Future-proofing stormwater systems for resilient communities

DAVID RUBINSTEIN, CEO, OptiRTC, Inc., Boston, Massachusetts

ABSTRACT | The escalating challenges of unpredictable weather patterns, rapid urbanization, and constrained public budgets demand a fundamental shift from reactive to proactive stormwater management. This paper introduces continuous monitoring and adaptive control (CMAC), also known as real-time control, to address these challenges. CMAC integrates weather forecasts and real-time sensor data to autonomously manage stormwater facilities, thereby providing an adaptable, equitable, and sustainable approach to managing water infrastructure that enhances community resilience and fosters long-term environmental sustainability. Case studies show CMAC's ability to reduce capital and operational costs, prevent combined sewer overflows, and create high-performing, future-proofed infrastructure that can adapt to evolving regulatory and climate realities. This article provides a comprehensive and practical guide for water professionals, discussing best practices for successful CMAC adoption—from systematic site assessment and navigation of the regulatory landscape to strategic vendor selection and robust project management best suited for an advanced digital infrastructure.

KEYWORDS | MS4, public outreach, stormwater utility, water quality, asset management, capital planning

The stormwater industry's current management approach is based on using passive infrastructure to capture and treat the runoff from a static design storm. This "design storm" is a fixed, historical rainfall event of a specific intensity and duration (e.g., a "100-year storm") that is assumed to represent the worst scenario. However, this methodology creates significant challenges in the era of climate change. Because historical data no longer accurately predict future weather, this rigid infrastructure is often undersized for the more frequent and intense storms of today, leading to widespread urban flooding, costly damage, and increased water pollution.

The maxim "change or die" certainly holds true for the stormwater industry. Technological advancements have rendered the reliance on passive, costly stormwater infrastructure obsolete, as this reactive, "set-it-and-forget-it" model is proving to be an inflexible and unreliable defense against modern climate realities. From an environmental perspective, a failure to embrace these advancements and alter our approach to managing stormwater will undoubtedly lead to adverse consequences for all. A paradigm shift is imperative; future development cannot be predicated on historical precedents. What was once considered a 100-year design storm has been reclassified, and precipitation patterns are demonstrating increased intensity. Meanwhile, four 1,000-year storms occurred across the United States this year alone (NBC News, 2025). Instead of adhering to outdated design-storm methodologies, a more agile and adaptable approach to stormwater challenges is required.

The software industry offers a valuable example. In the nascent stages of data processing, software development adhered to a "waterfall methodology," encompassing sequential phases of requirements gathering, design, construction, testing, and implementation (Atlassian, n.d.-b). By the time software was disseminated to users, business requirements had often become obsolete, leading to user frustration and exacerbating, rather than resolving, business challenges. The industry subsequently transitioned to the "agile methodology" in the 1990s, thereby facilitating rapid advancements in computing and at a reduced cost and risk compared to the former waterfall approach (Atlassian, n.d.-a).

Does this resonate? When a community endures prolonged waiting periods for a capital improvement plan, the original requirements become outdated, and costs invariably escalate. The integration of technology into infrastructure, combined with a design-bid-build framework, increases risk and cost. The business sector abandoned the design-bid-build model for software development with the advent of agile methodologies precisely for these reasons—to mitigate time, risk, and cost, while delivering superior outcomes.

The stormwater industry should consider a similar approach and transition to proactive, adaptable stormwater control systems. With increasing urbanization, today's passive facilities rapidly become obsolete. Passive facilities cannot react to forecasted and real-time conditions nor can they adapt when objectives change over time. The solution cannot always be to "build another storage basin" or "dig a deeper tunnel."

Stormwater management becomes much more efficient, cost-effective, and beneficial through technology. This concept is familiar, considering the technological advancements that have revolutionized outdated methods and best practices (e.g., the transition from rotary phones to smartphones, or retail on-site shopping to e-commerce). Our communities should, therefore, reap the benefits of these technological advancements. My experience confirms that change fosters opportunities.

SMART STORMWATER MANAGEMENT

Contemporary stormwater management has evolved into a future-proofing solution facilitated by continuous monitoring and adaptive control (CMAC), also referred to as real-time control. CMAC optimizes stormwater storage by integrating weather forecasts with real-time data to autonomously control facility operations. For example, the system can automatically lower water levels before a forecasted storm, increasing effective storage capacity by 40 to 60 percent to capture the anticipated runoff. Passive systems lack this capability, as their drawdowns are gravity-dependent, analogous to the outflow in a bathtub. CMAC can simultaneously address other site-specific objectives, such as modulating valves and gates to mitigate downstream erosion. This smart technology involves issuing commands that initiate actions based on real-time data, providing "instant, actionable insights," and eliminating the need for human intervention, keeping personnel safe during storm events. This approach minimizes dependence on an operator's manual input, as the system autonomously executes actions, continuously refines its algorithms, and provides real-time data for subsequent analysis.

CMAC technology offers numerous advantages that passive facilities cannot:

- Facilities can be retrofitted with CMAC technology, increasing capacity by 40 to 60 percent at approximately one-tenth of the cost of altering a facility or constructing a new one.
- CMAC is an optimal solution for urban environments where land is costly and constrained. New stormwater facilities may be eligible for downsizing due to the 40 to 60 percent capacity increase provided by CMAC. In one example, a private landowner saved $2 million by eliminating one of two underground detention facilities as a result of CMAC implementation.
- Stormwater can be leveraged as an asset through rainwater harvesting and reuse systems for property irrigation or other on-site water uses. One CMAC user reports annual savings on the municipal water bill of $80,000 by integrating rainwater harvesting with a retrofitted stormwater facility. This also contributed to an additional three Leadership in Energy and Environmental Design (LEED) credits, elevating the property to Gold certification.
- CMAC facilities can be interconnected to form a smart watershed network, which can deliver superior performance compared to the individual performance of each site. A smart watershed network integrates sensor readings from upstream and downstream locations, including the wastewater treatment plant, an effective strategy for reducing combined sewer overflows (CSOs).
- CMAC facilities demonstrate significant resilience, mitigating future damage. A recent study showed that every $1 invested in resilient solutions can save $10 in disaster recovery (WRI, 2025). As a future-proofing technology, CMAC provides long-term sustainability and resilience through real-time adaptation and controls.
- CMAC systems are highly intelligent and configurable. The extensive data collected provide insights into facility performance. In the event of regulatory changes, software configuration adjustments enable the system to adapt, whereas a passive system may increase construction expenses. The system can also alert operations and maintenance personnel to any behavioral anomalies within the facility.

CMAC provides an agile approach to community protection, bypassing lengthy and expensive capital planning to immediately address the most critical needs and deliver climate justice to vulnerable areas. Stormwater facilities can be implemented quickly and networked together over time, achieving long-term resilience goals without the cost and delay of a traditional capital plan. As an adaptive technology, CMAC provides a future-proof solution that ensures lasting sustainability, major cost savings, and peace of mind that comes from a system built to respond to real-time conditions.

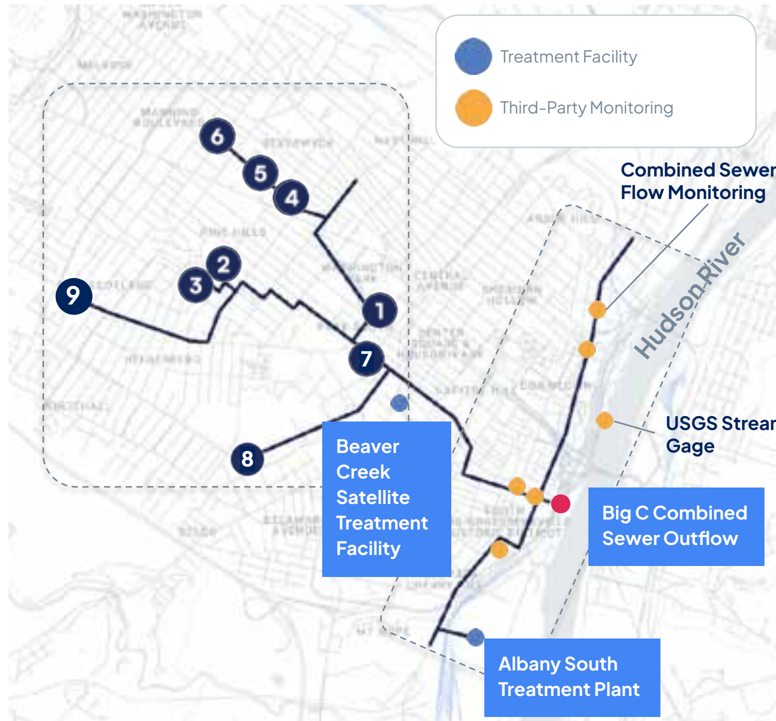

Figure 1. Map of the smart watershed network in the city of Albany, New York

CASE STUDIES

Apartment Complex in Bronx, New York

Developers of a 123-unit affordable housing complex in the South Bronx faced a dual challenge: maximizing rainwater harvesting to supply a 10,000 ft^2 (929 m^2) rooftop greenhouse while minimizing stormwater pollution entering New York City's waterways. Additional objectives included earning and maintaining LEED credits for water conservation and meeting strict regulations for mitigating CSOs.

CMAC was included in the system's design to control the timing of water discharge from a 15,000 gal (56,780 L) cistern. Using National Weather Service forecasts, the CMAC software predictively draws down the water level in the cistern ahead of a storm to maximize rainfall capture. Afterward, the captured water is retained for reuse.

Property managers use CMAC's web-based dashboard to monitor performance statistics, review historical data summaries, and enable automatic control of the outflow valve. The CMAC platform also helps them prepare quarterly reports with performance data to achieve environmental compliance and maintain building LEED Platinum and other certifications.

Within one year, the CMAC system increased efficiency by 4.6 times compared to traditional passive management. By adding CMAC climate adaptive controls, the developer achieved the following:

- Converted a passive system with two cisterns for storing 134,650 gal (509,705 L) to a CMAC active system requiring one cistern for storing 15,560 gal (58,900 L), thereby reducing capital expenditures
- Reduced the footprint needed by relocating the cistern under a parking lot, creating space for alternative use and additional revenue
- Prevented sewer overflows while reusing stormwater on-site to achieve LEED credits, thereby reducing potable water bills and operational expenditures

Smart Watershed Network in Albany, New York

Albany's largest sewershed, the Beaver Creek District, historically discharged over 530 MG (2,006 ML) of CSOs annually to the Hudson River. In response, the Albany Water Board launched an integrated plan featuring green, grey, and technological solutions. As the plan's core technology, the CMAC solution actively controls 17.5 MG (66.2 ML) of storage capacity to help solve the problem.

The smart watershed network consists of monitoring stations and eight stormwater facilities that use CMAC to control and coordinate the timing and rate of discharge based on weather forecasts and real-time data. The customer's platform receives monitoring data from three sources—two treatment facilities, four sewer monitoring sites, and one U.S. Geological Survey gauging station. The data show asset status, performance, and maintenance needs, allow early detection of potential problems and impending flooding, and inform decisions on the release of stormwater from CMAC sites.

Several stormwater facilities were retrofitted and enhanced by incorporating CMAC. Washington Park Lake, originally separated from the combined sewer, was retrofitted with CMAC controls to create 7 MG (26.5 ML) of storage that protects the downstream sewer system. A West Lawrence Street box culvert as well as two underground detention facilities were retrofitted with CMAC controls to allow intelligent runoff management that prevents CSOs and promotes infiltration by using coordinated, timed drawdown logic with other in-line facilities. Several new green infrastructure facilities were constructed throughout the sewershed as well. These include an underground infiltration gallery and stormwater harvesting facility in Woodlawn Park, and two constructed wetland systems.

This system integrates eight CMAC facilities with data from third-party monitoring stations. Releases from the CMAC facilities are coordinated with real-time monitoring data to strategically reduce wet weather contributions to the combined sewer system (Figure 1).

Together, the new and retrofitted facilities create the eight-facility smart watershed network. The CMAC system functions like a traffic control network to prevent CSOs into local waterways, with its actions guided by water levels at the "Big C" CSO outfall (Figure 1). Under normal conditions, the eight upstream control sites operate independently, managing water flow based on local data. However, during heavy rain, if the water level at the "Big C" rises to a predetermined height, a central network command activates. This central command overrides the local sites and closes their outlet valves, temporarily holding water back to prevent them from adding additional stormwater to the combined sewer. Once levels within the sewer system have decreased, normal, independent operation resumes at each site.

The smart watershed network provides many benefits to the Albany community, including CSO and flood mitigation and operational insights for targeted operations and maintenance. Prior to CMAC implementation, the system's wet weather capture was estimated to be only 10 to 20 percent of the annual stormwater runoff volume. By creating a smart watershed network, the wet weather capture rate increased to approximately 90 percent. In 2024 alone, almost 200 MG (760 ML) of stormwater were retained during wet weather, thereby greatly reducing contributions to the combined sewer system (Figure 2).

Wet weather flow volume reductions, as determined by using observed data, are presented in Figure 2 as a percentage of the annual total volume of stormwater runoff reduced (in millions of gallons). The system was modeled as a passive system (i.e., without CMAC), and wet weather volume reductions are shown for comparison. Veterans Health Administration Medical Center detention basin and Academy Road constructed wetland sites are not included, as they were commissioned in late 2024.

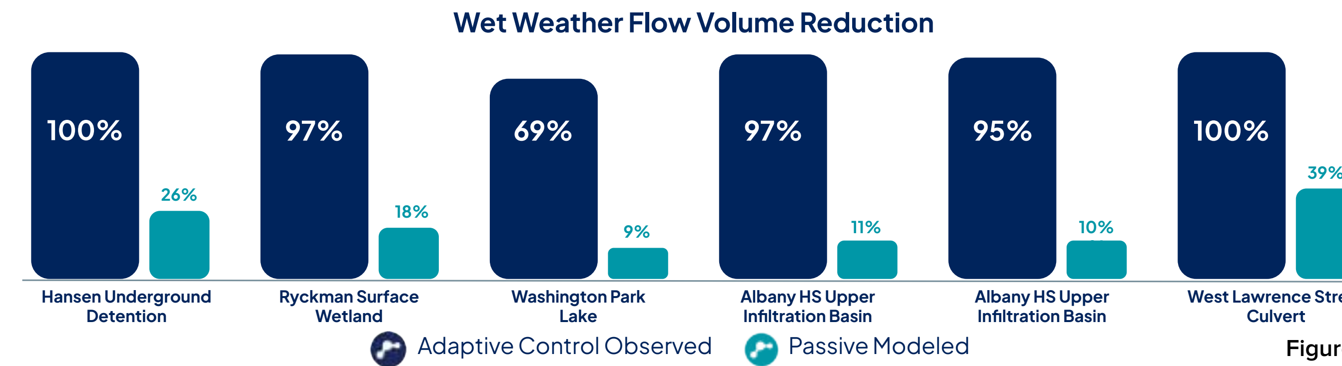

Figure 2. 2024 Wet weather flow volume reductions

BEST PRACTICES FOR IMPLEMENTING A CMAC SYSTEM

Site Assessment Framework

Before starting a CMAC project, the regulatory environment must be assessed and a site chosen that is conducive to CMAC implementation.

Navigating the regulatory landscape is a critical first assessment step. Some agencies seek CMAC solutions and are integrating them rapidly, while others may resist such changes. Moreover, regulations are not one size fits all; they can vary significantly based on federal, state, and local mandates. For example, while EPA sets national standards under the Clean Water Act, state and local agencies often have their own requirements and permitting processes. Understanding the rules that govern each facility is fundamental.

Before implementation, the following questions should be explored and answered:

- Can we achieve our specific regulatory goals—such as CSO reduction or water quality targets—with a CMAC system in our facilities?
- Which flow, volume, and pollutant regulations apply to each facility, and how will the system address them?
- Are there other applicable requirements, such as long-term control plan mandates, consent decrees, or watershed management goals?

Treating regulators as key stakeholders rather than hurdles is crucial, and this begins with early and continuous communication. Proactively engaging with regulatory bodies allows the agency to educate them on CMAC technology, build trust through a commitment to transparency, and collaboratively identify potential concerns before they become problems. This transforms the relationship from a simple compliance check into a true partnership focused on the shared goals of protecting water quality and community safety.

To satisfy regulators, the goal is to show that a CMAC system is a reliable and effective tool that will meet or exceed their mandates. A strong case should highlight how the system enhances control to manage flows and storage, minimizing downstream impacts. This is complemented by superior data, as high-resolution information offers unprecedented insight into more transparent reporting. Together, these features offer clear performance verification, using a data-backed record of operations to prove a commitment to protecting the community and the environment.

The second assessment step involves evaluating site suitability for CMAC implementation. Retrofitting a stormwater facility is often the most strategic starting point for a CMAC program due to its rapid implementation timeline and significantly lower cost than construction of a new facility. An underground detention facility can be retrofitted and made operational within four to eight weeks, while a stormwater pond can be retrofitted and made operational within 16 to 24 weeks; new construction projects can take months or even years to complete, extending the time to value realization.

A successful CMAC retrofit hinges on a systematic qualification process that evaluates a site's strategic objectives, technical feasibility, downstream impact, and logistical viability, as outlined below:

1. Define site objectives: Clearly establish the primary and secondary goals for the CMAC system. Common objectives include water quantity control (flooding), water quality enhancement, or channel protection. This will determine the required control logic and performance metrics.
2. Assess physical and hydrological feasibility:
   - Calculate Active Storage Volume: Determine the volume of water below the primary outlet that can be controlled by a valve or gate. A facility with significant active storage is a strong candidate.
   - Analyze Site Hydrology: Use hydrologic and hydraulic (H&H) models to understand the runoff characteristics (volume, timing) from the upstream catchment area.
   - Evaluate Outlet Structure: Confirm that the outlet is suitable for a retrofit. A single, concentrated low-flow outlet is ideal for installing an automated valve or gate.
3. Evaluate downstream network impact: Analyze the facility's role within the broader conveyance system. Use a hydraulic model to simulate CMAC control strategies and ensure that managed releases will not create or worsen downstream problems, such as flooding or erosion at vulnerable areas like undersized culverts.
4. Confirm logistical viability: Assess the practical aspects of installing and operating the system at the site. This includes the following:
   - Access: Ensure there is reliable, year-round access for installation and maintenance.
   - Power: Identify a continuous power source (grid connection is ideal; otherwise, evaluate solar feasibility).
   - Data Connectivity: Verify the site has a reliable data connection (e.g., cellular signal) for transmitting data and receiving commands.
   - Ownership: Resolve any land ownership or access easement issues.

A comprehensive analysis of these factors is critical to ensure that a CMAC retrofit will be both technically feasible and effective in achieving the operational objectives.

Implementing CMAC in a new development project offers a different opportunity compared to retrofitting. Instead of adapting to a facility's constraints, engineers can holistically design the stormwater management system around active control from the project's inception. This integrated approach can optimize the facility's footprint, potentially reducing land acquisition and earthwork costs by designing a smaller, more efficient basin that leverages technology rather than sheer volume. While the upfront budget must account for the technology and hardware, these costs can be offset by the savings in land and construction, making it financially viable for creating a high-performance, "future-proofed" development.

PROJECT MANAGEMENT

Research from the *PM World Journal* on information technology (IT) project failures offers a critical insight: Technology is rarely the cause of failure (Arcidiacono, 2017). Instead, projects typically fail due to human factors like poor stakeholder commitment, team misalignment, or an unclear return on investment. This principle applies to any complex initiative, and it is especially true for CMAC implementation, which inherently crosses departmental lines from engineering and regulatory to operations and maintenance. Therefore, successful implementation must begin with a focus on engaging the entire team and all stakeholders.

Treating CMAC implementation as an organizational change initiative is crucial. All stakeholders must be involved, engaged, and committed for alignment among people, processes, and the technology itself. Figure 3 illustrates a proven framework for managing such change, showing that five key

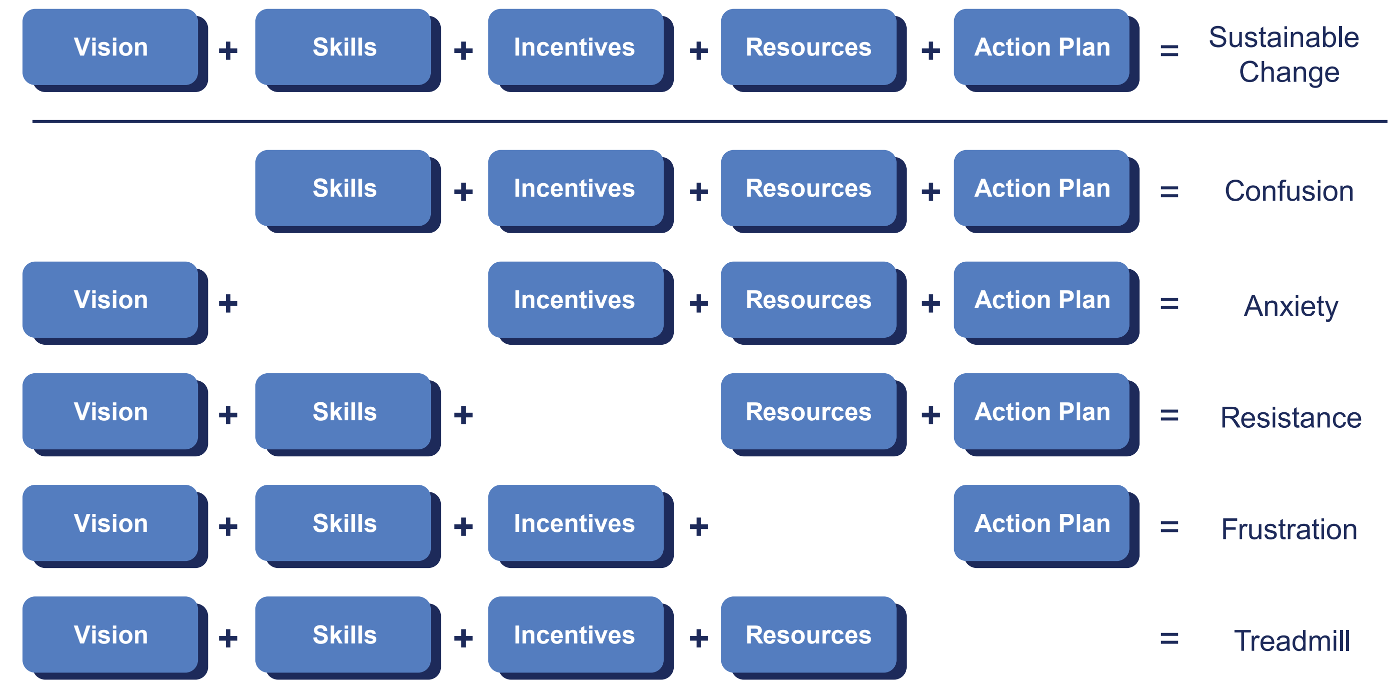

Figure 3. A framework for thinking about systems change

Adapted from Knoster, T., Villa, R., & Thousand, J. (Eds.), *Restructuring for caring and effective education: Piecing the puzzle together* (pp. 93-128). Baltimore: Paul H. Brookes Publishing Co. (2000).

components—vision, skills, incentives, resources, and an action plan—are essential. The absence of any single component can result in confusion, resistance, or frustration, hindering progress.

With this focus on people and process in mind, organizations can avoid two common pitfalls. The first is mistakenly treating technology as an afterthought, which significantly diminishes the likelihood of success. A proactive "involvement strategy" from the start is important. The second pitfall is in vendor selection; choosing a vendor based on the lowest price raises risk. Instead, the selection process must prioritize a partner's qualifications and delivered value, as this is a determining factor in achieving the desired outcome.

VENDOR SELECTION

The selection of a CMAC vendor requires an assessment of both software capabilities and technical infrastructure, encompassing cybersecurity, disaster recovery, and redundancy. This enumeration is not exhaustive, and many organizations may benefit from involving their IT department in evaluating technology vendors.

Since CMAC is a new software application, it's crucial to evaluate a vendor's maturity beyond just its hardware and software. When assessing CMAC vendors, it is imperative to confirm that the vendor possesses a documented implementation methodology that outlines roles and activities for your team and its affiliates. The presence of such a methodology signifies an experienced vendor committed to continuous improvement of its product and implementation services.

From a personnel perspective, it is desirable for the vendor to show extensive experience in software architecture, software engineering, and development operations. These core competencies are indispensable for any commercially viable software product. It is common for a new software application domain to feature numerous vendors that have rapidly developed the application yet lack critical software infrastructure components. Such solutions typically have a curtailed lifespan, often presenting cybersecurity vulnerabilities, scalability limitations, and designs not conducive to software upgrades. These capabilities are vital for sustained application performance and optimal outcomes.

CMAC SOFTWARE DESIGN

Software functionality and cybersecurity infrastructure are two core elements with CMAC software design.

Software Functionality

When evaluating software functionality, the focus should be on its capacity for predictive, data-driven control, which can be configured for one objective, like flood control, or for multiple objectives, such as simultaneously managing water quality and peak flow mitigation.

The system's cornerstone is its control logic. At a minimum, a CMAC platform should be able to perform forecast-based pre-event drawdowns to create storage capacity ahead of a storm, extend post-event retention durations, and modulate releases during wet weather to reduce peak flow. The software should also be able to manage both dry- and wet-weather target water surface elevations. Critically, this site-specific control logic should be flexible and easily configurable by users through an intuitive online interface.

A CMAC platform's intelligence is driven by its ability to integrate diverse data sources to make predictive decisions. CMAC should integrate with internet of things (IoT) technology for sensor data and leverage real-time weather forecasts from sources like the National Oceanic and Atmospheric Administration. A vital architectural feature is that the platform should be "sensor agnostic" with a robust application programming interface (API). This ensures the system can use a customer's monitoring networks and integrate with third-party sensors, actuators, and supervisory control and data acquisition systems, maximizing flexibility and protecting infrastructure investments.

For the stormwater operator, system management and performance verification are critical success factors. The software should provide user-specific dashboards that display real-time conditions and on-site operating parameters. The system should be able to summarize and display site data by individual storm events, essential outcomes for analysis, and regulatory reporting. To ensure timely responses, it should also be able to send automated email alerts to users based on configurable thresholds relating to current and future site conditions.

Cybersecurity Infrastructure

Cybersecurity is top of mind for all of us; it is in the news almost every day.

A CMAC platform must offer secure, continuous access to designated sites, built on robust security with strong encryption. Ideally, there should be single sign-on support and the option for multi-factor authentication, similar to many smartphone apps.

Security certifications such as SOC-II (Systems and Organization Control 2) tell us the vendor has wisely invested in cybersecurity. SOC-II is a security framework that specifies how organizations should protect customer data from unauthorized access, security incidents, and other vulnerabilities.

For a CMAC system, cybersecurity should also provide the following protections:

- Security for end-user sign-on and system administration
- A secure cloud environment that detects intruders
- A secure IoT layer that detects intruders

A cyber hack is a matter of "when" and not "if." When the system detects an intruder, end users should be notified and the system set into "manual mode." Manual mode turns the CMAC facility into a passive facility while intrusion detection is in process. During this process, all data should continue to be collected at the stormwater facility location. Once the intrusion process is completed (i.e., the system is secured), the system can be placed back in automatic mode. All data collected during the intrusion process should be loaded into the CMAC database for on-line queries and reporting.

PROJECT IMPLEMENTATION

Robust project management practices should be diligently applied throughout all project phases. The selected CMAC vendor should provide comprehensive solution design and analysis support for its hardware and software. One key is collaborative H&H modeling. Working with the customer's design team, the vendor should use the customer's site-specific data and storm scenarios to model and verify critical performance requirements like failsafe conveyance, drawdown times, and regulatory compliance.

Software

Before finalizing the design, the CMAC vendor must provide a software configuration report confirming that the proposed settings will achieve the site's objectives. For this report, the vendor translates high-level goals (e.g., flood mitigation) into specific software parameters, which are then validated for compatibility and simulated for performance. The final report must also include all data inputs and third-party integrations, and specify which metrics will be managed via the system's APIs.

Software implementation begins with provisioning the control panel, which acts as the system's decision-making hub. During this process, the vendor's cloud software is synchronized with the panel and configured for site-specific objectives, enabling it to process real-time sensor and forecast data to manage hardware like automated valves. This process is similar to downloading an app to a smartphone, as it sets up the data exchange between the app and the phone.

The operator experience is critical, requiring intuitive online dashboards for remote system control, real-time status monitoring, storm alerts, and performance analysis. The final phase integrates all key data sources, deploys device telemetry and public APIs, and establishes a user administration system with defined roles, permissions, and security protocols.

Hardware

A complete CMAC hardware installation includes several core components for autonomous operation:

- IoT sensors (e.g., level sensors, rain gauges) to gather real-time data
- Communications panel with reliable connectivity (cellular, Wi-Fi, etc.) to transmit data to the cloud
- Actuated flow control device (e.g., valve, slide-gate) to execute control decisions
- Reliable power source (solar or direct line) with a backup system to ensure continuous operation

Alongside the physical hardware, the vendor must deliver a complete documentation package for the site plan set and submittals. This includes installation details, electrical schematics, a full bill of materials, manufacturer specifications, and comprehensive construction specifications covering commissioning and quality assurance.

Support

As an integral part of its service, the CMAC vendor should offer full support to the end-user. This includes on-call remote customer support during regular business hours to address immediate needs and respond to inquiries. To manage issues efficiently from submission to resolution, a help desk and tracking system is essential. In addition to reactive support, the provider should also deliver periodic performance reports, offering insights into the system's operational effectiveness.

Post-Implementation Optimization

Following installation, site optimization is essential to validate the system's performance using real-world data, which provide more accurate results than modeling alone. During this period, the vendor and customer should collaborate to fine-tune software configurations and control logic, ensuring the system is fully optimized to meet the facility's primary objectives.

CONCLUSION

The stormwater industry is at a critical juncture, much like the software industry was before its transition to agile methodologies. Continuing to rely on the static "design-storm" approach is an inflexible and increasingly ineffective defense against a dynamic climate. By adopting CMAC, we shift from a passive, "set-it-and-forget-it" model to an active, intelligent one that maximizes performance, minimizes costs, and adapts our infrastructure to future challenges. This evolution is important to create safer, more sustainable communities prepared for an uncertain future. With a digital mindset, no challenge is insurmountable.

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ABOUT THE AUTHOR

Mr. Rubinstein has over 40 years of leadership in building and scaling high-tech startups. He has led the transformation of OptiRTC, Inc., from consulting services to a digital water product company. Throughout his career, Mr. Rubinstein has been a leader in digitally driven solutions to over a dozen industries. His expertise in business transformation, including change management and cultural alignment, has been a key ingredient for team success.