwater control measures (SCM) serve various purposes. From maintaining or improving a property's pre-development water quality and quantity conditions to promoting groundwater recharge and reducing downstream flooding and erosion to purely aesthetic considerations, every system is individually engineered to provide optimal performance for the watersheds.

The maintenance review includes the assessment of current maintenance tasks for several infrastructure types and aspects, which include the following:

- Drainage pump station maintenance (pumps and generators),
- Conveyance system cleaning and condition assessment,
- Maintenance hole cleaning, repair, and replacement,
- Drainage inlet and siphon cleaning,
- Channel maintenance,
- Basin and pond maintenance, and
- Access road and grounds maintenance.

Recommended modifications and additions to the current procedures are made to meet best practices and recommended regulatory guidelines. Detailed assessments and recommendations are proposed in the 5D-SAM below for each infrastructure type or aspect. Figure 3 shows the proposed performance-based operation and maintenance management model that considers the required corroboration of the whole stormwater infrastructure. This model consists of 10 modules; as follows:

1. Stormwater Condition Assessment Module,
2. Measurement Module,
3. Comparison Module,
4. Analysis Module,
5. Options Module,
6. Optimization Module,
7. Design Module,
8. Rehabilitation Module,
9. Re-measure Module, and
10. Final Assessment Module.

Module (1): Stormwater Condition Assessment. The condition assessment of an existing stormwater infrastructure determines whether the asset will function safely over a specified residual service life. Guidelines for the assessment of existing assets have been developed in many countries. They are commonly separated into phases, starting with a preliminary evaluation, followed by a detailed investigation, expert investigation, and finally, an advanced assessment, depending on the structural condition of the investigated stormwater facility. Based on the different applications of the selected articles, the relevant techniques are classified into five categories, as shown in Figure 4:

1. Visual Inspection (VI),
2. Testing Response (TR),
3. Finite Element Modeling (FEM),
4. Nondestructive Evaluation (NDE), and
5. Structure Health Monitoring (SHM).

Module (2): Measurement. Both performances of stormwater facilities and requirements should be expressed quantitatively.

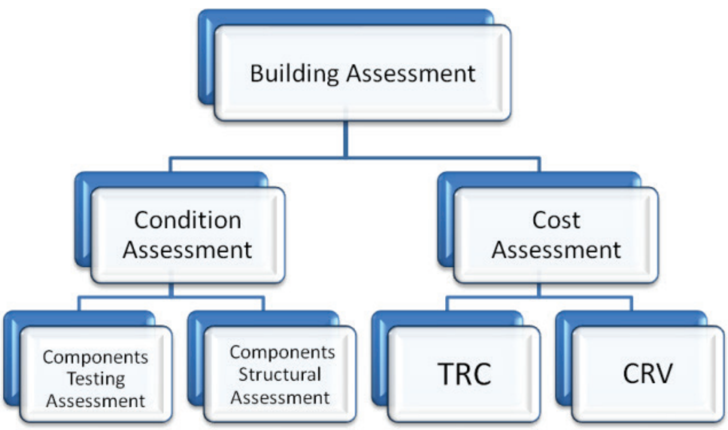

Fig. 2. Main Structure for Stormwater Facility Assessment

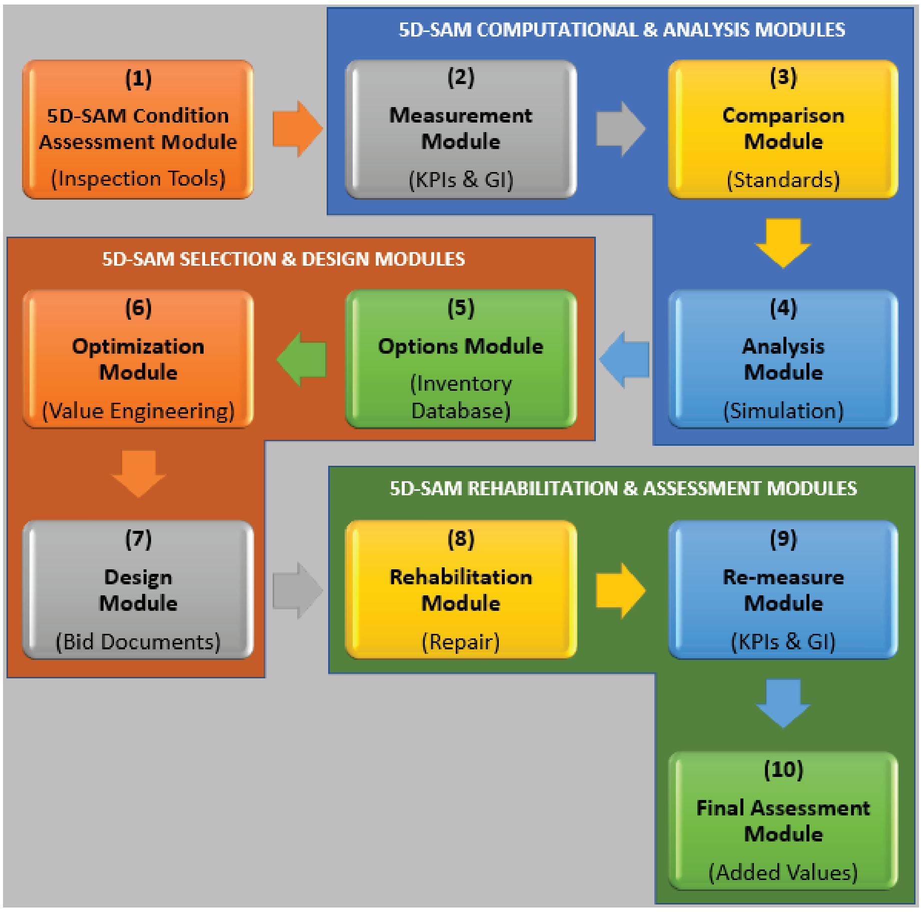

Fig. 3. Proposed stormwater assessment modules

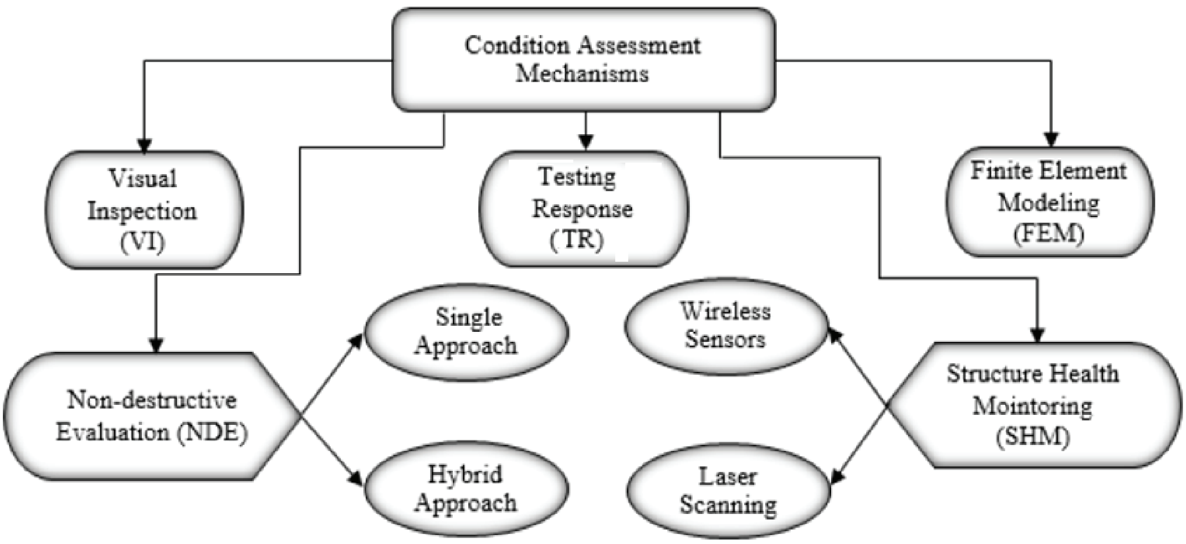

Fig. 4. Condition assessment mechanisms of a stormwater system

Hence, each performance item listed in Table 1 should be symbolized by a corresponding physical variable which can be evaluated through available computational methods. This variable is called a performance index. Table 1 (A-E) shows an example of performance indices for the selected performance items in this proposed operation and maintenance model of the stormwater control measure. The Overall Stormwater Asset Condition (OSAC) equation measures the stormwater infrastructure's general condition ratings (CAS) or performance/health index.

1. A. Performance indices for the Condition of the Stormwater Assets **(1. D = X, Y, Z)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
1	2	3	4	5	6
Stormwater Hydraulic Asset Condition (SHAC)	Indicating Pipes, Culverts, RCBs Damage Level S = Dia. or Width	Underground pipes to provide hydraulic control of surface flows from collection to treatment (Michael Baker International, 2017)			
	S ≤ 18 in.	Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 10 years 4–7 (Fair), if routine inspection bet. 10–12 years 1–4 (Poor), if routine inspection exceeds 12 years
	18 in. < S ≤ 48 in.		Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 5 years 4–7 (Fair), if routine inspection bet. 5–7 years 1–4 (Poor), if routine inspection exceeds 7 years
	48 in. < S ≤ 120 in.		Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 3 years 4–7 (Fair), if routine inspection bet. 3–5 years 1–4 (Poor), if routine inspection exceeds 5 years
	S > 120 in		Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 2 years 4–7 (Fair), if routine inspection bet. 2–3 years 1–4 (Poor), if routine inspection exceeds 3 years
	Indicating Drainage Inlets / Trench Drains Damage Level	Structures that include a drainage inlet and a sediment trap to store surface flows to allow sediment to accumulate			
		Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–5 years 1–4 (Poor), if routine inspection exceeds 5 years
	Indicating Manholes, Junction Boxes Damage Level	Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 5 years 4–7 (Fair), if routine inspection bet. 5–7 years 1–4 (Poor), if routine inspection exceeds 7 years
	Indicating Ditches, channels, swales, energy dissipaters Damage Level	Conveyance method used to reduce erosion, promote infiltration of runoff and settling of materials			
		Conveyance Asset State (VAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection every 5 years 4–7 (Fair), if routine inspection bet. 5–7 years 1–4 (Poor), if routine inspection exceeds 7 years

Continuation of Table 1. A

1	2	3	4	5	6
Stormwater Treatment Asset Condition (STAC)	Indicating Outfalls Damage Level	Locations where a pipe outlet meets criteria contained in the Department's Dry Weather Outfall Inspection Plan. The frequency of inspection of the Outfall of a pipe may differ from the required inspection frequency of the pipe itself			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Bioretention Basin / Bed Filter Damage Level	Basin or filter control structure and underdrain to collect treated water for transport to a discharge point			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Dry Basin / Detention basin Damage Level	Basin with outlet overflow to provide for storage and controlled sedimentation			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Gross Solids Removal Device (GSRD) Damage Level	The flow-through device removes trash, debris and coarse sediment in the water by capturing it in a tubular entrapment			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Infiltration Basin Damage Level	Basin used primarily for infiltration			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Infiltration Trench Damage Level	Infiltration system to temporarily store surface flows and divert underground by infiltration			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Spreading Structure / Level Spreader Damage Level	Structures that redistributes concentrated stormwater flow into sheet flow			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years

Continuation of Table 1. A

1	2	3	4	5	6
Stormwater Treatment Asset Condition (STAC)	Indicating Permeable Pavement Damage Level	An alternative to conventional asphalt and concrete in highly urbanized settings with low traffic speeds and volumes			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Sand Filter Damage Level	Structures that uses sand to remove sediment and pollutants from stormwater runoff through filtration			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection semi–annually 4–7 (Fair), if routine inspection bet. 1/2–1 year 1–4 (Poor), if routine inspection exceeds 1 year
	Indicating Sediment Trap / Traction Sand Trap Damage Level	Particle capture device connected to collection and conveyance system			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Wetland Damage Level	The permanent pond removes sediments and pollutants from stormwater runoff through physical, chemical and biological processes			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Hydrodynamic Separator Damage Level	The vault structure with various configurations to separate sediments from stormwater flows			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Tree Box Filter Damage Level	Designed to mimic natural systems such as Bioretention areas by incorporating plants, soil and microbes			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
	Indicating Vegetated Swale Damage Level	Vegetated channels that convey stormwater runoff as well as remove sediments and pollutants by filtration through grass and infiltration through soil			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years

End of Table 1. A

1	2	3	4	5	6
Stormwater Treatment Asset Condition (STAC)	Indicating Wet Basin Damage Level	The permanent pond removes sediments and pollutants from stormwater runoff through settling and biological processes			
		Treatment Asset State (TAS)	Semi-Deterministic (VI) & (TR)	Component	7–10 (Good), if routine inspection annually 4–7 (Fair), if routine inspection bet. 1–2 years 1–4 (Poor), if routine inspection exceeds 2 years
Stormwater Asset Structural Condition (SASC)	Indicating the instantaneous probability of failure	Probability of Failure (P_f)	Probabilistic	Section, Component & System	$P_f = P\left(M(t) \le 0\right) = \int_0^{\infty} F_R(x) f_Q(x) dx$, where R = Random resistance in a certain failure mode. Q = Random load effect in the same failure mode. $F_R(x)$ = Cumulative distribution function of R. $f_Q(x)$ = Probability density function of load effect Q.
	Providing a design margin over theoretical design capacity	Safety Factor in Allowable Stress Design (SF)	Deterministic	Section & Component	$SF = \frac{\sigma_u}{\sigma_{all}}$, where σ_u = Maximum usable stress, σ_{all} = Allowable stress.
	Ratio of the load-carrying capacity of the intact structure to the applied load	Reserve Strength Factor (R1)	Deterministic	Component & System	$R_1 = \frac{C}{Q}$
	The ability of a structure to prevent failure progression	Robustness (RO)	Probabilistic	System	RO, is one of the key measures in the field of progressive collapse and damage-tolerant structures
	Reduce probabilities and consequences of failure and recovery time	Resilience (RE)	Probabilistic	System	RE, can be measured by the infrastructure system functionality after a disaster and by the time it takes to return to pre-disaster levels of performance
Overall Stormwater Asset Condition (OSAC)	Indicating Overall Damage Level	Condition Asset State (CAS)	Deterministic (NDE) & (SHM)	System	$1 \le \text{CAS} \le 10$

1. B. Performance indices for the Functionality of the Stormwater System **(2. D = Quality/Functionality)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
1	2	3	4	5	6
Hydraulic Performance (HP)	Flow Attenuation at the Outlet (Cherqui, 2013)	Multiplicative and Additive Models (MAM)	Deterministic	Section, Component & System	$\frac{Q_{out}}{Q_{in}} = \left(a_0 + \sum_{i=1,3,4} a_i X_i\right)^{b+a_2 X_2}$ [5; 7]
	Volume Reduction at the Outlet (Cherqui, 2013)	Combined Sewer Overflows (CSO), m^3 (Niemczynowicz, 1989)	Probabilistic	Section, Component & System	It is calculated by applying statistical characteristics to several years of rainfall. It is possible to derive a parameterization of the rainfall input and the failure probability and return period of combined sewer overflow to receiving waters can be found
	Pumping Station Overflow (m^3) (Semanedi, 2005)	Dry Weather Flow (DWF)	Deterministic	Section, Component & System	A storage volume of 4 hours at Dry Weather Flow (DWF) shall be provided with DWF being calculated as follows: DWF (m^3/day) = $PG + E + I$, where P = Population in Catchment; G = Domestic Consumption m^3/hd/day); E = Industrial Flows (m^3/d); I = Infiltration (m^3/d)
	Overflow Frequency Indicator (Cherqui, 2013)	Total flow volume (m^3) CSO volume (m^3)	Simulation	Component & System	The overflow frequency of one per year (n = 1) depends on the rain series length, the total flow volume, and the CSO volume used for simulation
	Drainage Duration Frequency (Cherqui, 2013)	Time to peak discharge (time) Volume of peak discharge (m^3)	Deterministic	Component & System	It is calculated from the following formula (Darcy velocity with a hydraulic gradient equal to one)
Hydrological Performance (DP)	Runoff Frequency	Total runoff volume (m^3)	Simulation	Component & System	The runoff and rainfall frequency curves are parallel
	Mean Annual Runoff Volume	Runoff, precipitation, and actual evapotranspiration during year t	Deterministic	Component & System	$R_t = P_t - E_t = P_t - P_t F(\phi_t) = P_t[1 - F(\phi_t)]$ [5], where R_t, P_t, and E_t are runoff, precipitation, and actual evapotranspiration during year t, and $F(\phi_t)$ is a functional relationship relating actual annual evapotranspiration to annual precipitation during year t

End of Table 1. B

1	2	3	4	5	6
Hydrological Performance (DP)	Volume of Base Flow and the Stormwater released as Filtered Flows	Pipe flow ratio	Deterministic	Component & System	The pipe flow ratio is defined as $R_q = Q_1/Q_2$, where Q_1 is the flow at the main pipe 1, while Q_2 is the flow at the branch pipe 2.
	Volume of Inflow, Outflow, and Evapotranspired	Inflow to the sewer system (m^3) Inflow to WWTP (m^3)	Deterministic	Component & System	the inflow and outflow/overflow volume are calculated as: $Q_i = \frac{8}{15} utg \frac{\theta}{2} \sqrt{2gh^{2.5}}$ [7], where Q_i is the instantaneous flow of inflow and outflow/overflow, m^3/s
	Catchment-Scale Outcomes	Frequency of flood Duration of the flood (h)	Deterministic	Component & System	The flood frequency can be determined using instantaneous peak discharge data (Log-Pearson Type III distribution).

1. C. Performance indices for the Time-Effectiveness of the Stormwater System **(3. D = Time)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
Time Condition (TC)	Lifespan and Long-Term Effectiveness	Long-term functionalities	Modeling of Simulation	Component & System	▪ establishment period efficiency = f (vegetation establishment, microbial community assemblage, soil development); ▪ starting efficiency = f (design, installation, local conditions); ▪ efficiency for each storm event = f (storm event features, time of year, watershed conditions, BMP conditions during each storm event); ▪ efficiency between maintenance = f (engineered capability of practices, seasonal changes of vegetation); ▪ efficiency over life cycle = f (maintenance frequency, restored BMP perfomance, failure point); ▪long-term efficiency for each BMP and each environmental concern (runoff/pollutant) = f (establishment period efficiency, starting efficiency, efficiency for each storm event, efficiencybetween maintenance, efficiency over life cycle)
	Lag-Time	Monitoring and maintenance checklist Times	Probabilistic	Component & System	Creating manual outlines procedures and checklists as guidelines for the inspection, monitoring and maintenance.

1. D. Performance indices for the Cost-Effectiveness of the Stormwater System **(4. D=Cost)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
Environmental and Social Condition (ESC)	Pollutant Concentration Attenuation	Event Mean Concentration (EMC) for predicting water quality	Deterministic	Component & System	$EMC = \frac{\text{total pollutant loading per event}}{\text{total runoff volume per event}} = \frac{\sum_{i=1}^{n} V_i C_i}{V}$, where EMC is the event mean concentration, mg/L; V is the total runoff volume per event, L; V_i is the runoff volume proportional to the flow rate at the time i, L; C_i is the pollutant concentration at time i, mg/L; and n is number of samples during a single storm event
	Event-Based Pollutant Removal	(%)	Deterministic	Component & System	$Removal\ (\%) = \frac{\sum Inlet\ loading - \sum Outlet\ loading}{\sum Inlet\ loading}$
	Pollution Retention Performance	Pollutant removal rates	Semi-Deterministic	Component & System	$PR_{tot} = (RVR \times PR_{ret}) + ((100 - RVR) \times PR_{over})$, where PR_{tot} is the percent annual pollutant removal rate; RVR is the percent annual runoff volume retained; PR_{ret} is the percent annual pollutant removal rate applied to the yearly water volume retained (RVR) by the BMP; and PR_{over} is the percent annual pollutant removal rate applied to the yearly water volume routed downstream
	Percentage of Satisfaction	Customer satisfaction	Semi-Deterministic	Component & System	Questionnaire
	Level of Security for the Staff or the Public	Accident frequency rate Accident severity rate Composite Index	Semi-Deterministic	Component & System	Frequency rate = (number of disabling injuries/number of man-hours worked) × 1000,000; Injury severity rate = (number of work-days lost + light-duty days lost) × × 200,000 / total hours worked; Composite index of the frequency rate = the average time loss per case

1. E. Performance indices for the Environmental and Social Impact on the Stormwater Assets **(5. D = Environmental)**

Category	Item Description	Indicator Designation	Assessment Mechanism	Level	Indicator Formula
Cost Condition (CC)	Optimize Preliminary Costs	Value Engineering	Deterministic	Component & System	Implement the systematic approach of VE including all phases: (1) General phase, (2) Information phase, (3) Function phase, (4) Creation phase, (5) Evaluation phase, (6) Investigation phase, and (7) Recommendation phase.
	Optimize Construction Costs	Value Engineering	Deterministic	Component & System	
	Optimize Operational Costs	Value Engineering	Deterministic	Component & System	
	Savings/Return on Investment	Value Engineering	Deterministic	Component & System	

Module (3): Comparison. 5D-SAM calculates the general condition ratings (GCRs) to describe the existing, in-place stormwater infrastructure compared to the as-built condition. The physical, structural condition, functionality/quality, time, cost, and environmental/social aspects are considered. This information is used to determine the GCRs on a numerical scale of 0–9. 0 refers to (failed condition) while 9 is (excellent condition), as described in the Coding Guide (Table 2) and the Equation: $1 \leq GCR \leq 9$

Module (4): Analysis. After almost four decades of use, the general condition ratings are well established in assessing the current condition of the major components of the stormwater infrastructure being inventoried and inspected. The same GCR is true of the appraisal ratings for assessing functional capacities. Changes in these ratings over time reflect the general performance of the stormwater infrastructures. The ratings are used to classify the assets as deficient or not deficient.

Stormwater infrastructures with low GCR condition or appraisal ratings are flagged and classified as follows:

• **SD**: A stormwater asset is classified as structurally deficient if the item Overall Stormwater Asset Condition (OSAC) is rated «poor» condition or worse (coded 4 or lower on the 5D-SAM rating scale).

• **FO**: A stormwater asset classified as functionally obsolete is not SD, but its Hydraulic Performance (HP), Hydrological Performance (DP), and Environmental/Social Aspects are outdated. Classification as FO is triggered by a code of 4 or lower for the three items.

Module (5): Feasible Rehabilitation Strategies. This model establishes existing asset conditions, preservation, rehabilitation, and replacement inventory database guidelines. The determination of the most appropriate intervention for existing stormwater infrastructure is primarily based on the following factors:

- Operation and maintenance conditions
- Stormwater infrastructure conditions
- The extent of corrosion in existing asset
- The extent and widths of cracks
- Functionality conditions
- Strength of materials

The cost analysis of preserving the existing asset should consider the following, as applicable:

- Preserving or replacing the stormwater items
- Effects associated with the elimination of cracks
- Repairing stormwater components
- Impact strengthening on stormwater components with a history
- Mitigating effects of functionality deficient
- Replacing severely corroded or non-functional items
- Adding possible redundancy to system components
- Seismic retrofit, if needed

Module (6): Optimization by Value Engineering. The stormwater asset health index concept is based on a ratio of the current element to the total element values. The health index formulated ranges between 0 % and 100 %. The 5D-SAM rating of 6.9 may be comparable to a health index of 77 %.

2. Common Actions Based on the General Condition Ratings

Code	Description	Common actions
9	EXCELLENT CONDITION	Preservation / Cyclic maintenance
8	VERY GOOD CONDITION – No problems noted	
7	GOOD CONDITION – Some minor problems	
6	SATISFACTORY CONDITION – Structural elements show some minor deterioration	Preservation / Condition-based maintenance
5	FAIR CONDITION – All primary structural elements are sound but may have some minor section loss, cracking, spalling, or scour	
4	POOR CONDITION – Advanced section loss, deterioration, spalling, or scour	Rehabilitation or Replacement
3	SERIOUS CONDITION – Loss of section, deterioratuion, spalling or scour have seriously affected primary structural components. Local failures are possible	
2	CRITIAL CONDITION – Advanced deterioration or section loss present in critical structural components	
1	IMMINENT FAILURE CONDITION – Major deterioration or section loss present in critical components	
0	FAILED CONDITION – Out of service, but beyond corrective action	

Module (7): Design. A new structural and/or hydraulic design of the stormwater infrastructures should be considered for cases of health indices less than 40 %.

Module (08): Stormwater Asset Rehabilitation. Rehabilitation involves major work required to repair the structural integrity of a stormwater asset and work necessary to correct major safety and functionality defects. Stormwater asset rehabilitation projects provide complete or nearly complete restoration of elements or components. Rehabilitation work can be done on multiple elements and components of a structure. Agencies may choose to combine preservation activities on several elements while rehabilitating a component. These projects require significant engineering resources for design, a lengthy completion schedule, and considerable costs. Total replacement of an existing stormwater system with a new facility constructed in the same system requirements must meet the facility's current design aspects and needs over its design life.

Module (09): Re-measure. Inventory items pertain to stormwater infrastructure's characteristics. These items are permanent characteristics for the most part, which only change when the asset is altered in some way, such as rehabilitation. So, inventory items should be replaced after rehabilitation and include the following items:

• Identification – Identifies the structure using location codes and descriptions.

• Structure Type and Material – Categorizes the structure based on the material, design and construction, and wearing surface.

• Age and Service – Information showing when the structure was constructed or reconstructed features the structure information.

• Geometric Data – Includes pertinent structural dimensions.

• Design Aspects – Includes the structural and hydraulic design.

• Navigation Data – Identifies the existence of navigation control, protection, and waterway clearance measurements.

• Classification – Identifies the classification of the structure.

• Required Inspections – Includes designated inspection frequency and critical features requiring special inspections or special emphasis during the inspection.

Module (10): Final Assessment and Solutions to Green Stormwater Infrastructure. The final rehabilitation assessment will be completed and recommendations for green stormwater infrastructure will be proposed involving media filtration, infiltration, ponds, facility design requirements, detention structures, distribution pipes, pumps, basins, and permeable pavements. These items tend to be widely implemented and often unsatisfactorily maintained (Erickson et al., 2013). Guidelines and examples for green stormwater infrastructure solutions will be based on recent scientific research and practitioner experience. Inspection and maintenance examples will be provided in the next research and drawn from practical examples and maintenance suggestions depending on regional characteristics.

Conclusion. The maintenance of stormwater control measures is essential for efficient water management. Very often, some parameters are missing or are expensive to measure. Because of many influential factors, it is challenging to precisely predict the operation and maintenance. Some of which can be changed easily and quickly, but also because of the consequences due to incorrect predictions. The 5D-SAM is beneficial for this purpose to support the final decision that can be made based on a probability distribution. Further, in the 5D-SAM model, the parameters are conditionally independent; thus, it is easy to manipulate the data (add, delete, change) within the ten modules. Finally, the model in this work accurately predicts the optimal solutions and gives correct results when some data are missing.

Recommendations. As a recommendation for future studies, a more rigorous analysis with more variable parameters for minute-level accuracy could be performed. Real-world validation is another scope.

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П'ЯТИВИМІРНА МОДЕЛЬ ОЦІНКИ ЕКСПЛУАТАЦІЇ ТА ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ ЗАХОДІВ ПО БОРОТЬБІ ЗІ ЗЛИВОВИМИ ВОДАМИ – ІНСТРУМЕНТ СТРАТЕГІЧНОГО ПЛАНУВАННЯ І КРИЗОВОГО УПРАВЛІННЯ

М. Аскар[1], доктор філософії, та М. Іслам[2], доктор філософії

[1] Університет Південної Юти, інженерно-технічний відділ, США, асоц. проф.,
e-mail: mohamedaskar@suu.edu;
[2] Університет штату Колорадо-Пуебло, факультет цивільної інженерії, США, асоц. проф.,
e-mail: md.islam@csupueblo.edu

Анотація. *У Сполучених Штатах більшість систем зливової каналізації старіють і руйнуються. Американське товариство інженерів-будівельників (ASCE) у своєму звіті про американську інфраструктуру за 2021 рік оголосило, що дощова інфраструктура отримала оцінку «D». Основна мета дослідження полягає в тому, щоб допомогти особам, які приймають рішення, ефективно впоратися із заходами контролю обмеженого бюджету, неоднозначного та непослідовного застосування експлуатації та обслуговування дощової інфраструктури. Було розроблено п'ятивимірну модель оцінки експлуатації та обслуговування засобів контролю зливових стоків (5D-SAM), включаючи аспекти розташування, якості, часу/кількості, вартості та екологічних аспектів. Модель дуже ефективно допомагає особам, які приймають рішення, визначити поточний стан зливової інфраструктури, спрогнозувати майбутній стан, керувати кількістю та покращити якість зливових стоків у найбільш економічно ефективний спосіб. Це допомагає визначити, чи доцільно знести пошкоджену дощову систему чи її ремонт, реконструкція чи модернізація буде економічно ефективним. Крім того, модель може бути використана для швидкої та точної оцінки та кращого розподілу ресурсів для стратегічного планування інфраструктур зливової каналізації.*

Ключові слова: *модель оцінки, експлуатація та технічне обслуговування, заходи з контролю зливових стоків, зливові інфраструктури*