Adaptive Level Control Systems

Research on Maximizing Stormwater Pond Functionality

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University of Minnesota Water Resources Center
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Certification

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.

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For more information about the program, visit the website at wrc.umn.edu/stormwater

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Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the Water Resources Center or the Minnesota Stormwater Research Council.

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Abbreviations

AACE	Association for the Advancement of Cost Engineering
AI	Artificial Intelligence
ALCS	Adaptive Level Control System
ASTM	American Society for Testing and Materials
BMP	Best Management Practice
CAPEX	Capital Expenditures
CMAC	Continuous Monitoring and Adaptive Control
CRWD	Capitol Region Watershed District
CSO	Combined Sewer Overflow
CWMS	Corps Water Management System
DDPG	Deep Deterministic Policy Gradient
DNR	Department of Natural Resources
DORA	Dynamic Over-flow Risk Assessment
DOT	Department of Transportation
DSS	Decision Support System
EAW	Environmental Assessment Worksheet
FIRO	Forecast Informed Reservoir Operations
GI	Green Infrastructure
GIS	Geographic Information System
HDPE	High Density Polyethylene
HEC	Hydrologic Engineering Center
HLM	Hillslope Link Model
IFIS	Iowa Flood Information System
LACFCD	Los Angeles County Flood Control District
LARWQCB	Los Angeles Regional Water Quality Control Board
LCCA	Life Cycle Cost Analysis
LEED	Leadership in Energy and Environmental Design
LLM	Large Language Model
MDE	Maryland Department of the Environment
MIDS	Minimal Impact Design Standards
MPC	Model Predictive Control
MPCA	Minnesota Pollution Control Agency
MS4	Municipal Separate Storm Sewer System
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NSF	National Sanitation Foundation
NWS	National Weather Service
O&M	Operation and Maintenance
OCWD	Orange County Water District
OHWL	Ordinary High Water Level
OPEX	Operational Expenditure
RBC	Rule-Based Control
RL	Reinforcement Learning
RTC	Real-Time Control
RWMWD	Ramsey-Washington Metro Watershed District

SCADA	Supervisory Control and Data Acquisition
SRC	Stormwater Research Council
SSO	Sanitary Sewer Overflow
SWMM	Storm Water Management Model
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
TVA	Tennessee Valley Authority
UMN	University of Minnesota
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WCM	Water Control Manual
WSN	Wireless Sensor Network

1 Executive Summary

Stormwater management in urban and suburban settings faces increasing challenges from climate change, urbanization, and aging infrastructure. Traditional best management practices (BMPs) such as detention ponds and infiltration systems are often limited by available land and passive, fixed-geometry outlets. Adaptive Level Control Systems (ALCS) offer a practical evolution of these systems, using sensors, telemetry, and actuated controls to dynamically manage water levels in response to real-time or forecasted conditions. This report documents current knowledge, costs, and implementation strategies for how ALCS can be a viable retrofit to existing BMPs, with particular attention to applications and permitting within Minnesota.

ALCS is a new term meant to encompass distributed or interconnected BMPs that have controllable outlets (valves, gates, or pumps), fitted with control algorithms that are continuously making decisions and adapting to changing conditions and forecasts, all to control water levels, flow rates, discharge volumes and loads for public and ecosystem benefit.

The first step in this research was to complete a thorough literature review. More than 100 relevant published documents were reviewed for this research. The literature review focused on synthesizing and summarizing findings related to: the primary purposes and historical application of ALCS; U.S. states that have already established pathways for evaluation and approval; regulatory and other barriers that exist making design, permitting, construction, and operation challenging; other anticipated co-benefits associated with ALCS beyond water quantity management and water quality improvement; methods for ownership and operation as ALCS can often depend on or impact multiple stakeholders and agencies; current and upcoming tools for evaluation, design, and testing of control algorithms; and costs associated with ALCS.

The research conducted to date is extensive and overwhelmingly supports the use of ALCS in stormwater management. Studies consistently highlight its benefit in managing water quantity and flood risk, improving water quality and reducing downstream pollutant loading, and providing additional ecological co-benefits.

Following the literature review and documentation of the findings, additional research and analysis was conducted focused on the costs of ALCS, particularly in a situation where an outlet of an existing BMP is retrofitted to be active rather than passive. The analysis aimed to give planners and stormwater managers practical methods for estimating planning-level costs of an ALCS project. These planning-level cost estimates are useful for evaluating feasibility alongside more traditional BMP alternatives to achieve the same goals.

Drawing upon our experience with analysis, design, and construction of ALCS projects in Minnesota, we developed informed assumptions regarding design and construction. Using these assumptions, we estimated the initial capital cost for construction and implementation of an ALCS project. The costs were estimated across a wide range of target stormwater storage volume achieved by adaptive control of the BMP outlet. The findings indicate that retrofitting ALCS outlets to existing BMPs equipped with passive outlets enables access to previously inaccessible dead storage, resulting in increased stormwater storage volume in an efficient and cost-effective manner.

While ongoing maintenance and operational costs for active outlets are higher than for passive outlets, the savings in initial capital expenses can outweigh these incremental additional annual expenses, even when considered over periods of 20 to 30 years. ALCS offers several benefits and potential savings, making it a relevant consideration for stormwater evaluations aimed at reducing flood risk, improving water quality, or supporting ecological or public safety goals.

Accordingly, our research team conducted an evaluation of overarching strategies applicable to initiating, executing, and completing an ALCS project. A review of the literature revealed common approaches and stages within this process. These findings were further substantiated by our experience in the state of Minnesota where we have designed, permitted, constructed, and are actively monitoring ALCS installations, with additional ALCS projects currently underway at new sites.

Drawing upon insights gained from these projects, we developed a dedicated section that addresses strategies tailored specifically for implementation within Minnesota. We present a streamlined approach, providing guidance on all of the necessary considerations throughout the process to help prevent potential pitfalls and significant impacts on schedule and/or cost. In Minnesota, ALCS retrofits have so far proven feasible (although this conclusion is based on a limited number of projects) within existing permitting frameworks but require close coordination with agencies such as the Department of Natural Resources (Public Waters Work Permits), local watershed management organizations, and municipal stormwater authorities. Success depends on early engagement, transparent operating plans, and inclusion of manual override capabilities and monitoring commitments to build regulatory trust.

We conclude this report with recommendations for further research into where there are current challenges. A key challenge is demonstrating that active control, sometimes based on predictions, can operate effectively without resulting in unintended and undesirable consequences. This process requires thorough evaluation across a range of scenarios, in addition to clear communication with regulators and stakeholders to ensure their understanding of both the procedures involved and the control algorithm. As the algorithms increase in complexity, incorporating multi-dimensional dependencies and even autonomous decision-making, it becomes increasingly challenging to interpret and communicate these processes. Furthermore, a primary source of uncertainty identified in the literature, particularly for Minnesota, involves the complexities associated with managing uncertainties in weather forecasts. Current model speed and computational resources appear insufficient for addressing uncertainties in real-time while also pursuing optimization goals. Further research is recommended in these areas. In the meantime, approaches can be taken to de-risk ALCS projects through scenario testing ahead of implementation, and developing comprehensive control plans, with review and approval by appropriate permitting agencies.

The research confirmed our initial hypothesis: ALCS can substantially improve the effectiveness of existing BMPs, achieving equivalent outcomes for a fraction of the cost of constructing new BMPs, particularly in developed urban and suburban areas. ALCS should be considered as one of the tools available for stormwater managers, engineers, and regulators in our collective efforts to improve and protect water resources in Minnesota.

2 Background Information

It is widely recognized that effective stormwater management is an increasingly critical need. The demand for managing both stormwater quantity and quality continues to grow due to growing populations, increased urbanization, changing climate conditions, and aging infrastructure. Traditional best management practices (BMPs) generally rely on storage, conveyance, and various treatment methods to improve water quality. Other flood risk reduction strategies can include relocating infrastructure and/or people away from areas prone to highwater levels. However, one of the challenges with these traditional approaches, especially in urban areas, is the lack of available space for additional storage and the fact that higher discharge rates are typically not an acceptable option. Unless stormwater is discharged into engineered hardscapes, such as pipes and concrete-lined channels, higher flow rates can cause erosion, raise downstream water levels, and increase flooding potential.

One potential solution that has been recently studied and developed takes advantage of the time variable by transforming what is typically dead storage into live, active, and usable storage. This approach is referred to here as an Adaptive Level Control System (ALCS), a term first specifically coined by Ross Bintner, Engineering Services Manager at the City of Edina, MN. The phrase is both specific and intentional and is akin to other commonly used, similar phrases. It is:

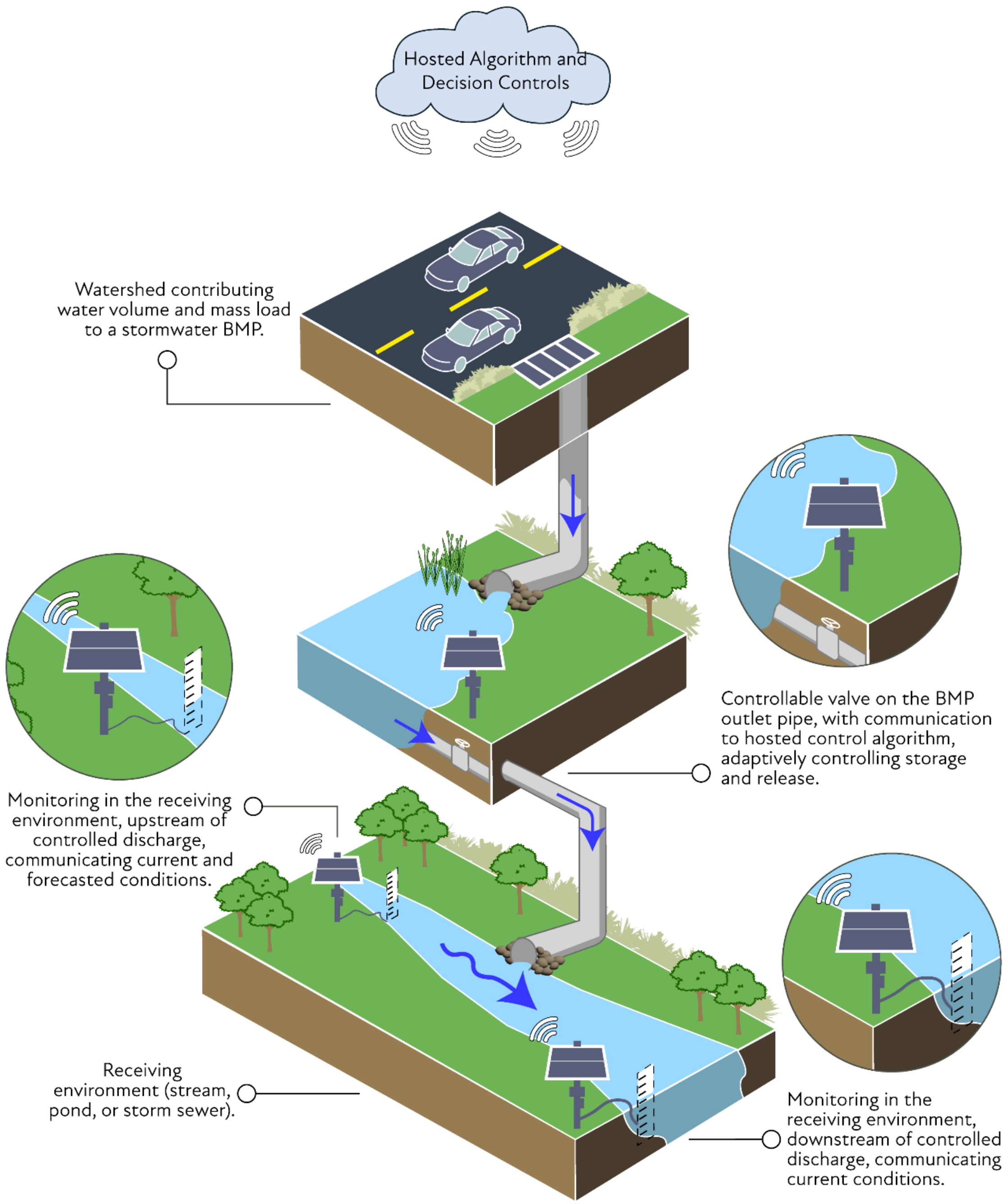
- Adaptive – this solution is dynamic and responsive to current, changing, and projected (or forecasted) conditions. It continuously integrates available and relevant data to assess current states and predict future ones, supporting informed decision-making.

- Level – this solution is primarily focused on water levels. This includes water levels in reservoirs and lakes, and in channels where levels are closely tied to flow rates. Managing water levels can help reduce flood risk while also providing water quality and broader ecological co-benefits.

- Control – this solution is active rather than passive. It transforms a traditionally fixed outlet structure, designed with a single geometry to accommodate a range of conditions, into an active system that can adjust flow rates dynamically in response to changing conditions.

- System – this solution is not constrained to one site. It can operate as a coordinated, connected network of active outlets, collectively managed to optimize stormwater management across the entire system.

Note that the description of ALCS above does not inherently include “forecast” or “predictive” capabilities. ALCS operation does not require reliance on forecasts; controls can adapt to changing conditions using real-time data from actual events. While ALCS can incorporate forecast-based functionality, it is not dependent on it. A schematic representation of ALCS is shown in Figure 1, which illustrates its various components. The cloud above the other components represents a cellular-connected, controller, often said to be “in the cloud,” where computations are performed and decisions are made. The top layer with the road and cars represents the catchment. This catchment drains to a water body in the middle layer, possibly by storm sewer or natural channels. The water body has an existing outlet, but it is modified to have a control (gate, valve, or pump, for example) and fitted with monitoring and controls. Additionally, the downstream environment, the bottom layer, may also be fitted with monitoring and communications, possibly upstream and downstream of the middle layer’s outlet. All monitoring and communication points transmit data to the control system, which makes operational decisions using either optimization algorithms or rule-based logic, and then sends control signals to the active outlets. Collectively, these components form the Adaptive Level Control System (ALCS).



Graphic by Wen Martinez, University of Minnesota

Figure 1 Schematic of an ALCS and its various components

ALCS includes (either in new projects or by retrofitting to existing BMPs) controllable components such as valves, gates, and pumps on BMPs, combined with data collection and forecasting information to actively manage storage and flows. ALCS can go by many other similar names, such as real-time control (RTC), continuous monitoring and adaptive control (CMAC), smart infrastructure, or model predictive control (MPC). Webber et al went into detail in their paper, making sure to define terms (Webber et al. 2022). They differentiate between "smart technology" (covers a wide range of technologies that sense, monitor, communicate, manage, control, optimize, etc.), "real-time control" (systems that include actuators, controllers, sensors, and telemetry), “passive/active control”, and “Internet of Things". Webber et al also provide a history of the rise of RTC in stormwater management, as well as a literature review.

ALCS is not wholly a new or recent concept. The application to stormwater management, however, is relatively new and growing. Historically, urban drainage RTC dates back more than five decades, and interestingly, the first RTC application in urban drainage was noted to be implemented in Minneapolis in the late 1960s (Brasil et al. 2021). ALCS is also akin to active control of large reservoir systems in much larger drainage basins that government agencies such as the United States Army Corps of Engineers (USACE), United States Bureau of Reclamation (USBR), and Tennessee Valley Authority (TVA) have been doing for many years. In those cases, controlled storage and release are active, with decisions being made based on current conditions and expected changes. The benefit on those systems is that inflows tend to be on very long timescales (days to weeks), with long-running USGS gages on the rivers upstream. This information gives managers good information well before action is needed, and is based on a known, changing hydrologic response. Additionally, the USACE has been researching and working to implement Forecast Informed Reservoir Operations (FIRO).

FIRO, a similar form of ALCS, is being codified in USACE Water Control Manuals (WCMs), which function as the governing operations manuals for flood-control infrastructure. In California’s Yuba–Feather system, work plans explicitly aim to modernize WCMs to “incorporate FIRO operations,” with multi-agency coordination and targeted completion dates, subject to compliance with relevant USACE engineering regulations (Ralph et al. 2023). At Prado Dam (CA), the regulatory process uses interim WCM modifications and minor deviations as a pathway to permanent inclusion: “Two WCM updates are planned… WCM update #2 will include a formal consideration of FIRO. During the Interim Operations period… work will continue to further develop the FIRO approach.” (Ralph et al. 2023). The interim WCM has already been modified to increase buffer pool elevation, with further updates planned to integrate FIRO alongside infrastructure upgrades. Seven Oaks Dam (CA) is following a similar staged FIRO viability process designed to inform a WCM update; the WCM explicitly allows for future modification to accommodate water conservation, though current authorization is for flood risk management only (F. M. Ralph et al. 2024). Washington State’s Howard A. Hanson Dam is pursuing FIRO via deviations and eventual WCM updates; the work plan states that operational changes must be approved by USACE and incorporated into the WCM (M. Ralph et al. 2024).

Research is also growing in the area of optimization of decisions and controls, with respect to stormwater. Optimization has been tested in stormwater management using genetic algorithms, neural networks, and fuzzy logic control.

Some of the challenges that smaller-scale, urban stormwater systems face, relative to larger-scale active operations, are the time of concentration. Hydrologic response in an urban system is much faster, increasing the reliance on weather forecasts to provide sufficient time to act. This then requires making decisions not only before inflows have reached a reservoir or BMP, but before events have even happened. Additionally, computational costs limit the application of optimization algorithms that would aid in the decision-making process and control process.

However, data collection is growing, and with the growth of available data, alongside the growth of computational power and methods, the opportunities are expanding. Networks of sensors continue to grow, with perhaps the largest unified flood monitoring network being the Iowa Flood Information System (IFIS), which draws on a network of over 200 cellular-enabled sensor nodes (Bartos et al. 2017).

The Center for Watershed Protection published a study in 2024 titled “Accounting for Climate Change in Post-Construction Stormwater Standards” (Caraco et al. 2024). This document focused on the readiness of each state in the U.S. for managing climate change in stormwater, with recommendations specific to each state given their assessed vulnerability and readiness. For Minnesota specifically, the recommendations for both high precipitation and drought included “incorporate Smart BMP Technology into standards and provide recommendations for its use in adapting to changing storm patterns” (Appendix D of Center for Watershed Protection, 2024). In addition to applying ALCS at the single site level, decentralized, distributed, and coordinated application of smart technologies to manage stormwater at the catchment scale has the potential to realize significant future benefits for resilient and sustainable systems (Troutman et al. 2020); (Webber et al. 2022). The research presented in this report is focused on addressing this recommendation and presenting how ALCS can be a beneficial tool for stormwater management, particularly with respect to retrofitting outlets on existing BMPs.

3 Literature Review

Our team began this research with a review of the available literature. Searches for relevant literature were primarily conducted online. Terms and phrases that our team focused on, all in the context of stormwater management and best management practices, were: “real time control”, “reinforcement learning”, "model predictive control”, "nature based solutions", “smart systems”, “smart infrastructure”, “active control”, “adaptive level control”, “OptiRTC” (Opti is a vendor for Real-Time Control systems), “CMAC” (Continuous Monitoring and Adaptive Control), “Internet of things”, “data-driven management”, and “SCADA” (Supervisory Control and Data Acquisition). The search was intended to find a body of literature that answered the research questions described in Section 4.

The literature review identified 105 documents of varying relevance (53 classified as “High”, 40 classified as “Medium”, and 12 classified as “Low”). Documents classified as low relevance generally answered only one of the research questions, were for a region of the United States (US) that was not directly applicable (Florida, for example), or were heavily focused on one detailed aspect that supports ALCS (weather prediction, for example). Documents were included from all over the world, as stormwater managers from urban centers worldwide are likely grappling with the implications of increasing pressure to manage stormwater with limited space and funds. Figure 2 shows the publication year of each of the documents (where a publication year was available), indicating the recent growth of research on this topic.

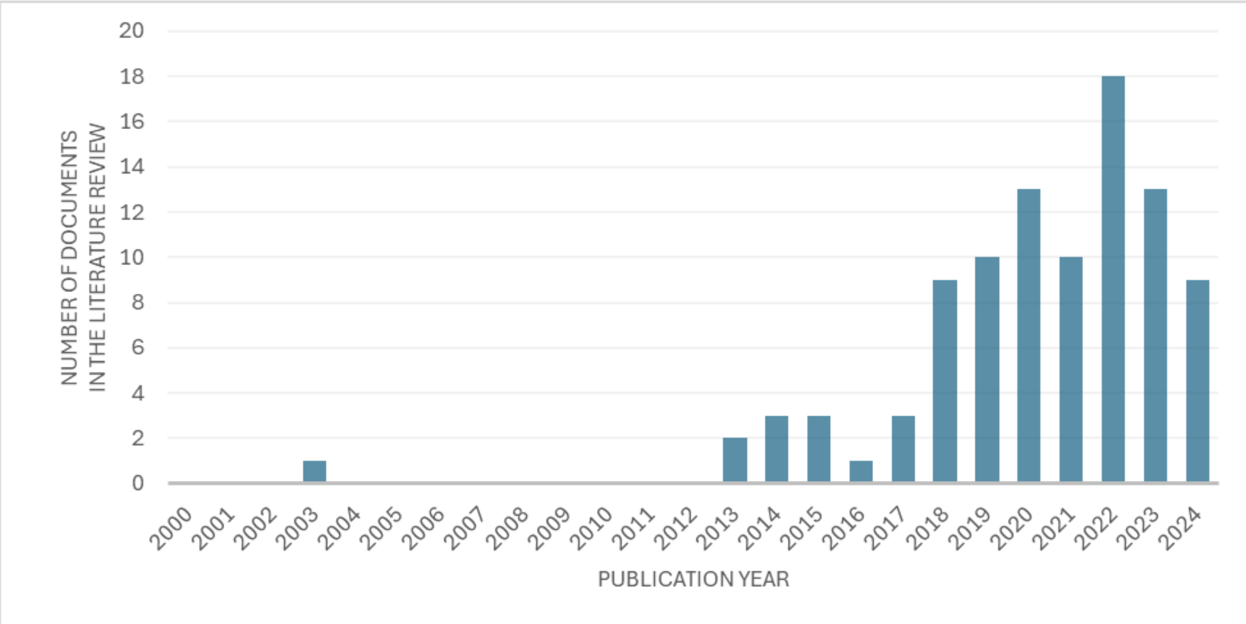


Figure 2 Publication years of documents compiled in for the literature review

Our team developed a spreadsheet table to track and briefly summarize each of the documents. The spreadsheet table is included as Appendix A and the supporting literature documents have been shared electronically with the Minnesota Stormwater Research Council. The table includes information on the following:

- The document title, author(s), and publication year
- The primary geographic location of the documented work

- A short description of the conclusion as well as key takeaways
- A hyperlink to an online version of the document
- The selected category of the document (options: review, case study, existing infrastructure, data collection and analysis, other)
- The classification of the document's relevance (options: low, medium, high)
- A description of whether the document focuses on water quantity, water quality, or both
- Identification of which research questions the document addresses

The documents have been stored and are publicly available on the Minnesota Stormwater Research Council's website. The research conducted to date is extensive and overwhelmingly supports the use of ALCS in stormwater management. Studies consistently highlight its benefit in managing water quantity and flood risk, improving water quality and reducing downstream pollutant loading, and providing additional ecological co-benefits. However, there is also consensus that while upfront capital costs are generally lower than those of traditional passive systems, ongoing maintenance costs tend to be higher.

The following section summarizes the key findings from the literature review as they relate to the research questions. Readers interested in exploring the potential of ALCS as a stormwater management tool are encouraged to review the referenced documents for more detailed information.

3.1 Large Language Model (LLM) to Support Literature Review

To efficiently synthesize findings from a large body of literature, a large language model (LLM) was used to assist in summarizing and organizing information from more than 100 peer-reviewed publications and technical reports. The LLM was applied as a tool to support human-led analysis, not as an autonomous author. Its role was to identify key themes, summarize relevant findings, identify disagreements, and compile responses to a structured set of research questions developed by the project team.

For readers less familiar with the term, an LLM is a type of artificial intelligence (AI) trained to understand and generate human-like text. In this context, the LLM functioned as a sophisticated language processing tool (similar to other AI applications) but was guided and constrained by project-specific instructions to ensure focused, accurate, and traceable results.

To ensure accuracy, consistency, and transparency, the LLM was provided with a custom guide that specified the desired structure, tone, and format for citations. This guide outlined expectations for evidence-based summaries, proper citation of original sources, and a clear distinction between findings from different studies. The model was only provided with the publications identified in the literature review to ensure that its source information came exclusively from trusted, relevant documents rather than the internet as a whole.

For each of the research questions, a separate LLM-assisted synthesis document was generated, reviewed, and refined by the project team. Subject matter experts then validated, edited, reorganized, and added to the LLM outputs to confirm that the summaries accurately represented the literature, that references were correctly attributed, and that contextual nuances were preserved. This combined approach, leveraging the LLM's efficiency in text synthesis with expert review and interpretation, allowed for a comprehensive, traceable, and methodologically consistent summary of current knowledge across the identified research questions.

4 Research Questions

Nine key questions were formulated to gain insight into how Adaptive Level Control Systems (ALCS) are currently being used in stormwater applications. These questions included the following:

1. **Purpose of ALCS Use** - Are ALCS applications being used for both water quantity and water quality purposes, and if so, is one use much more frequent than the other?
2. **Primary Application: Retrofits or New Construction?** – Are ALCS being installed mostly as retrofits to existing BMPs (and if so, what kind), or are they mostly being installed as new types of projects, and if so, what types of BMPs are they being installed in?
3. **Location and Use Setting** – Where are ALCS being used (urban/metro areas, rural areas), and in which regions of the United States and other countries?
4. **States with Precedent for Approval** – What US states might have already approved ALCS for use as acceptable BMPs? Does this technology exist in any stormwater manuals?
5. **Regulatory and Other Barriers** – What regulatory roadblocks are being encountered when trying to implement ALCS, and what can be done to overcome them? What other issues or barriers might this create (public perception, risk, etc.)?
6. **Co-Benefits Beyond Water Quantity and Quality** – What other environmental service/benefits does ALCS potentially provide?
7. **Ownership and Operation** – What does ownership, operation, and maintenance look like when ALCS are implemented (i.e., who is taking responsibility for these systems)?
8. **Modeling Software to Support ALCS** – What is the best predictive modeling software for ALCS, including forecasting ability?
9. **ALCS BMP Costs in Literature** – What are the costs of installing/implementing ALCS (initial cost, ongoing maintenance costs, subscription fee costs, etc.)?

These questions were addressed through the literature review, with summaries presented in the following subsections. Full details are available in the referenced resources.

Two additional questions were the primary focus of additional research conducted: (1) What are the recommended approaches and considerations for implementing ALCS in Minnesota? and (2) How does the cost of retrofitting ALCS to existing stormwater BMPs compare to construction of other traditional BMPs? Section 5 presents the methods, data, and results of the cost comparison, while Section 6 focuses on implementation.

The synthesis presented in this section was generated with assistance from a large language model (LLM) (as described in Section 3.1 above) to support the analysis, summary, and organization of findings, with further editing and verification conducted by the research team.

4.1 Purpose of ALCS Use

ALCS for stormwater has emerged to enhance flood risk reduction and water quality by actively managing storage and release across networks of assets. In practice, these systems are deployed at scales ranging from individual ponds and green infrastructure assets, to watershed-wide networks, often with multi-objective operating rules that toggle between quantity- and quality-focused control based on current conditions as well as forecasts (Bartos et al. 2017), (Oh and Bartos 2023), (Shishegar et al. 2021). Throughout the US, cities have embraced technology to enhance various aspects of life (transportation, wi-fi, and various other connectedness), but integration of this 'smart' technology has lagged behind in water systems. However, application of ALCS in stormwater offers new inroads for dealing with some of the most pressing urban stormwater challenges (e.g., flash flooding, aquatic ecosystem degradation, and runoff pollution) (Bartos et al. 2017)). Momentum is evident in expanding sensor networks, pilot programs (e.g., UK Flood and Coastal Resilience Innovation Programme), and open-source platforms (Kerkez et al. 2016); (Sweetapple et al. 2023), (Chen et al. 2023).

The benefits span both water quantity (e.g., flood mitigation, peak shaving, CSO/SSO reduction) and water quality (e.g., pollutant removal via extended detention, erosion control) (U.S. Environmental Protection Agency 2021); (Kerkez et al. 2016); (Chen et al. 2023), (Sharior et al. 2019). For example, adding valves, gates, or pumps to existing stormwater facilities (retrofit) can extend hydraulic retention time, thereby promoting the capture of sediment-bound pollutants. Modulation of flows (hydrograph shaping) may reduce downstream erosion by limiting discharge rates as well as reduce flooding (Bartos et al. 2017).

Studies and municipal projects frequently prioritize flood metrics (e.g., flood levels, overflow volume, peak discharge, CSO counts), with water quality either as a secondary performance indicator or an indirect co-benefit (Oh and Bartos 2023); (U.S. Environmental Protection Agency 2021). As one review notes, "literature almost universally agrees that smart technology is, or will be, beneficial… technology has reached partial maturity in terms of quantity management, although this has not yet transferred to water quality" (Webber et al. 2022). The imbalance is attributed to the relative maturity of level/rain sensing and actuation versus real-time chemical/biological monitoring; quality-focused implementations thus more often rely on proxies (e.g., turbidity) or modeled constituents (Sweetapple et al. 2023), (Webber et al. 2022). Despite the technology lagging in the water quality space, a recurring operational pattern among research and case studies is to emphasize water quality during small/frequent storms and emphasize flood control during larger events—demonstrating adaptive, multi-objective use across the event spectrum (Wong and Kerkez 2018); (Mullapudi et al. 2018); (Bartos et al. 2017).

Quantity-only deployments remain common in combined sewer contexts to reduce overflows (Lund et al. 2020). Quality objectives are increasingly integrated, particularly in detention basins and RTC-enabled green infrastructure (Brasil et al. 2021); (Chen et al. 2023). Where studies report both objectives, many show that quantity targets are consistently met across events, while quality targets (e.g., specified detention times) are satisfied for most small-to-moderate storms. For example, a modeling study of a single detention basin in Quebec, Canada, with an ALCS found that peak flows were reduced by 46% on average, and extended detention (36 h for quality control) was achieved for the majority of events and runoff volume; notably, "a total of 77% of the runoff volume was fully detained for 36 h" in the modeled season (Bilodeau et al. 2019). Similarly, forecast-based control schemes of a single site reduced downstream hydraulic shocks without overflows and improved TSS removal (from 46% to 70–90%) (Gaborit et al. 2015).

City-scale, multi-site deployments illustrate routine dual-purpose operation and tracking. The City of Lynchburg's (VA) CMAC retrofits explicitly target peak mitigation and nutrient/TMDL credits, reporting increased residence time and automated management of wet weather discharges (Opti by aliaxis, n.d.-d). In Beckley, WV, the city's iPond, an intelligent stormwater management project developed by the Beckley Sanitary Board, reports elimination of local flooding while increasing average detention to 45 hours and achieving modeled nutrient/TSS removals (Opti by aliaxis and Johnson, n.d.). At Port Tampa Bay (FL), measured performance shows concurrent increases in flood attenuation volume (84%) and in nitrogen removal (44%) (Opti by aliaxis, n.d.-g). In Montgomery County, MD, in a combined sewer context, active controls captured 86% of storms with no outflow, reducing CSO loadings alongside flood risk (Opti by aliaxis, n.d.-a). System-level RTC in Ann Arbor reduced peak depths and flood durations while removing up to 67% of TSS (Li et al. 2024).

Several studies focus primarily on water quality while acknowledging quantity trade-offs. Real-time controlled bioretention achieved phosphorus removal comparable to amended media with a smaller footprint, highlighting a “digital” alternative for quality goals (Mason et al. 2022). Column and pilot work demonstrate RTC schemes that manage soil moisture and storage to improve nutrient/metal removal, while calling for further hydrologic quantification to balance quality with storage needs for impending storms (Persaud et al. 2019).

Where quantified, dual-purpose performance is tracked with multi-metric dashboards (e.g., peak flow, overflow hours, TSS load, detention time), and as described above, case studies routinely report simultaneous improvements. This suggests ALCS can reliably deliver flood benefits now, while offering meaningful and growing water quality gains as sensing and data integration mature (U.S. Environmental Protection Agency 2021); (Webber et al. 2022); (Sweetapple et al. 2023). Overall, research agrees that there is great potential with ALCS applied to stormwater management, both for water quantity and quality, to preserve watershed and ecological stability. Additionally, ALCS should be applied not only to individual sites but should incorporate systems thinking, using engineering solutions to optimize stormwater performance for entire watersheds (Bartos et al. 2017)).

4.2 Primary Application: Retrofits or New Construction?

Across the literature, the dominant implementation pathway is retrofitting existing stormwater best management practices (BMPs) with sensors and actuators to convert passive outlets into controllable ones, thereby “sweating” existing assets rather than constructing new facilities (Bartos et al. 2017); (Bowes et al. 2021); (Mullapudi et al. 2020); (Rimer et al. 2021); (Oh and Bartos 2023). This is primarily due to cost-effectiveness, minimal disruption, and the ability to leverage existing storage and conveyance. Retrofit mechanisms typically involve replacing or augmenting passive structures (orifices, weirs) with remotely operated valves, adding level sensors, and integrating controls with SCADA or cloud-based platforms; these interventions are often minimally invasive and lower cost (Bowes et al. 2021); (Mullapudi et al. 2018); (U.S. Environmental Protection Agency 2021).

Studies in Ann Arbor (MI) and Norfolk (VA) demonstrate retrofits by replacing fixed weirs with controllable valves at existing ponds to unlock full-volume active storage and coordinated releases (Bowes et al. 2021); (Li et al. 2024); (Oh and Bartos 2023). Foundational reviews emphasize augmenting, rather than replacing, both green and grey assets via low-cost, reliable actuators and connectivity (Bartos et al. 2017); (Kerkez et al. 2016); (Rimer et al. 2021). Case studies of retrofits show measurable flood attenuation and improved pollutant removal without new construction (Bartos et al. 2017); (U.S. Environmental Protection Agency 2021).

Of the BMPs typically used by stormwater managers and engineers, the following are most often retrofitted to incorporate ALCS:

- Detention/retention basins and stormwater ponds: the most frequent retrofit targets, with controllable valves added to convert static outflows to adaptive operations (Bartos et al. 2017); (Gaborit et al. 2013); (Sharior et al. 2019); (Mullapudi et al. 2018). Municipal programs report retrofits of regional wet ponds and extended detention dry ponds for water quality credits and peak flow reductions (Opti by aliaxis, n.d.-a); (U.S. Environmental Protection Agency 2021).
    - In a rural context, research has also focused on distributed small dams/ponds: rural and peri-urban networks retrofitted with gated outlets for flood peak reduction across many assets (Post, Quintero, Krajewski, et al. 2024).
- Constructed wetlands and lakes: integrated into controlled networks for coordinated release and capture (Mullapudi et al. 2018).
- Rainwater harvesting systems and underground detention: retrofit of tanks and vaults with CMAC to anticipate storms and manage reuse (U.S. Environmental Protection Agency 2021); (Opti by aliaxis, n.d.-a).
- RTC is also commonly applied to bioswales (Bowes et al. 2021).

One of the significant benefits of ALCS is the ability to mechanically create dynamic storage. In developed settings where space is a premium, this provides a particular advantage and makes retrofitting existing stormwater assets with available dead storage most appealing (Lund et al. 2018).

Although retrofits to existing BMPs dominate the typical application, several projects embed smart controls from the outset of planning and design. Regional capture and reuse systems incorporate actuated valves, pump stations, and large underground cisterns integrated with SCADA and weather-driven predictive logic. For the Bolivar Park project in Lakewood, CA, designers highlighted that “rapid, predictive, and responsive control provides ‘hard’ infrastructure with flexibility and resiliency that could not otherwise be achieved through traditional hydraulic structures” (Fussel and Watson 2019). Some jurisdictions require automated controls in new developments, enabling smaller detention footprints and dual-use vaults for harvesting and attenuation (Opti by aliaxis, n.d.-c). Large networks may also include new inline storage vaults designed for RTC within existing conveyance systems (U.S. Environmental Protection Agency 2021).

Outside of application of ALCS to wet or dry ponds, and to lakes and constructed wetlands, active control in green infrastructure (GI) is also emerging. Bioretention retrofits demonstrate improved nutrient removal by modulating water levels to create aerobic/anaerobic zones (Mason et al. 2022); (Persaud et al. 2019). Experimental active control schemes in bioretention show promise relative to free-draining and internal water storage designs, but require optimization to balance retention benefits with storage needs (Persaud et al. 2019). Green roofs present potential for future RTC applications but are less commonly directly controlled to date (Brasil et al. 2021). Other BMPs traditionally considered as green infrastructure such as rainwater tanks, underground storage for reuse, and infiltration basins are also prominent targets for ALCS application (implemented singly or as coordinated networks) underscoring a shift toward distributed GI integration (Webber et al. 2022).

In combined sewer systems, retrofits focus on CSO regulators, siphons, and inline storage dams to transform gravity systems into managed conveyance and storage (Kerkez et al. 2016); (U.S.

Environmental Protection Agency 2021). Simulations and real-world scenarios demonstrate activating static regulators and weirs via remote control to improve overflow performance (Rimer et al. 2021). At a larger scale, a combined sewer network in South Bend, IN uses over 120 flow and depth sensors along with nine valves to actively modulate flows into the city's combined sewer system, optimizing the use of existing in-line storage and achieving a roughly five-fold reduction in combined sewer overflows from 2006-2014, all without the construction of additional infrastructure (Bartos et al. 2017).

It is clear that ALCS can be applied to a variety of existing and new BMPs. Cities that have embraced, implemented, and advanced this technology have coordinated adaptive control across multiple varied assets (e.g., underground detention, wetlands, lakes) to reduce wet-weather volumes and CSOs. Agencies, owners, and engineers can prioritize retrofit-ready BMPs to realize cost-effective benefits quickly, while planning for coordinated controls in new developments to achieve catchment-scale flood and water quality outcomes.

4.3 Location and Use Setting

Evidence overwhelmingly reflects urban and suburban contexts, with occasional references to rural siting when land values push storage tanks off-line (Rathnayake and Faisal Anwar 2019). This common setting reflects the concentration of flood risk, aging infrastructure, and regulatory drivers in cities. ALCS adoption in stormwater remains nascent and largely urban, with system-wide stormwater management applied only occasionally (Sweetapple et al. 2023). Application scales range from property-level green roofs and smart rain barrels to street-scale bioretention and neighborhood- to watershed-scale detention (Brasil et al. 2021); (Chen et al. 2023). An appendix to a USEPA report includes 22 case studies about communities across the country that have implemented smart data infrastructure technologies (U.S. Environmental Protection Agency 2021). Increased interconnection of decentralized stormwater assets in these urban settings may enable watershed-scale management that coordinates local users toward regional outcomes (Kerkez et al. 2022).

Geographic coverage across regions is broad but urban-centric. Most documented U.S. deployments are in city-scale or neighborhood-scale systems. By region, some examples are:

- Midwest and Upper Midwest: continuous monitoring and controlled detention was recommended, though not implemented in Roseville, MN (Twin Cities) (Janke et al. 2022); the Morningside Flood Infrastructure Project in Edina, MN (Barr, 2022); improved flood control capacity in Falcon Heights, MN (U.S. Environmental Protection Agency 2021); a modified outlet on Lake Phalen in MN; controlled basin retrofits in Milwaukee, WI (Sharior et al. 2019); and river and sewer monitoring in Green Bay, WI (U.S. Environmental Protection Agency 2021); system-wide control of detention basins in a long-term monitored urban watershed in Ann Arbor, MI (Bartos et al. 2017); (Oh and Bartos 2023).

- Northeast and Mid-Atlantic: smart watershed network management in Albany, NY (Opti by aliaxis, n.d.-f); building- and campus-scale systems in the Boston metro area (Watertown, MA) (Opti by aliaxis, n.d.-e); and county-scale pond retrofits serving the Washington, DC suburbs (Montgomery County, MD) (Opti by aliaxis, n.d.-a), alongside historic neighborhood pond retrofits in Harrisburg, PA (Bathhurst 2021).

- South: urban flash-flood monitoring and watershed control networks in the Dallas–Fort Worth metroplex, TX (Bartos et al. 2017); and broader smart sewer deployments in San Antonio, TX and Louisville, KY (U.S. Environmental Protection Agency 2021).

- West: regional capture and predictive control in Southern California (Los Cerritos Channel watershed) (Fussel and Watson 2019) and combined sewer RTC in San Francisco, CA (U.S. Environmental Protection Agency 2021).

A national compilation further documents deployments in major metros and smaller cities, including Albany, Cincinnati, Louisville, San Antonio, San Francisco, Philadelphia, Washington, DC, and many others (U.S. Environmental Protection Agency 2021). Recent case studies also show metropolitan and industrial applications in coastal and port environments, such as Norfolk, VA, and Port Tampa Bay, FL, where tidal and space constraints motivate predictive controls and retrofits (Bowes et al. 2021); (Opti by aliaxis, n.d.-g). In Minnesota, this may be particularly useful around Duluth and along Lake Superior. These examples point to consistent urban adoption across coastal, inland, and Great Lakes regions, with suburban and small-city implementations emerging where watershed-scale benefits incentivize controls.

4.3.1 International deployments and emerging programs

Internationally, deployments span Europe, Latin America, Asia, and Oceania. Documented systems include UK riverine WSNs and Spain flash-flood monitoring; Honduras networks; and the Paris MAGES system and decentralized RTC in Italy (Bartos et al. 2017); (Chen et al. 2023). Bordeaux, France integrates RTC across a legacy combined sewer system to manage riverine flood risk (U.S. Environmental Protection Agency 2021). Large-scale water distribution monitoring is established in Singapore, with household-scale sensor networks in Mexico City capturing urban heterogeneity (Martinez Paz et al. 2022). MPC-based urban flood mitigation is demonstrated in Shenzhen’s Sponge City program (Sun et al. 2024). Together, these cases indicate growing international uptake centered on urban basins and combined systems.

4.4 States with Precedent for Approval

ALCS has some formal traction in the U.S., with formal acceptance in some state programs. Regulatory acceptance hinges on whether agencies approve these systems as BMPs for compliance with permits and how they are referenced in stormwater or related design/operations manuals. The literature indicates that Maryland and California are two of the most prominent states accepting and approving ALCS in stormwater. The following subsections list examples of how these states have not only approved ALCS projects on a site-by-site basis but have formalized inclusion of this as a BMP at the regulatory or government level.

USEPA published a “living document that is continually updated” describing wet weather control and decision support (U.S. Environmental Protection Agency 2021). The document not only supports abundant data collection and concludes that operators can shift their approaches toward preventative and predictive O&M practices as technology and data collection advance, but also includes case studies from New York, West Virginia, Pennsylvania, Ohio, Indiana, Michigan, Wisconsin, California, Florida, Kentucky, Vermont, Texas, and Minnesota. These case studies reflect the widespread consideration and approval of ALCS as a suitable engineering and operational solution to issues with flood risk, water quality, and other issues related to overflows (CSOs).

4.4.1 Maryland

Maryland has multiple examples of regulatory acceptance for adaptive controls in municipal stormwater programs. Following successful demonstrations, the Maryland Department of the Environment (MDE) approved CMAC retrofits in both wet and dry ponds for meeting MS4 water quality requirements; the Chesapeake Bay Program’s Urban Stormwater Expert Panel also endorsed pollutant-removal credits for

CMAC retrofits: “Success led to the Maryland Department of the Environment (MDE) approving Opti’s CMAC for wet pond retrofits… [and] unanimous endorsement of the use of CMAC retrofits for pollutant removal credits. The same case study reports MDE approval for dry pond retrofits to meet MS4 restoration requirements (Opti by aliaxis, n.d.-a). At the local level, Howard County implemented adaptive controls at stormwater ponds to comply with MS4 permit targets within the Clean Water Howard initiative, with state and USEPA-supported evaluation and prioritization of additional sites (Opti by aliaxis, n.d.-b). Beyond MS4 programs, the Maryland Department of Transportation (MDOT) established a public–private approach in which smart pond retrofits on private property generate credits purchased by MDOT through a water quality trading program, signaling formal use of adaptive controls to meet regulatory obligations: “MDOT purchases excess credits from Walmart, instead of building new assets” and is “the first U.S. state department of transportation to purchase credits from a Water Quality Trading Program” (Opti by aliaxis, n.d.-a).

4.4.2 California

California has approved adaptive controls in urban stormwater capture and reuse projects through multi-agency permitting and programmatic pathways. The Bolivar Park project in Los Angeles County integrates SCADA-enabled predictive pumping tied to weather forecasts to preemptively move water and create storage ahead of storms, under a watershed management plan approved by the Los Angeles Regional Water Quality Control Board (LARWQCB). It advanced under the Caltrans Cooperative Implementation Agreement (CIA) Program and added to the Caltrans Statewide Stormwater Permit in 2014 to support TMDL compliance, illustrating program-level acceptance (Fussel and Watson 2019). Permitting required coordination with the Los Angeles County Flood Control District (LACFCD), LARWQCB, California State Water Resources Control Board’s Drinking Water Division, and other agencies—an example of formal, multi-agency regulatory approval for RTC-based BMPs (Fussel and Watson 2019).

Explicit listing of “smart” or RTC-based practices in statewide stormwater BMP manuals is not consistently documented; instead, acceptance commonly occurs through MS4 crediting, permit amendments, or case-by-case approvals. And even so, obtaining approvals on a case-by-case basis is also challenging because the existing stormwater management rules were not necessarily written considering proactive, predictive, or real-time modulation of storm events. Trends point toward increasing formalization via credit trading, programmatic permit pathways, and integration of decision support. In summary, approval seems to ultimately come down to trust, which heavily relies on predictability and understanding (Webber et al. 2022). Passive structures (when operating normally without issues such as clogging) provide this predictability and trust and are well understood. ALCS projects include additional layers and complexity that make it more difficult to initially understand, predict, and therefore trust. However, as the catalog of case studies grows, this can be gained, smoothing the path toward approval and adoption.

4.5 Regulatory and Other Barriers

Adaptive level control systems (ALCS) for flood risk reduction promise to improve performance and resilience by using sensors, forecasts, and automation. Additionally, regulatory frameworks increasingly recognize and credit RTC/CMAC retrofits (Opti by aliaxis, n.d.-a). Yet the literature consistently highlights substantial technical, financial, operational, and institutional barriers that limit broader implementation and scaling across catchments and cities. ALCS implementation often stalls on regulatory, permitting, and crediting hurdles that span standards, governance, environmental compliance, and institutional capacity. Regulatory bottlenecks largely reflect fragmented standards, complex permitting, data governance, institutional capacity, and statutory constraints. Additionally, benefit-cost assessment is difficult, which complicates investment cases and stakeholder buy-in (Eggimann et al. 2017). The literature points to practical pathways: standards and interoperability frameworks, early multi-agency coordination, operator-centered design and training, and robust DSS aligned with approved systems. Advancing these pathways, while building clearer evidence and incentives, will be pivotal to mainstreaming ALCS for flood risk reduction. The following synthesis organizes these barriers thematically to provide a concise, practice-oriented understanding of current constraints.

4.5.1 Regulation, governance, and permitting complexity

Across jurisdictions, regulation related to "smart" stormwater remains piecemeal, with unclear mandates and few incentives to adopt nontraditional solutions. As one review notes, "regulation related to smart stormwater management [is] piecemeal at best" and "if there are no regulatory incentives then adoption of smart technologies is highly unlikely" (Sweetapple et al. 2023). Trust concerns are amplified by ambiguous ownership and accountability for distributed assets and by severe consequences for poor outcomes, motivating utilities to seek clarity on operation and standards before deploying network-wide systems (Webber et al. 2022). Where ownership and jurisdiction are across watershed-scale deployments, liability frameworks are needed for multi-stakeholder control (Kerkez et al. 2016).

Smart stormwater installations often trigger multi-agency review, with requirements beyond typical storm sewer permits. In Los Angeles County's Bolivar Park project, approvals involved flood control, public health, drinking water, sanitation, regional water quality, and vector control agencies; design requirements included NSF 350 water quality sampling, flap gates and sealed covers to prevent mosquito entry, and manual overrides for actuated valves. Clear maintenance agreements were needed to manage multi-jurisdictional assets and liability (Fussel and Watson 2019). In Minnesota, additional study on potential for thermal and bacteria loading issues were needed for approval associated with an ALCS project, acknowledging heightened concerns that understandably come with new technologies and approaches (Barr, 2022). More broadly, ALCS must be reconciled with Clean Water Act frameworks (CSO, TMDL, MS4) and, where applicable, Safe Drinking Water Act constraints, which can shape adoption decisions (Meng and Hsu 2019). These experiences highlight the value of early, sustained coordination with regulators and incorporating agency-specific features into design to streamline review. Further discussion on the importance of early stakeholder engagement is included in Section 6.

4.5.2 Institutional capacity and operator trust

Institutional resistance and risk aversion pose major barriers, requiring changes in operational practice, decision-making, and culture (Sweetapple et al. 2023); (Eggimann et al. 2017). This again comes down to the ability to trust, which is ultimately about predictability and understanding. Permitting an operating plan that can be described on paper with words, charts, and tables is easily comprehendible, yet allows for only dependencies of few variables. As interconnected systems come online and are informed by streams of high-dimensional data, the ability to understand and predict is diminished and nervousness increases.

Operator acceptance is central; stronger operator involvement, training, intuitive dashboards, and transitional off-line or pilot operations are recommended to build confidence. System reliability hinges on robust sensors, actuators, communications, and fail-safe strategies. Historical limitations in hardware and communications have constrained advanced control adoption, and operator trust remains low where automated strategies are counterintuitive. Fail-safe modes and fault-tolerant control are necessary to mitigate irregular behavior and component failures (Lund et al. 2018). One common theme heard from regulators and managers is the suggestion to use ALCS to make informed suggestions, which are sent in real-time to operators, who ultimately have decision and control rights. In this case, ALCS is not in an autopilot mode making decisions and taking action, but is still utilizing the available information and capabilities of optimization to assist an operator in making better, active decisions.

4.5.3 Interoperability and standardization

Another recurrent barrier is the prevalence of proprietary, non-interoperable legacy systems and the absence of end-to-end solutions. Traditional SCADA architectures lack extensibility, spatial coverage, and secure integration with modern analytics, impeding watershed-scale coordination and optimization; this often isolates stormwater operations from downstream wastewater facilities and contemporary GIS or modeling platforms (Bartos et al. 2017). As adjacent communities and stormwater managers begin to adopt ALCS, there is potential disconnect if the systems cannot communicate with each other and work in a coordinated effort, highlighting the need for interoperability. Wireless sensor networks (WSNs) face similar challenges of limited discoverability, consistent documentation, and open interfaces, risking the repetition of legacy isolation without community standards (Bartos et al. 2017). The need for interoperable standards for data, communications, and control is widely recognized, as proprietary architectures and rapid IoT evolution exacerbate risk and inhibit integration into existing frameworks (Webber et al. 2022); (Gourbesville 2016).

4.5.4 Data uncertainty and computation

Uncertainty—spanning weather forecasts, control models, and sensor measurements—remains a pivotal technical and operational barrier. "Reliable and consistent real-time operations can only be achieved by exhaustively quantifying the role of uncertainty in control operations," with poorly designed algorithms posing risks to infrastructure and public safety (Kerkez et al. 2016). Uncertainty in rainfall forecasts is one of the most commonly heard concerns by the general public and challenges in developing optimization schemes. One study found no additional improvement gained for predictive scenarios over purely reactive schemes when using real forecasts, due to errors in the forecasts (Gaborit et al. 2015).

Seasonal forecast systems exhibit regional and lead-time dependent skill, with systematic underestimation of extremes and lower discrimination in extratropical regions, constraining reliable impact-based decisions for flood mitigation (Roy et al. 2020); (Nikraftar et al. 2024). Forecast errors propagate into RTC operations at site scale (e.g., unnecessary pre-release or missed events)complicating both experimentation and practice, highlighting the need for careful controller design and longer forecast windows where practical (Xu et al. 2020); (Persaud et al. 2019); (Post 2024). A recent study essentially concluded that the critical skill index for precipitation forecasting is worse for the warm season (rainfall), and worse in the central U.S. and Upper Mississippi River Basin where convective storms dominate the extremes, rather than synoptic storms (as on the coast) (Cordeira et al. 2025). Minnesota is in a "skill desert" (a region where predictive models show little or no forecast skill). Unfortunately, predicting large rainfall events to support forecast-based ALCS in small watersheds in Minnesota is especially challenging, as it's one of the most difficult regions in the country to predict, and this occurs during the most unpredictable season of the year (warm season with rainfall).

Long-standing precipitation data uncertainties and limited discharge observations for validation further impede robust runoff estimation and calibration, particularly in dry regions and for rapid-event runoff generation (Fekete et al. 2004). Forecast postprocessing (e.g., bias correction) improves some metrics but leaves high uncertainty for extremes; evaluation is constrained by variable scope, error metrics, and limited reference data (Roy et al. 2020); (Fekete et al. 2004); (Samaniego et al. 2019). Advances in forecast skill or bias correction are needed. Model simplifications and safety factors to attempt to account for uncertainties and errors can trigger unintended surface storage, trading CSO reduction against nuisance and perception risks for example; tuning these trade-offs is nontrivial (Lund et al. 2020).

For water quality, real-time sensing of chemical and biological parameters is less mature, costly, and subject to measurement uncertainty, limiting multi-objective controls (Webber et al. 2022); (Sharior et al. 2019). Proxies must be developed which can be measured in real time in the field, with data transmitted to a control system. Development of proxies itself imposes uncertainties.

Catchment-scale, real-time optimization is challenged by computational cost, model complexity, and generalizability. MPC implementations must balance internal model fidelity with tractable formulations and time resolution; non-linear dynamics increase solver demands and limit system or control trajectory size (Lund et al. 2018). Many optimization approaches cannot be applied in real time at network scale due to computational burdens (Webber et al. 2022), and forecast horizons introduce additional real-time computation demands in MPC/RTC, with diminishing returns beyond characteristic times of concentration in urban stormwater management (Brasil et al. 2021). Through some of our own parallel efforts on projects in Minnesota, we have observed similar results. Even our simplest hydrologic routing models show that traditional, physically-based, time-stepping approaches are too slow to effectively evaluate potential issues given a forecast, especially when attempting to account for uncertainty and developing an optimized operation plan.

Machine learning–based controllers are promising but require significant human and computational resources, with limited generalizability and sensitivity to hyper-parameters, metrics, and random seeds; risk quantification and high-dimensional uncertainty interpretation remain open problems (Mullapudi and Kerkez 2023). Further development of hydrologically-purposed neural networks, transformers, or algorithms may be the next technological advancement to close the gap on speed to provide a range of model outcomes in real time to support decisions. Studies have shown that a Long-Short-Term Memory neural network has the ability to capture hydrologic response, even better than dedicated, calibrated traditional hydrologic models, particularly when trained on many watersheds (Anderson and Radic 2022); (Grey S. Nearing et al., n.d.).

4.5.5 Data, privacy, and cybersecurity

Data governance introduces sensitive regulatory issues—privacy, security, access, and ownership—especially as monitoring becomes granular and forecasts inform control actions. Reviews emphasize privacy risks from personalized data and the vulnerability of “smart” systems to cybercrime and the demonstrated consequences of infrastructure attacks, recommending common standards, ethical guidelines, and legal regulations to legitimize data-driven approaches (Eggimann et al. 2017); (Kerkez et al. 2016). To cope with the issue of cybercrime, SCADA networks are often isolated from public networks, such as the internet, which can ultimately defeat the purpose and potential of ALCS, particularly where forecasts inform decisions (Bartos et al. 2017). As ALCS systems increasingly depend on data and active control capabilities, these questions need to be addressed during the planning and design stages of an ALCS project.

4.5.6 Public perception and design-mediated acceptance

Perception is highly sensitive to visible landscape change. In experiments using visualizations of smart ponds, manipulated high or low water levels were perceived as less attractive, neat, and safe than typical conditions, with effects moderated by context, slope, and planting. Thoughtful design, such as steeper basin slopes, woody or perennial plantings, and prioritizing certain contexts, can mitigate negative perceptions while enhancing biodiversity and carbon services; targeted outreach with the impacted public can address context-specific concerns (Li et al. 2022). Intentional surface storage is especially sensitive: "Keeping stormwater runoff intentionally on the surface may at first sound risky," necessitating explicit attention to nuisance, safety, and communication (Lund et al. 2020).

4.5.7 Pathways to overcome barriers

Despite the challenges identified in the literature and summarized in this section, the evidence of gains achieved through ALCS application outweighs the costs and risks. As in any engineered system, there are potential modes of failure and conditions that can push a system past its design and function, yet on the whole, when the value outweighs the risk, the case can be made for implementation.

One pathway that may be available for overcoming barriers is the need for updating management plans, control manuals, and operating plans. Triggers for updates may include external factors such as updates to precipitation data (such as the expected NOAA Atlas 15), or changes in zoning or other community management documents. These opportunities open the door for consideration and inclusion of ALCS as an acceptable strategy or BMP. As a parallel example based on FIRO and large-scale reservoirs, federal statutory and procedural frameworks create a similar pathway. USACE's authority under the Flood Control Act of 1944 governs use of federally funded flood storage, necessitating compliance with Corps regulations and Water Control Manuals (WCMs). Candidate FIRO strategies must satisfy relevant USACE engineering regulations, use certified analytical tools compatible with the Corps Water Management System (CWMS), and adhere to inviolable operational constraints, including release rate limits and spillway operations. A critical barrier is outdated WCMs based on historical hydrology and unbuilt infrastructure. These are being modernized to reflect improved forecast skill, new facilities, and FIRO operations (Ralph et al. 2021). Implementation proceeds via planned deviations to test operations, followed by WCM updates. Similar processes are documented at Prado, Seven Oaks, and Hanson dams, including DSS development, CWMS integration, environmental documentation, and phased model migration (Ralph et al. 2023); (F. M. Ralph et al. 2024); (M. Ralph et al. 2024).

Consistent themes in successful pathways include: developing shared standards and specifications through collaborative and open bodies and projects (e.g., @qua, HarmonIT/OpenMI) to address interoperability and maturity gaps (Gourbesville 2016); engaging regulators and stakeholders early and iteratively to build trust and incorporate requirements into design (Fussel and Watson 2019); (Sweetapple et al. 2023); (Kerkez et al. 2016); creating tailored data dashboards that manage uncertainty without overwhelming operators; and managing procedural risks by using stress-tested tools, best available data, and clear project governance (Ralph et al. 2021).

4.6 Co-Benefits Beyond Water Quantity and Quality

The literature consistently reports environmental, social, and economic co-benefits beyond flood mitigation, while also identifying technical, institutional, and social risks and barriers that shape public acceptance. There is strong consensus that adaptive controls yield environmental co-benefits, including improved water quality, ecosystem health, and multi-benefit water supply operations, alongside social and economic gains in O&M efficiency and avoided costs.

As described earlier in Section 4.1, across scales, adaptive controls improve water quality by extending detention times, moderating hydraulic shocks, and aligning releases with receiving-water objectives. Field and modeling studies show increased settling time and pollutant removal in controlled basins and ponds, with extended detention (often >24–36 hours) enhancing sedimentation and reducing downstream erosion and peak flows. In capture-and-reuse systems, pretreatment and managed storage remove trash, oil, and >80% TSS, and can provide substantial groundwater recharge and irrigation offsets (Fussel and Watson 2019).

Emerging evidence links adaptive controls to stream health. By using multi-day forecast windows, real-time control can restore baseflows and deliver outflows closer to natural flow regimes, reducing flashiness and geomorphic disturbance (Xu et al. 2020). Recent evaluations have determined that these changes in the hydrologic regime can reduce overall sediment delivery downstream (Barr Engineering Co. 2025b). Other considerations that have been discussed include using a controlled outlet for vegetation management, expecting that raising or lowering levels at specific times of the year may promote or inhibit growth of certain aquatic plant species. Modulating the level of a wet pond, lake, or constructed wetland at specific times of the year may also impact aquatic or amphibious species, in ways that promote or inhibit their presence in the waterbody. A parallel to these functions is the low-level outlet often included in the design of a dam, which allows for the lowering of the reservoir for specific purposes such as inspection, dredging, or maintenance. These types of controls on the reservoir can be actuated, infrequently, for additional purposes beyond the main purpose of the reservoir. Likewise, ALCS can serve additional environmental and ecological co-benefit purposes on an infrequent basis through activation and level control.

On the operational side, smart systems enable proactive operations and maintenance (O&M), centralized dashboards, and early warning alerts that improve public safety and emergency response (City of Lynchburg Department of Water Resources, Chesapeake Bay TMDL Action Plan (Opti by aliaxis, n.d.-d). Community-scale deployments report avoided costs relative to major grey infrastructure upgrades and support strategic planning through performance data (Opti by aliaxis and Johnson, n.d.). At the site scale, adaptive controls can reduce cistern footprints, facilitate reuse (e.g., urban agriculture), support LEED certification, and lower utility costs (Opti by aliaxis, n.d.-c). While advantages of ALCS are apparent, long-term proofs of systemwide savings remain emergent (Eggimann et al. 2017); (Lund et al. 2018).

4.7 Ownership and Operation

As systems scale across watersheds and integrate forecasts, clarity on who owns hardware and software, who operates and maintains assets, and how decisions are governed becomes central to safety, regulatory compliance, and public trust (Kerkez et al. 2016).

Across the U.S., municipal agencies, utilities, and public works departments are the primary owners, operators, and maintainers of smart stormwater systems. Meng and Hsu’s study with officials in water utilities and agencies frames water/stormwater departments, public works, and engineering divisions as the main prospective adopters and day-to-day managers of smart green infrastructure (Meng and Hsu 2019). USEPA’s national compendium of smart wet-weather projects reinforces this pattern by explicitly listing city departments and utilities as owners in case after case (U.S. Environmental Protection Agency 2021).

Though not the main purpose of this research, parallels continue to exist between active multi-objective management of large reservoir and basin-level systems, and ALCS for stormwater management at smaller water bodies. Ownership and operations at large multi-purpose reservoirs, follow established federal–state–local arrangements, with adaptive control layered through formal governance and decision support. The U.S. Army Corps of Engineers (USACE) typically owns and operates dams for flood control under Water Control Manuals (WCMs), while local agencies may operate water supply/conservation pools or downstream recharge operations. Under FIRO, a Research and Operations Partnership and Steering

Committee structure coordinates science, operations, and policy across agencies; USACE retains release authority above the top of conservation reservoir level, while local partners operate within their jurisdictions, with temporary deviations and eventual WCM updates providing the legal pathway for change. At Lake Mendocino (CA) for example, the owner is the USACE, while the cooperating agency which owns and operates the water conservation space is Sonoma Water (Jasperse et al. 2020).

Similar structures are documented for Yuba–Feather (Yuba Water and California Department of Water Resources as owner-operators; USACE oversight; shared DSS; multi-agency Steering Committee) (Ralph et al. 2021), and Prado Dam (USACE as dam operator; OCWD leading recharge operations; a Steering Committee guiding policy and technical work; phased implementation via deviations leading to WCM changes) (Ralph et al. 2023). At Seven Oaks Dam, three county flood control districts sponsor, operate, and maintain the project under the USACE WCM, with a FIRO Steering Committee and work teams integrating research and operations (F. M. Ralph et al. 2024). These arrangements formalize shared responsibilities via Terms of Reference, task roles, and consensus processes, while preserving statutory operational authority with the dam owner (Jasperse et al. 2020). These may offer blueprints for relationships and agreements between multiple cities, watershed organizations, and other stakeholders.

Smart controls are also deployed on privately owned assets and through public–private partnerships, decoupling asset ownership from service provision, with vendors and NGOs supporting outcomes-based compliance. The Maryland DOT model shows Opti and The Nature Conservancy retrofitting private Walmart ponds, with MDOT purchasing excess water quality credits—private entities own/operate ponds and platforms, while public agencies procure verified outcomes for compliance (Opti by aliaxis, n.d.-b). Building-scale projects, such as Blue Sea Development's Arbor House in New York, demonstrate developer-led ownership with building managers handling daily monitoring, control, and compliance reporting via the vendor's platform (Opti by aliaxis, n.d.-c).

Operator roles remain central even when controls are automated. USEPA emphasizes, "The operators are ultimately responsible for the system operation and performance," and should be engaged from design through post-construction monitoring. Utilities commonly retain manual override authority and integrate controls into SCADA and decision support workflows. Furthermore, operational responsibility extends beyond installation. Utilities and agencies must budget for staffing, training, SOPs, and post-event analysis; define roles and communication channels; and integrate operator input from the outset (U.S. Environmental Protection Agency 2021). Literature also notes organizational capacity gaps—new skillsets spanning IT, communications, and control systems—and cautions that software and institutional processes can be a greater barrier than hardware (Eggimann et al. 2017); (Kerkez et al. 2016). Practitioners should plan early for O&M budgets, operator training, data governance, and cybersecurity, and use MOUs/Terms of Reference to delineate roles across owners, operators, and technology partners (Kerkez et al. 2016); (U.S. Environmental Protection Agency 2021); (Eggimann et al. 2017).

4.8 Modeling Software to Support ALCS

Key tools required for evaluating ALCS projects are: water quantity and water quality models (simulators), rule-based and real-time control modules within or applied to the models, optimization tools and methods, and weather forecasting tools. Each one of these is complex, requiring experience, judgment, and calibration. There is no single "best" software; rather, tools perform best when matched to system scale, objective (flood, water quality, energy), and available forecasts.

4.8.1 Simulators and Models

EPA SWMM is open source hydrologic and hydraulic modeling code, making it a widely used software for stormwater management at the watershed scale (larger than site scale, smaller than basin scale). Often, EPA SWMM is used through other developed Graphical User Interfaces such as XPSWMM and PCSWMM. Its widespread adoption also makes it the most likely process engine for smart stormwater, extended via Python (PySWMM), MATLAB (MatSWMM), and open-source MPC tooling (swmm_mpc) to enable stepwise simulation, state access, and control-policy optimization (Sun et al. 2024); (Rimer et al. 2021); (Wong and Kerkez 2018). These addons to EPA SWMM allow for testing ALCS operating plans, strategies, and scenarios. In practice, swmm_mpc delivers dynamic optimization at sub-hourly horizons. For larger networks seeking to evaluate multiple scenarios, or perform optimization tasks, this may require high performance computing (Bowes et al. 2021).

MIKE URBAN (high-fidelity Saint-Venant) coupled with MIKE OPERATIONS has also been used. This combination supports MPC using convex optimization and linear surrogate models, achieving sub-5-minute runtimes on standard laptops—suitable for operations (Lund et al. 2020). For basin and riverine scales of large, interconnected system of upwards of hundreds of connected BMPs, the Hillslope Link Model (HLM) has been used for real-time forecasting and optimization of distributed storage, tightly integrated with high-resolution rainfall (Post, Quintero, and Krajewski 2024). HLM has also been coupled with stochastic storm transposition to generate thousands of synthetic years for planning and stress testing (Post, Quintero, Krajewski, et al. 2024).

Taken together, SWMM/PySWMM (urban drainage), MIKE OPERATIONS (MPC-ready), and HLM (network-scale storage) emerge as leading engines where selection is governed by scale, fidelity needs, and computational budgets. Some of these models may have the capabilities to model water quality as well. The water quality model P8, often used for BMP design and evaluation in Minnesota, does not inherently have methods for evaluating active controls and therefore outlets in the model must be modified to attempt to reflect the effects of ALCS on water bodies and BMPs.

Outside of traditional hydrologic models, other computational methods (often lumped together as Artificial Intelligence, Machine Learning, or Neural Networks) may support faster, more real-time simulation of watershed systems, driven by data rather than physical processes. Inflow forecasting with artificial neural networks often outperforms macroscale hydrologic process models at small-basin scales and supports 1–7 day lead times (Ahmad and Hossain 2019). Surrogate discovery via pySINDy learns parsimonious, interpretable differential equations that predict rapidly, making it suitable as a forecasting or high-performance computing surrogate layer (Dantzer and Kerkez 2023). Linear state-space models underpin observability/controllability analyses and can serve as fast internal models for MPC (Bartos and Kerkez 2021); (Lund et al. 2018).

4.8.2 Controls and Algorithms

Beyond tools to model hydrologic and hydraulic response, additional tools are needed to help determine and model the control algorithm of the ALCS. These can be developed simply through testing of various scenarios, and establishing a set of rules that govern operation (RBC). This approach lends itself to assessing only a few variables (water level of one or maybe two locations, season or time of year, forecast, etc.) to determine what the appropriate operation is. For more complex situations, different methods are needed to develop control algorithms. And in theory, as these algorithms are developed, tested, and proven successful, they can be implemented more autonomously and in real-time, as long as the source information is reliable.

For algorithm development and benchmarking, pystorms provides standardized scenarios atop SWMM via PySWMM, enabling cross-comparison of control policies (Rimer et al. 2021). Open storm demonstrates end-to-end ingestion of minute-level forecasts and real-time control over urban networks (Bartos et al. 2017). Advanced MPC formulations optimize weighted objectives for peak flow, overflow, and pollutant load, showing simultaneous reductions in peak flow and water quality parameters such as TSS under uncertainty (Oh and Bartos 2023).

MPC is the dominant optimization-based strategy for anticipating future states and enforcing constraints: The USEPA reports that "in the last 20 years, model predictive control has been the most extensively used optimization-based strategy." (U.S. Environmental Protection Agency 2021). Reinforcement learning (DDPG via TensorFlow/keras-rl) scales to continuous actions and can ingest rainfall/tide forecasts for proactive control (Bowes et al. 2021). Bayesian Optimization (GPy/GPyOpt) offers an "off-the-shelf" alternative that is more computationally efficient than genetic algorithms and natively quantifies control uncertainty (Mullapudi and Kerkez 2023).

4.9 ALCS BMP Costs in Literature

Cost comparison of ALCS retrofits to the construction of new stormwater facilities is discussed in greater detail in Section 5, particularly related to upfront installation (capital) costs. Available literature also provides insight on cost. Retrofits are favored where enlargement of facilities is costly or impractical, aligning with broader goals to rehabilitate existing systems amid climate and urbanization pressures (Li et al. 2024). Sun, Xia, and She show that MPC outperforms rule-based control, static control (passive), and implementation of low impact development features alone. Flood volume stored, peak flow discharged, and environmental benefits were all improved the most with MPC, all the while costing the least (Sun et al. 2024). Lifecycle analyses report real-time control retrofits achieving target performance at substantially lower cost than passive alternatives (Kerkez et al. 2016), with documented multi-fold performance gains at a fraction of cost in storage networks (U.S. Environmental Protection Agency 2021).

Across the literature, costs for adaptive level control systems range widely by scale (single-asset retrofits to city-wide programs), technology (open-source vs. commercial), and integration depth (sensing/telemetry only vs. full real-time control with optimization). USEPA case studies show CMAC retrofits achieving comparable or superior performance at a fraction of passive storage costs—e.g., three storage sites reduced combined capital needs from $4.6 million (passive) to $0.3 million (CMAC). Bordeaux Métropole's RTC implementation (€8 million for 15 sites) averted an estimated €222 million in traditional storage. St. Joseph's CSO solution fell from $23.2 million to $5.2 million by leveraging near-real-time data (U.S. Environmental Protection Agency 2021). Vendor case studies echo these trends: Albany reported a $6.4 million (98%) CAPEX reduction and $0.005 per gallon wet weather capture; NHSA cited 95% CAPEX savings and $0.04 per gallon compared to >$1 with passive controls (Opti by aliaxis, n.d.-c). Even where instrumentation/control costs increase, effective storage "amplification" can yield better returns on capital (Fussel and Watson 2019). Private developments report combined CAPEX and OPEX savings >$2 million by downsizing storage and reducing water purchases (Opti by aliaxis, n.d.-e). Municipal programs also show productivity savings from condition-driven O&M once sensing/control is in place (U.S. Environmental Protection Agency 2021).

Routine maintenance requirements persist, however, for smart assets. Flow metering, for instance, requires cleaning, inspection, and calibration at least twice per year to maintain data quality (U.S. Environmental Protection Agency 2021). Connectivity costs for distributed sensing/control are comparatively small: "IoT cellular data plans can be purchased for under $5 per month per node (1–10 MB)" (Bartos et al. 2017). Beyond connectivity, smart programs incur recurring IT, software, training, and field service/warranty costs. Performance-linked operating costs show advantages for RTC. In one utility case, the annual cost to reduce wet weather flow was “$0.02 per gallon with CMAC versus $0.36 per gallon with the passive design.” (U.S. Environmental Protection Agency 2021) Similar OPEX benefits appear in building-scale reuse: Arbor House reported 87% OPEX savings ($0.16 vs. $1.28 per gallon) with adaptive controls (Opti by aliaxis, n.d.-c).

Despite numerous capital and performance metrics, gaps remain. O&M and subscription line items (e.g., software licensing, cloud services, cybersecurity) are not consistently reported, and monitoring/maintenance burdens are sometimes acknowledged but not quantified (Mason et al. 2022); (U.S. Environmental Protection Agency 2021). Open-source deployments can minimize licensing costs but may shift effort to in-house integration and support (Bartos et al. 2017). Utilities should plan for explicit O&M and IT budgets, track performance-linked operating costs, and document subscription/licensing expenditures to support life-cycle cost evaluations and procurement decisions (U.S. Environmental Protection Agency 2021); (Sun et al. 2024).

The following section describes the research we completed to better understand the costs of an ALCS, and how those costs compare to traditional BMPs.

5 Costs of Adaptive Level Control Systems

Cost estimate scenarios are presented for a range of sizing and feature assumptions intended to capture key considerations and tradeoffs for typical types of ALCS applications using 2025 technology. This research approaches cost estimates from the standpoint of furnishing and installing active outlets into existing BMPs to accomplish adaptive level control, as a function of storage volume and outflow rate targets, using a variety of controllable technologies such as actuated gates, actuated valves, and operable pumping systems. The planning-level approach assumes typical ALCS features constructed in a typical urban/suburban Minnesota context.

One intended use of the cost information presented is to support planning-level ALCS life-cycle cost evaluations and procurement decisions. A second intended use is to inform project planners about ALCS from a benefit/cost perspective, for comparison to other traditional or alternative stormwater storage BMPs. The analysis and cost ranges presented here are derived from professional engineering experience and typical contexts observed in practice. However, these estimates are intended for planning and comparative evaluation only. Actual costs and benefits can vary considerably depending on site-specific conditions, design constraints, regulatory requirements, and project objectives. Accordingly, the values reported should not be interpreted as definitive or universally applicable, but rather as representative examples to inform early-stage evaluation and decision-making.

5.1 Approach Methods

5.1.1 Cost Estimate Methodology

This section summarizes the general methodology used to calculate estimated quantities and to develop estimated capital expenditure (CAPEX) and operational expenditure (OPEX) of an ALCS project. In general, the methodology was to select a desired volume of storage created by ALCS (i.e., 20 acre-feet), and then, within the constraints of reasonable precipitation forecast windows (e.g., 24 hours), identify the flow rate required to create that volume. This flow rate would then define the discharge rate through an ALCS outlet needed to achieve the desired drawdown within the specified time.

Once the target flow rate was defined, infrastructure size was estimated based on assumed design constraints, such as maximum allowable drawdown limits. For example, if a tipping gate were designed to lower by 2 feet (thus limiting the drawdown to 2 feet), the required gate width to pass the desired flow could be calculated. Because infrastructure components are typically available only in standard nominal sizes, the next larger size was selected as the representative gate size for achieving the desired drawdown volume. The same approach was applied for various outlet types.

For pump-driven systems, cost estimates were informed by professional engineering experience with pump station design and operation at comparable flow rates, reflecting typical and practical design assumptions. This process enabled estimation of the infrastructure sizes and associated costs necessary to achieve a specified storage volume prior to a forecasted storm event. The methodology was repeated across a range of target volumes to characterize cost variability.

Additionally, assumptions were made regarding the size of structures required to house valves, gates, and pumps of these dimensions, as well as the associated footprints, lengths of infrastructure, pipe sizes, and other general components needed to retrofit a BMP with a new, actively controlled outlet that provides a defined flow capacity.

The conceptual designs from this process are further defined using feasibility-level hydrologic, hydraulic, environmental, geotechnical, structural and civil engineering design considerations. After determining ALCS construction quantities for each storage volume, we applied estimated unit costs to calculate project CAPEX. We also outlined operation and maintenance tasks to estimate annual OPEX under assumed site conditions for each ALCS scenario. Estimated costs are presented to design, construct, and operate the adaptive level-control systems projects.

5.2 Data and Assumptions

5.2.1 Unit Prices and Project Cost Benchmarking Data

Cost data was gathered from representative civil engineering water resources projects in the upper Midwest, providing relevant estimates for Minnesota. Actual costs may vary due to site-specific conditions and design requirements. Unit prices are based on preliminary work analysis, contractor input, estimates based on typical observed costs, similar flood risk reduction projects, material quotes, recent bids, and published construction cost indices. These prices are then compared with historic project costs (corrected using appropriate historical cost indices), including:

- Capitol Region Watershed District and City of Saint Paul, MN. Ford Plant Site Redevelopment Green Infrastructure, Phase 1. Technical Memorandum: Ford Plant Stormwater – Phase 1 Summary & Sustainable Stormwater Management Plan. 2016.
- Barr Engineering Co., Ackerman-Estvold, CPS, Moore Engineering Inc. Mouse River Enhanced Flood Protection Project. Preliminary Engineering Report (PER) prepared for North Dakota State Water Commission, Souris River Joint Board. Appendix G. 2012.
- City of Edina. Morningside Flood Infrastructure Project, Phase 2 Bid Tabulation. 2022.
- City of Maplewood. Bartelmy-Meyer Area Street Improvements Bid Tabulation. 2014.
- Capitol Region Watershed District (CRWD). Stormwater BMP Performance Assessment and Cost-Benefit Analysis. 2012.

Benchmarking (as defined by AACE International Recommended Practice No. 10S-90) is a measurement and analysis process that compares practices, processes, and relevant measures to those of a selected basis of comparison (i.e., the benchmark) with the goal of improving estimating performance. The comparison basis includes internal or external measures. Examples of measures are estimated costs, bid tabulations or actual construction costs. Benchmarking of this preliminary estimate was performed by comparing the total project cost and the categorical breakdowns of costs to data obtained for the following projects:

- Minnesota Department of Transportation. MnDOT Plan for Mitigating the Effects of Climate Change on Pedestrians. 2023
- Minnesota Department of Transportation. Technical Memorandum: MnDOT Land Use Contexts: Types, Identification, and Use. 2018
- Minnesota Pollution Control Agency (MPCA), MIDS Work Group. Minimal Impact Design Standards (MIDS). 2011

- Ramsey-Washington Metro Watershed District. RWMWD Stormwater Best Management Practice Cost-Benefit Summary. 2018

5.2.2 Quantity Calculations and Concept Design Data

Dimensions, areas, and volumes for ALCS retrofit designs use the calculation method above and reference similar projects. Measurements are tabulated in spreadsheets, with key dimensions determined by engineering analysis or judgement. The estimate utilizes both parametric and deterministic methods for estimating quantities as a basis for cost calculations. Cost estimates are based on the following methods:

- For project features with greater project definition, deterministic methods are used to estimate costs based on quantity takeoffs and estimated unit costs for assemblies and individual components.

- For project features with lesser project definition, stochastic and parametric methods are used where project definition limits the degree to which feature quantities can be itemized, counted or measured.

In some of these cases, where itemized quantity calculations of assemblies or individual components are not easily estimated due to limited project definition, lump sum allowances or percentage estimates based on similar historical project references are used to estimate the cost typically required for such work.

Approximations are necessary to account for less costly items (generally considered those representing not more than 5% of the estimated cost of a given facility/component of the Project), utilizing cost engineering judgment, and are expected to be refined during detailed design. Where the current project definition does not allow for the estimation of itemized construction quantities, allowances are estimated based on published references, similar project estimates or bid tabulations, or other methods as described below.

5.2.3 Assumptions

Generally, it is assumed that a best management practice (BMP) is present, equipped with a passive gravity outlet such as a weir or culvert, and that the objective is to modify this outlet in order to retrofit the BMP with a controlled outlet. The following specific assumptions were made to develop the opinion of cost for planning level design:

- Site Selection, Lands and Easements and Site Access assume the following:

    1. The new active outlet can discharge to existing gravity storm sewer or open channel.
    2. The selected discharge point from the BMP is approximately 300 to 500 feet from nearest public Right-of-Way, which would contain existing storm sewer.
    3. Costs of acquiring land by fee title or easement are not included in the planning level cost; in general this will be unnecessary. Additional discussion is included in Section 5.3.2.

- Construction of the retrofit ALCS outlet, regardless of the type, assumes the following:

    1. Time to reach the target drawdown volume is within the range of 12 to 24 hours.
    2. Target drawdown is approximately 2 feet, limited by assumed regulations by permitting agencies, particularly for DNR Public Waters.

3. The proposed structure's hydraulic capacity is similar to the existing outlet, minimizing excessive pre-storm releases that could cause downstream erosion and reducing the need to enlarge storm sewer pipes.
4. Mobilization is estimated at 7.5% of the construction cost.
5. Removal and disposal of the existing outlet structure (i.e., pipe, weir, or other) assumed to cost between $600 and $800
6. Water control and dewatering are necessary for all alternative approaches, with a lump sum allocated for this purpose.
    a. For the pump station approach to an ALCS retrofit, the range was assumed to be $60,000 to $100,000.
    b. For the gate approach to an ALCS retrofit, the range was assumed to be $40,000 to $80,000.
    c. For the in-line valve approach to an ALCS retrofit, the range was assumed to be $40,000 to $60,000.
7. A construction pad is required near the site, measuring approximately 50 ft by 50 ft, or 2,500 square feet, which would be sufficient to accommodate the equipment expected to be required for this level of construction.
8. A construction access road is required to provide access from the nearest Right-of-Way; the road will measure approximately 300 to 500 feet in length and 20 feet wide.
9. Clearing and grubbing will be required prior to construction to be equivalent to total disturbance area (footprint of the outlet structure, construction pad, and construction access road).
10. Site restoration will be required over the same disturbance area, largely composed of turf establishment.
11. Project construction is expected to last 1.5 to 3.5 months for estimating contractor supervision and observation costs.
12. Minor dredging will be required around the area of the proposed structure. All dredged materials will be hauled and disposed of offsite as regulated/contaminated soil.
13. For any ALCS structure type (pump, valve, or gate), only shallow foundations are assumed; costs exclude deep (pile) foundations, which should be accounted for separately if needed.
14. Wetland mitigation, whether temporary or permanent, is site-specific and excluded from construction and restoration costs; it should be considered separately.
15. Public Waters OHWL impact mitigation may be necessary; however, due to its site-specific nature, it is not included in construction and restoration costs and should be evaluated independently.
16. The one-time initial cost of control system from an ALCS product vendor (e.g., Opti) is approximately $100,000, ranging from $90,000 to $120,000 based on assuming coordinated systems or controls with features that support both water quantity and water quality.

- Water Level Control Approach: Pump Station(s) assume the following:

1. The pumped rate is a net outflow (i.e., inflow equals zero, or the pumped rate is higher to offset the assumed inflow over the pumping time period).
2. The new pump station structure is underground with the top slab at grade, and with no above-grade out-building to limit the aesthetic changes.
3. Electrical capacity (i.e., 480 V) is available and in close proximity, requiring a standard level of effort by an electrician to establish a connection.

4. Contains a backup power generator, as well as a pump control system, which operates independently from the active control that communicates with the decision controls.

- Water Level Control Approach: Actuated Valve(s) assume the following:

1. Gravity discharges to existing storm sewer system and downstream outfalls.
2. Proposed pipe(s) will connect to existing storm sewer infrastructure.
3. Installing an inline valve within the piping system necessitates replacing the current gravity pipe and lowering its upstream elevation. The invert of the proposed pipe is approximately four feet below that of the existing pipe invert, allowing for a maximum drawdown of two feet.
4. Actuated gate valve to be the same size as the proposed pipe size (i.e., in line with the pipe).
5. The proposed pipe will discharge into the existing storm sewer, which is assumed to have sufficient capacity to convey the proposed flow. Because the new pipe is set lower at the upstream end and connects to the existing storm sewer at the downstream end, it will have a milder slope than the original pipe, which was designed with a typical storm sewer gradient. As a result, the new pipe may be too flat to maintain free-surface flow under design conditions. Accordingly, hydraulic losses in the pipe were calculated based on friction losses associated with pressurized, full-flow conditions.
6. Proposed pipe(s) material will be HDPE, and require a minimum of 2 feet of cover above the proposed pipe(s) for pipe stability.
7. Precast concrete is required for manhole structures housing in-line valves, except when alternatives have more than three parallel pipes; in those cases, a Cast-in-Place structure is recommended.

- Water Level Control Approach: Actuated Weir or Gate(s) assume the following:

1. Gravity discharge to existing storm sewer system and downstream outfalls.
2. The maximum gate height (tipping or sliding length) is 3 feet, to be able to achieve the target drawdown. Gate heights may range from 1 to 3 feet to accommodate scenarios requiring a reduced drawdown.
3. The gate width is determined from height and target flow rate to achieve the required withdrawal volume.
4. The downstream pipes won't need replacing since the passive weir is being swapped for a sliding or tipping gate, keeping the crest above them.
5. The existing structure is replaced with a new precast or cast-in-place structure, sized to accommodate the sliding or tipping gate.

- Planning, Engineering and Design, Permitting and Regulatory Approvals (additional detail in Sections 5.3.4).

1. Approximately 20% of construction cost for all of these items in total

- Operation and Maintenance (additional detail in Section 5.3.3).

1. Maintenance is estimated to range from $2,500 to $5,000 per year for gate and valve type ALCS retrofits.
2. Maintenance is estimated to range from $4,000 to $6,000 per year for pump system type ALCS retrofits

3. Operation is estimated to range from $7,000 to $15,000 per year for annual software or control system subscriptions for ALCS retrofits (i.e., decision support system in the cloud, data dashboards, etc.)

- Construction Contingency

1. The total construction cost includes a 30% contingency.
2. In this report, contingency refers to an allowance intended to cover unforeseen conditions that cannot be precisely determined based on the available information when preparing the cost estimate, but should be included as a sufficient amount to address potential issues.

- Anticipated Accuracy Range

1. The planning level cost estimate range is -50% to +100% which reflects ASTM 2516-11, Class 5 (representing less than 5% project definition)

5.3 Cost Estimates

5.3.1 Estimated Construction Costs

This section provides estimated construction costs for ALCS retrofits based on the outlined methodology and assumptions. These estimates cover construction activities only and exclude land acquisition, operation, maintenance, monitoring, engineering design, and permitting.

5.3.1.1 ALCS Gate Option

ALCS slide gate or weir construction costs were calculated for up to 80 acre-feet of storage, with both low and high estimates. To estimate construction costs and set storage volume goals, a drawdown depth of one to three feet within 12–24 hours was used to calculate the necessary weir or gate size. Three weir sizes were estimated for each target storage volume goal to handle the required flow for drawdown targets. Once these weir dimensions were set, the outlet structure size was determined. A summary of the opinion of probable costs is provided below in Table 1.

Table 1 Opinion of total construction cost for ALCS actuated gate retrofit options

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$426,000	$780,000
20	$436,000	$889,000
30	$455,000	$974,000
40	$465,000	$1,081,000
50	$476,000	$1,176,000
60	$509,000	$1,285,000
70	$516,000	$1,379,000
80	$532,000	$1,487,000

These cost ranges are based on estimated ranges in units costs and in quantities; at planning level, the accuracy range of -50%/+100% should be applied to these costs

The largest anticipated capital cost associated with construction features for an actuated weir or gate project is typically the outlet structure, which includes both the gate and its housing structure. A summary of the opinion of probable cost for the outlet control structure of an actuated gate project is provided below in Table 2

Table 2 Opinion of construction cost of the outlet structure for ALCS actuated gate retrofit options

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$18,300	$40,900
20	$22,100	$94,900
30	$31,600	$148,000
40	$36,400	$208,000
50	$41,200	$261,000
60	$53,700	$322,000
70	$61,500	$375,000
80	$69,200	$436,000

These cost ranges are based on estimated ranges in units costs and in quantities; at planning level, the accuracy range of -50%/+100% should be applied to these costs

ALCS gate or weir structures are expected to cost between $10,000 and $20,000 annually for operation, maintenance, and subscription fees. Repair or replacement is discussed further in Section 5.3.3. These costs may escalate over time and should be considered when planning for a stormwater project that includes ALCS.

5.3.1.2 ALCS Valve Option

Construction costs for the actuated valve solution were evaluated for up to a 50 acre-feet storage target, considering both low and high cost estimates. Compared to weir or gate alternatives, the valve option offers a lower achievable drawdown volume due to constraints imposed by pipe size and flow capacity. When using an in-line valve and connecting to an existing storm sewer, there are limitations on how deeply the new pipe with the valve can be buried. As the upstream BMP's water level lowers, flow through the pipe becomes limited, especially below the pipe inlet's crown. Pipes larger than 36 inches were not permitted; for extra capacity, up to three parallel pipes could be used. Due to hydraulic constraints, maximum achievable drawdown was set at 50 acre-feet

A drawdown depth of one to four feet within 12 to 24 hours was set as an initial target for estimating pipe sizes, construction costs, and volume requirements. For each specified target volume, at least two pipe sizes were estimated according to the necessary flow rates to achieve the drawdown objectives. Once the approximate dimensions for these pipes were established, the design of the structure could be finalized (including valve housing, subcut, and subgrade required for pipe installation). A summary of the opinion of probable costs is provided below in Table 3

Table 3 Opinion of total construction cost for ALCS actuated valve retrofit options

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$542,000	$806,000
20	$591,000	$843,000
30	$615,000	$869,000
40	$662,000	$930,000
50	$770,000	$1,054,000

These cost ranges are based on estimated ranges in units costs and in quantities; at planning level, the accuracy range of -50%/+100% should be applied to these costs

For an actuated valve project, the largest anticipated initial capital cost is typically the pipes, which must be properly sized and may need to be laid in parallel for higher volume targets. Recall, the assumption for the length of new pipe was 300 to 500 feet to reach the existing storm sewer system in the Right-of-

Way. The processes of removing, bedding, installing, and burying this amount of pipe represent considerable costs. A summary of the opinion of probable cost for the pipes, valves, and structure housing the valve is provided below in Table 4

Table 4 Opinion of construction cost of the outlet structure and pipes for ALCS actuated valve retrofit options

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$62,100	$87,300
20	$103,000	$128,000
30	$115,000	$138,000
40	$119,000	$143,000
50	$160,000	$189,000

These cost ranges are based on estimated ranges in units costs and in quantities; at planning level, the accuracy range of -50%/+100% should be applied to these costs

ALCS gate or weir structures are expected to cost between $10,000 and $20,000 annually for operation, maintenance, and subscription fees. Repair or replacement is discussed further in Section 5.3.3. These costs may escalate over time, and should be considered when planning for a stormwater project that includes ALCS.

5.3.1.3 ALCS Pump Option

Construction costs for the actuated pump option were estimated for up to a 100 AC-FT volume, with both low and high-cost estimates. To estimate construction costs and establish feasible volume targets for the alternative, a preliminary drawdown depth of one to four feet within 12 to 24 hours was selected as the basis for calculating the necessary pump size to achieve the drawdown requirement. Once the pump discharge capacity was determined, pump sizes and pre-packaged pump stations with submersible pumps were identified to achieve the desired flow and volume. Costs were estimated based on these pumps and stations. A summary of the opinion of probable costs is provided below in Table 5

Table 5 Opinion of total construction cost for ALCS pump station retrofit options

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$864,000	$1,263,000
20	$903,000	$1,340,000
30	$941,000	$1,417,000
40	$980,000	$1,495,000
50	$1,019,000	$1,572,000
60	$1,056,000	$1,656,000
70	$1,095,000	$1,736,000
80	$1,135,000	$1,810,000
90	$1,172,000	$1,888,000
100	$1,211,000	$1,898,000

These cost ranges are based on estimated ranges in units costs and in quantities;
at planning level, the accuracy range of -50%/+100% should be applied to these costs

ALCS gate or weir structures are expected to cost between $11,000 and $21,000 annually for operation, maintenance, and subscription fees. Repair or replacement is discussed further in Section 5.3.3. These costs may escalate over time and should be considered when planning for a stormwater project that includes ALCS.

5.3.2 Land Acquisition

A unique advantage provided by ALCS systems for stormwater management is the flexibility that it offers in managing runoff in constrained environments or areas where construction space is limited. This is especially advantageous in urban or suburban areas, where the expense of acquiring land may be prohibitive. Traditional stormwater management practices may require the acquisition of properties in or around impacted areas to build out structures such as retention or infiltration ponds, whereas ALCS systems can meet the runoff management needs provided by traditional BMPs through the retrofit of existing stormwater management infrastructure, providing significant cost savings. However, in regions with more available space for construction, such as newer development areas lacking stormwater infrastructure or where flood risks are not yet established, the absence of land acquisition in ALCS systems offers limited benefit compared to traditional stormwater management methods.

For planning purposes, it is advisable to include potential land acquisition as a line item in the planning-level cost estimate, particularly when evaluating alternatives such as constructing or expanding wet or dry ponds. In urban and suburban areas, land costs can vary significantly. Acquiring land may range from five thousand per acre for agricultural pasture or cropland, to hundreds of thousands of dollars per acre in metropolitan or suburban areas, depending on factors such as location and land value.

To provide context, constructing a new pond with a storage capacity of 30 acre-feet for stormwater management would likely necessitate acquiring approximately 10 acres of land (+/- 5 acres). This estimation is based on typical conditions in Minnesota, where relatively flat topography limits the achievable vertical live storage in a stormwater detention pond to between 3 and 6 feet before overflow occurs. Furthermore, regulatory setbacks between adjacent property boundaries are required, and integrating a stormwater pond within the confines of an existing parcel often results in inefficiencies, leaving portions of acquired land unused. Considering estimated costs ranging from five thousand to several hundred thousand dollars, land acquisition expenses alone may range from approximately $50,000 to over $1,000,000. The total cost of land depends entirely on location and availability, and planners may be able to use these numbers, along with their own local knowledge and expertise on land value, to estimate this line item.

5.3.3 Operation, Maintenance, and Monitoring

The operation, maintenance, and monitoring of ALCS projects following construction share several standard O&M requirements among the various alternatives; however, these activities are also significantly influenced by the specific characteristics of the site where the ALCS solution is deployed. Operation and maintenance are expected to consist of the following annual items, regardless of whether the ALCS approach is using a gate, valve, or pump station.

- Annual inspection and documentation
- Mechanical maintenance of the motors, actuation system, seals, and lubrication
- Electrical maintenance of the control panel
- Site maintenance clearing sediment and debris
- Structural maintenance of any corrosion, the hatches, and access and safety
- Electricity consumption for actuating the gate, valve, or pump station

- Licensing and subscription costs for the ALCS controls

Additionally, repair, rehab or replacement of the ALCS components will be required on longer time frames, and it varies by approach. Typically, gates and valves may need replacement or repair every 15 years on average. Pumps may need replacement or repair every 10 years on average. For all ALCS retrofit types, dredging of sediment in the pond and around the structure inlet is expected, likely once every 10 years.

These costs are best estimated by owners and operators who know their managed systems and their staff well. The annual costs for these items should be considered, and added to the construction costs listed in Section 5.3.1 to fully consider the cost of ALCS retrofits to existing BMPs. These costs are important to consider because they likely are higher in total for an actuated ALCS system than for a passive outlet structure.

ALCS scenarios utilizing pump systems are more dependent on the long-term maintenance of mechanical pumping systems than systems using gates or valves and relying on gravity. Pump system maintenance and replacement schedules are unique, but in general are likely to require more frequent and more effort-intensive maintenance interventions than gate or valve systems. For example, the life cycle cost analysis (LCCA) for 10 acre-foot ALCS drawdown options were compared for pump, valve, and gate approaches using a life cycle costing tool developed by North Dakota State Water Commission (50-year analysis duration, and 2.75% discount factor for present value calculations). More comprehensive maintenance of pumping systems at 10-year intervals is typically necessary in addition to the higher up-front capital cost of pumping systems. The anticipated maintenance intervals and present value maintenance costs for each system type are shown in Figure 3 and Figure 4.

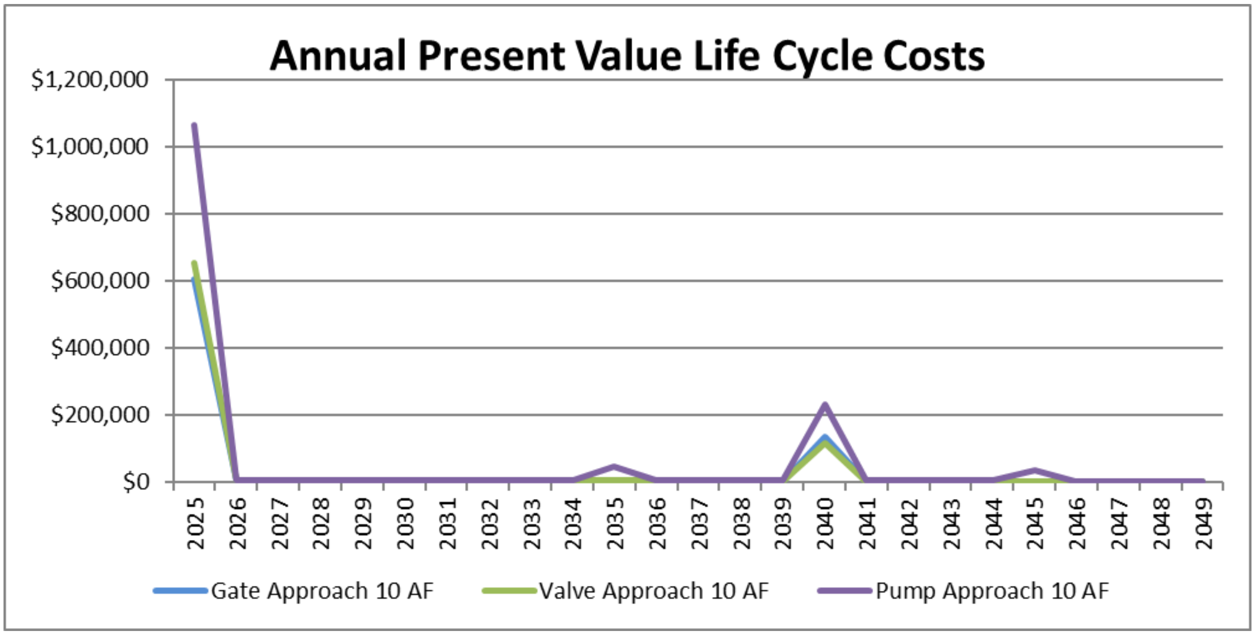


Figure 3 Annual life cycle costs, including initial capital (2025), and repair and replacement costs

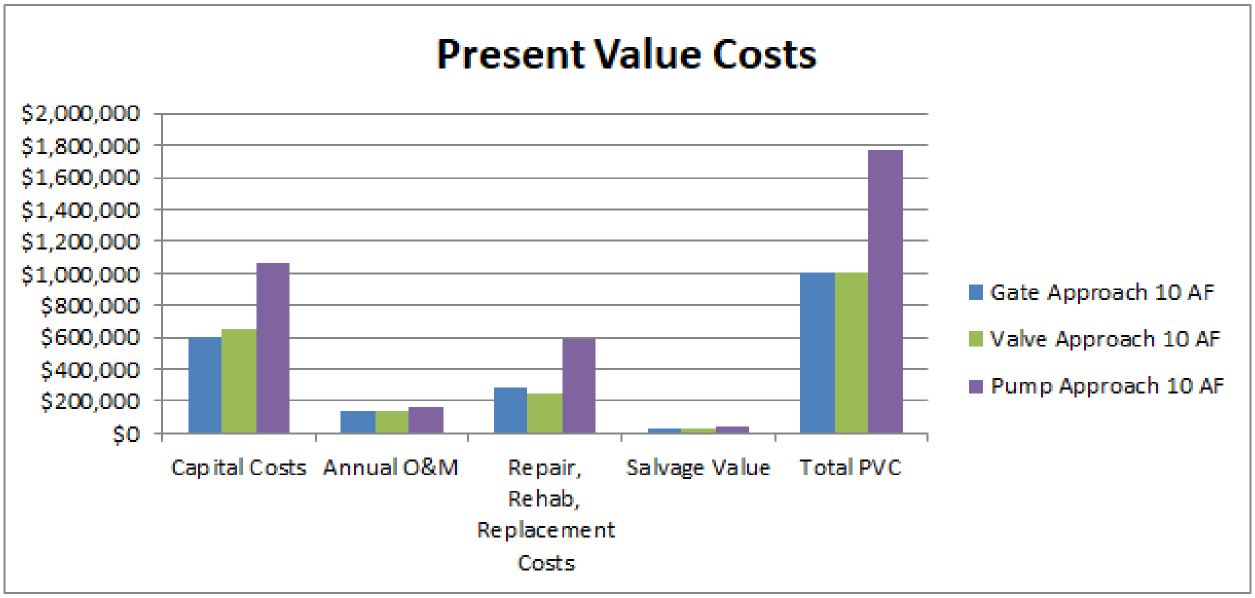


Figure 4 Present value costs for three ALCS approaches, for initial capital, annual O&M, repair, replacement, and returned value from salvage

As the cost of annual maintenance increases, the affordability in terms of present value becomes more challenging. Emphasizing ALCS opportunities that rely on retrofitting existing facilities to utilize gravity strategies such as gates and valves (as opposed to mechanical pumping systems) reduces a project's exposure to the impactful influence of higher maintenance costs on the project's long-term benefit-cost relationship.

Finally, at this time, subscription costs for ALCS are anticipated to be between $7,000 and $15,000 per year, depending on the complexity of the controls. These costs may escalate over time.

5.3.4 Engineering Design and Permitting

At the planning stage, cost estimates typically allocate a portion for engineering and design, which is often calculated as a percentage of the projected construction cost. As project size and complexity increase, the scope of design work expands, generally requiring more engineering time to complete the design process. This estimation approach relies on professional experience with comparable stormwater management projects, connecting overall construction expenditures to the requisite engineering and design effort. Our assumptions related to construction cost estimates are detailed in Section 5.2.3. It is essential to account for the site chosen, as varying site factors may significantly influence the engineering and design costs of the selected alternative. Factors may include the distance from storm sewer infrastructure, watershed size or existing stormwater practices at the proposed ALCS site, soil conditions affecting foundations and construction, vegetation, construction constraints, and proximity to structures.

This line item also includes the cost of designing the control algorithm. For single sites, given hydraulic constraints of available storage and discharge limits, the plan can be relatively simple to identify, test, define and refine (on the order of tens of thousands of dollars). For projects involving multiple sites or plans with several competing objectives, defining, testing, and demonstrating the function of these plans can be challenging and may require substantial financial resources. Project goals should guide the allocation for this line item, which may need to be increased to accommodate complex operating plans, intricate site conditions, or variations from initial cost estimate assumptions.

In addition to the engineering and design, the cost estimates also include assumptions for the effort associated with permitting. Implementation of any BMP typically requires permits from municipal authorities, watershed management organizations, state agencies, and potentially federal entities. Retrofitting ALCS to existing stormwater BMPs like constructed ponds or reservoirs generally requires less permitting than retrofitting ALCS to Public Waters such as lakes. The number of permitting agencies can vary between the two cases. The estimate for construction costs includes permitting expenses; however, adjustments may be necessary for locations that are expected to involve more complex permitting processes or heightened agency involvement. Additionally, pilot projects will necessitate greater investment and increased agency involvement if programmatic ALCS operational conditions are not established with the relevant agencies prior to implementing individual projects. Section 6.2.3 outlines the ALCS Implementation process, including agencies and permits that may be necessary. Planners can use this section to determine the level of agency involvement and permitting required for their planned ALCS retrofit site and make corresponding adjustments to cost estimates.

5.4 Cost Comparison Summary

Based on the methodology outlined in Section 5.1, the assumptions detailed in Section 5.2, and the cost estimates for construction and related items provided in Section 5.3, this section presents a comparison of these costs with the anticipated costs of traditional BMPs. All costs provided pertain to a typical ALCS system within a typical operational context. It is important to note that local site conditions, design constraints, and specific design criteria may vary from those assumed here and should be carefully considered when making comparisons during actual ALCS project planning.

Retrofitting ALCS to existing BMPs provides a high level of value compared to construction of new traditional BMPs when considering construction cost per volume produced. Based on the cost estimates developed for retrofitting ALCS to existing BMPs, the typical average value, including actuated gates, valves, or pumps, is approximately $1 per cubic foot of volume. In contrast, the average typical construction cost of a retention storage BMP, such as above grade wet ponds, is approximately $5 per cubic foot of volume, ranging from as low as $2 per cubic foot for large ponds, to as high as $15 per cubic foot for small ponds. Underground storage as a retention BMP is not even comparable, with average construction costs over $20 per cubic foot of storage. Green infrastructure BMPs such as rainwater gardens are even more costly to construct, with an average typical value of nearly $30 per cubic foot of volume. A summary of comparisons of typical BMP costs per cubic foot of storage is provided below in Table 6. For the traditional BMPs listed in Table 6, the cost per cubic foot is for construction costs, including line items such as mobilization, engineering and design, and permitting. This was to make these costs directly comparable to those costs for ALCS retrofits described in Section 5.3.1.

Table 6 Comparison of typical BMP cost per cubic foot of storage to estimated ALCS cost per cubic foot of storage

Retention Storage BMPs	Installation	Low Typical $/cf Volume	Average Typical $/cf Volume	High Typical $/cf Volume
Underground Storage	underground	14	21	28
Above Grade Wet Ponds (Large, ~50 ACFT)	above ground	1	2	3
Above Grade Wet Ponds (Medium, ~10 ACFT)	above ground	3	5	10
Above Grade Wet Ponds (Small)	above ground	10	15	50
Green Infrastructure BMPs	**Installation**	**Low Typical $/cf Volume**	**Average Typical $/cf Volume**	**High Typical $/cf Volume**
Rainwater Garden (infiltration)	above ground	13	18	22
Rainwater Garden (biofiltration)	above ground	16	21	27
Enhanced Media Filter	above ground	21	24	27
Stormwater Planters	above ground	21	27	34
Tree Trench (infiltration, filtration)	above ground	35	53	70
ALCS BMPs	**Installation**	**Low Typical $/cf Volume**	**Average Typical $/cf Volume**	**High Typical $/cf Volume**
Actuated Gate Weir (Medium, ~10 ACFT)	retrofit	0.98	1.38	1.79
Actuated Gate Weir (Large, ~50 ACFT)	retrofit	0.22	0.38	0.54
ALCS Pump Station (Medium, ~10 ACFT)	retrofit	1.98	2.44	2.90
ALCS Pump Station (Large, ~50 ACFT)	retrofit	0.47	0.59	0.72
ALCS Pump Station (Very Large, ~100 ACFT)	retrofit	0.28	0.36	0.44
Actuated Valve (Medium, ~10 ACFT)	retrofit	1.24	1.55	1.85
Actuated Valve (Large, ~50 ACFT)	retrofit	0.35	0.41	0.47

Similar to traditional BMPs, as the target storage volume increases, the cost per cubic foot of volume decreases for all ALCS alternative approaches. However, at the higher end of proposed volume targets, some alternatives, such as the actuated valve approach, approach a lower limit and/or become likely infeasible. In contrast, approaches that use a pump station could in theory just keep going larger and larger. For all of the proposed approaches to ALCS retrofits, the construction cost appears to asymptotically approach less than $0.50 per cubic foot of storage created. As a stormwater management approach that can provide flood storage volume, modulate flows to reduce downstream erosion, potentially provide ecological co-benefits, all with limited aesthetic modifications at the surface, and usually without the need for land acquisition, the cost comparison to traditional BMPs is very appealing. A figure illustrating the relationship between proposed volume and price per cubic foot is provided in Figure 5 below.

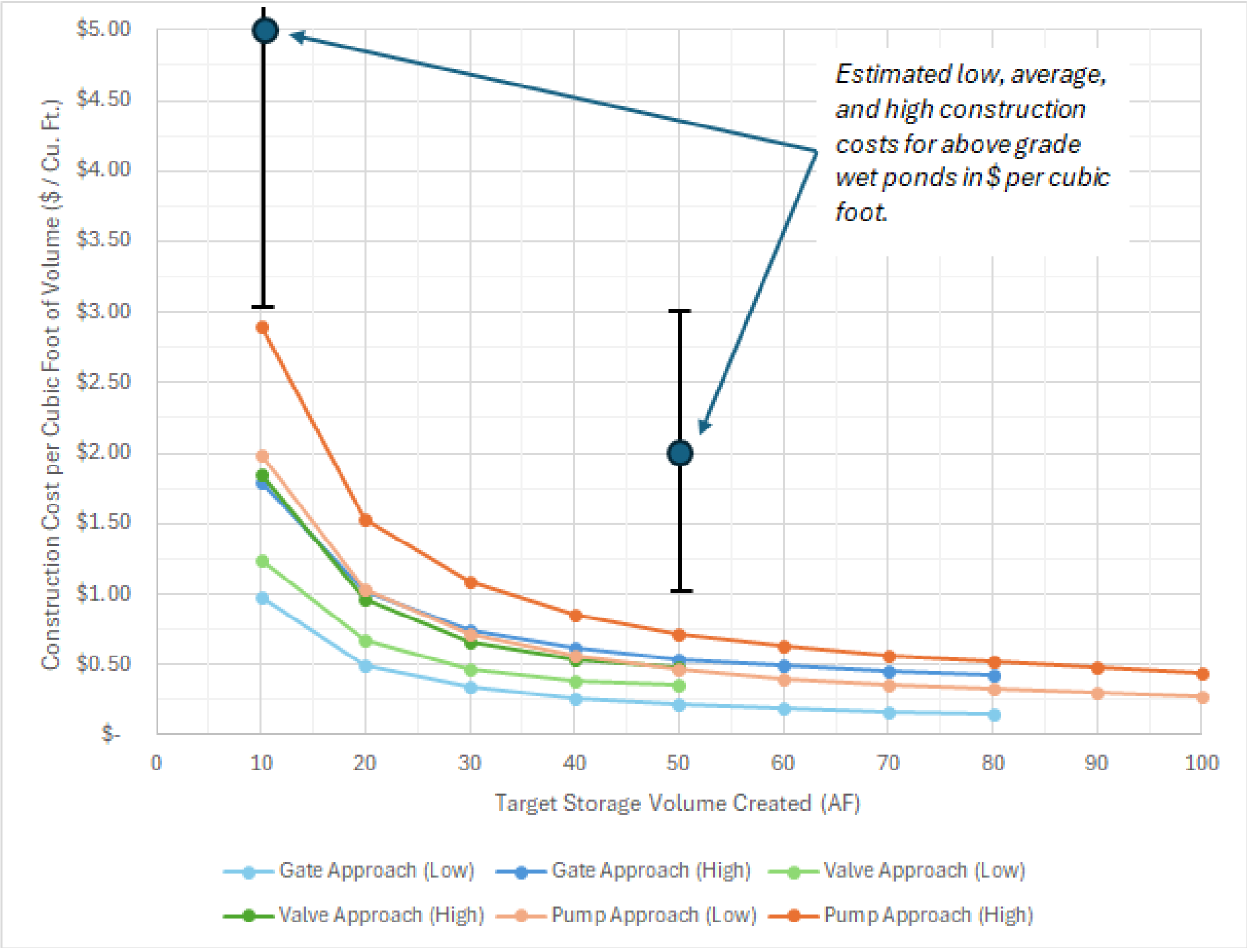


Figure 5 **Construction cost per cubic foot of created volume for ALCS retrofits**

5.4.1 Example Approach to Quickly Establish a Planning Level Construction Cost Estimate

Commonly, stormwater managers begin with a need to store a known volume in acre-feet, or treat (via creating storage) a known depth of runoff from the watershed, often a goal of 1.1 inches in Minnesota. For purposes of flood risk reduction, the inflow volume from upstream areas must be estimated, such as to solve an upstream flooding issue, to determine the additional storage required in an existing BMP. For stormwater treatment purposes, the storage volume required to capture runoff is often related to the watershed impervious area. For planning, the watershed area can be multiplied by the estimated impervious area, and multiplied by the target runoff depth for capture and storage, and with proper unit conversion, used to estimate the storage volume desired. Table 7 is provided to help planners quickly approximate the storage volume that would be required to capture runoff from a contributing watershed, if the intent is to capture a given runoff depth.

Table 7 Storage volume required to contain a given runoff depth from the impervious areas, as a function of watershed area and imperviousness

Watershed Area (ac)	25% Impervious			50% Impervious			80% Impervious		
	0.5 in	1.1 in	2.5 in	0.5 in	1.1 in	2.5 in	0.5 in	1.1 in	2.5 in
10	0.10	0.23	0.52	0.21	0.46	1.0	0.33	0.73	1.7
50	0.52	1.1	2.6	1.0	2.3	5.2	1.7	3.7	8.3
100	1.0	2.3	5.2	2.1	4.6	10	3.3	7.3	17
200	2.1	4.6	10	4.2	9.2	21	6.7	15	33
500	5.2	11	26	10	23	52	17	37	83
1,000	10	23	52	21	46	104	33	73	167

For example, to collect 1.1 inches of runoff from a 600-acre watershed with 25% impervious surfaces, storage of 14 acre-feet would be necessary. Capturing 2.5 inches of runoff from a 100-acre watershed with 80% impervious surfaces would require creating a storage of 17 acre-feet. For this example, assume a target volume of 15 acre-feet.

After estimating the needed volume, use Figure 5 to determine construction costs per cubic foot for different ALCS retrofit types. For this example, if 15 acre-feet was the target, and the gate or valve approaches were being considered due to feasibility with the existing infrastructure, the cost per cubic foot could be estimated to be approximately $1.10/cf, and potentially up to $1.50/cf. The construction cost can then be quickly estimated to be about $720,000, and could be upwards of $980,000. Very quickly, a planner could be estimating budget needs for subsequent years to retrofit an ALCS component onto an existing BMP.

This presumes that the current BMP is capable of providing the necessary 15 acre-feet of storage. It is recommended to conduct a preliminary feasibility assessment by comparing the footprint of the existing BMP with the target storage volume. If the existing BMP footprint exceeds half the target volume (in this case, more than 7.5 acres), the ALCS retrofit is more likely to produce the target volume. This is due to an assumption that an ALCS retrofit will have an easier permitting process if the target drawdown is 2 feet or less, particularly if the existing BMP is a Public Water. If the BMP is not a Public Water, as in the case of a constructed stormwater pond, the footprint can be much smaller, as the target drawdown may be able to be deeper.

This also assumes that the downstream infrastructure can handle the anticipated dry-weather discharge (pre-storm releases) from the existing BMP to create the desired storage volume. An approximate method is to determine whether the downstream infrastructure, such as pipes or channels, can accommodate a flow rate ranging from one-half of the storage volume up to the full storage volume over a period of 12 to 24 hours. In this scenario, where a storage volume of 15 acre-feet is desired, the corresponding flow rates range from 7.5 cubic feet per second (cfs) to 15 cfs. This estimate assumes that the total volume is discharged uniformly over a period of 12 to 24 hours preceding a storm event.

If the target volume is limited by either available space or downstream hydraulic capacity, it is necessary to adjust the target volume accordingly. This involves reducing the target volume, updating cost estimates, and recalibrating expected benefits, such as diminished flood risk mitigation or decreased volume available for runoff treatment.

If the planner has identified a feasible existing BMP where ALCS could potentially be applied and has estimated the construction cost (in this example, between $720,000 and $980,000) it is worthwhile to also estimate the construction cost to achieve the same level of storage volume, using traditional BMPs. An above-grade wet pond may cost $4/cf, and up to $8/cf (slightly larger than “medium” size), totaling $2.6M to over $5M for construction cost. Underground storage or rainwater gardens achieving the same storage volume could both cost around $20/cf, totaling over $10M for construction.

Another advantage of implementing an ALCS retrofit is that it may eliminate the need for land acquisition. Similarly, underground storage typically does not require land acquisition, although it may necessitate relatively minor easements. New wet ponds and rainwater gardens, however, may require land acquisition, potentially around 5 acres of land for this example. Depending on the location of the proposed project within Minnesota, the acquisition cost for 5 acres of land may range from $50,000 to $500,000 or higher as an additional upfront expense.

Operation, maintenance, and monitoring costs should be incorporated as well. Over 30 years, as an example, the costs for operation (ignoring escalation or inflation costs) of this gated or valved retrofit could be $210,000 to $450,000. The costs for maintenance, including two replacements (once per 15 years) could total over $500,000 over the 30 years. These ongoing costs, while more than would be for a passive structure, when added to the initial construction cost still show economic advantage over newly constructed BMPs.

5.4.2 Cost Estimate Interpretation, Uncertainty and Sensitivity

Cost uncertainty for the conceptual ALCS design scenarios is greater due to factors such as limited project definition and assuming typical location and site conditions. For example, typical assumptions do not capture an actual project’s context-specific hydrology, uncertainty related to unit prices, uncertainty regarding design and analysis assumptions, limited on-site investigations, unforeseen constraints, and unforeseen constructability issues. In general, uncertainty will decrease as greater project definition is developed, and more detailed information becomes available to reduce the uncertainty associated with these and other risk factors. Use and reference of the BMP cost information in this report should consider this section on uncertainty and sensitivity when selecting an appropriate anticipated accuracy range for opinions of cost.

5.4.2.1 Benefit-Cost Sensitivity to Operational Drawdown Effectiveness

The cost estimates for the ALCS pumping scenario do not include consecutive events. Stormwater storage level drawdown duration and conceptual pump sizing assumes standing water level at the start of drawdown and no contributing inflow to the stormwater storage basin while the ALCS is drawing down the standing water level. For ALCS scenarios assuming pumping systems, this could directly affect pumping rates and pump system costs.

5.5 Disclaimer

The feasibility level construction cost estimate provided in this report is made on the basis of Barr’s experience and qualifications and represents our best judgment as experienced and qualified professionals familiar with projects of this nature. The costs presented here are based on concept-level design. In addition, because we have no control over the eventual cost of labor, materials, equipment or services furnished by others, or over a contractor’s methods of determining prices, or over competitive bidding or market conditions, Barr cannot and does not guarantee that proposals, bids, or actual construction costs will not vary from the opinion of probable construction cost presented in this report.

6 Strategies for Implementation

6.1 General ALCS Implementation Framework

Based on the literature review described in Section 3, the research indicates that ALCS projects typically follow a multi-phase implementation process that can be applied broadly across jurisdictions. Most programs use iterative "nominate–simulate–evaluate–iterate" processes to define alternatives, simulate performance under common hydrometeorological datasets, compute metrics, and refine designs for selection (Ralph et al. 2021). Generally, "nominate–simulate–evaluate–iterate" can be defined as follows:

- Nominate: identify and propose potential design or operational alternatives for evaluation.
- Simulate (model): test nominated alternatives under realistic or historical conditions.
- Evaluate: assess performance using consistent, quantitative metrics (e.g., flood risk reduction, capital cost, etc.).
- Iterate: refine and improve based on evaluation results.

Clearly defining each phase helps project teams manage tasks and stakeholders at each step. Table 8 summarizes the typical ALCS implementation phases and key activities associated with each.

Table 8 ALCS Implementation Phases, from the literature review

Implementation Phase	Key Activities
Planning and Feasibility	Define the problem, engage stakeholders, and assess organizational readiness, costs, and risks. Evaluate technologies, governance, and control architectures. Build organizational commitment and establish clear roles and schedules.
System Design, Modeling, Control Strategy Selection, and Permitting	Select and design control approach (RBC, MPC, or RL) and develop supporting models. Build/calibrate models and encode objectives (flood mitigation, water quality) and constraints. Optimize for real-time performance and computational feasibility. Coordinate permitting, interagency collaboration, and regulatory approvals. Pilot systems to de-risk operations and enable broader expansion.
Hardware Deployment and Communications Architecture	Retrofit infrastructure with sensors, actuators, and telemetry. Implement layered system: field hardware → cloud services → application logic (visualization, alerts, automation). Integrate with SCADA/Decision Support System (DSS) to manage flows and storm responses.
Forecasting, Data, and Decision Support	Set up automated data flows and systems for real-time forecasting and integrate forecasts into operations. Develop decision support tools (dashboards, indicators, model integration). Ensure data quality and adjust automation based on forecast performance.
Operations, Maintenance, and Governance	Establish O&M programs, documentation, and staff training. Incorporate cybersecurity, interoperability, and standardization. Maintain monitoring and oversight, ensuring reliability and human control.

Each implementation phase derived from the literature review is described in detail in the sections that follow, highlighting key tasks, considerations, and decision points.

6.1.1 Planning and Feasibility

Across the literature, implementation begins with clear problem definition, stakeholder engagement, and an assessment of organizational readiness, costs, and risks. The U.S. Environmental Protection Agency outlines a practical roadmap that includes visioning, realistic scheduling, rigorous technology evaluation, detailed planning, phased deployment, and continuous improvement, supported by early and sustained staff buy-in, defined roles, and clear performance expectations (U.S. Environmental Protection Agency 2021).

Early technical scoping involves determining whether to use centralized or distributed control architectures and aligning control objectives with site types (e.g., detention basins vs. small-scale green infrastructure), monitoring requirements, and costs (Brasil et al. 2021). Understanding user needs and adoption drivers is also critical; surveys indicated that agency preferences are influenced by construction and maintenance costs, performance, and additional functions such as monitoring or water reuse, highlighting the value of testing scenarios with practitioners before procurement (Meng and Hsu 2019).

Governance and jurisdictional questions—such as ownership, interoperability, and liability—should also be resolved early, particularly for watershed-scale deployments involving multiple owners (Kerkez et al. 2016). In the similar, parallel domain of large reservoirs, Forecast-Informed Reservoir Operations (FIRO) projects formalize planning through cross-disciplinary teams and Preliminary Viability Assessments that define technical tasks, monitoring, decision support, and communication strategies to guide operationalization (M. Ralph et al. 2024).

6.1.2 System Design, Modeling, Control Strategy Selection, and Permitting

Following initial planning, implementers select control strategies and develop supporting models. Studies compare rule-based control (RBC), model predictive control (MPC), and reinforcement learning (RL), each involving distinct steps for policy development, training or optimization, and testing (Bowes et al. 2021). Site-scale hydrologic models such as SWMM or PySWMM are typically calibrated to represent storage, conveyance, and underdrains, and may include pollutant sub-models when water quality outcomes also matter (Mason et al. 2022). In RBC systems, explicit real-time rules often link water-depth thresholds to valve positions and retention targets (Li et al., 2024). MPC approaches instead optimize over a receding time horizon using forecasts and constraints related to overflows, erosion, and water quality (Oh and Bartos 2023). Foundational real-time control (RTC) schemes may be reactive or predictive but must encode key objectives (e.g., flood mitigation, water quality) and operational constraints (e.g., mosquito control, maximum detention time) (Gaborit et al. 2015).

For all of these types of projects, a hydrologic, hydraulics, and possibly water quality model will be needed to evaluate the potential benefits and potential impacts of implementing various control strategies. The various rules, sets of logic, and decisions will need to be tested to ensure that undesirable and unexpected outcomes do not occur when the system is operated as intended.

Municipal projects identify permitting, interagency coordination, and design timelines as critical path items. Innovations like manual override requirements, vector controls, and health standards may surface in reviews and should be incorporated early (Fussel & Watson, 2019).

Regulatory pilots and controlled deviations help de-risk operations, build stakeholder confidence, and secure formal approvals and performance credits, supporting system expansion (i.e., a pilot can identify and mitigate potential issues before expansion) (Opti by aliaxis, n.d.-a). Demonstrations of computational feasibility, such as model predictive control (MPC) cycles executing within sampling intervals on standard hardware, further validate readiness for operational deployment (Lund et al., 2020).

6.1.3 Hardware Deployment and Communications Architecture

Physical implementation involves the retrofitting of existing assets with sensors and actuators connected through low-power, cloud-linked controllers. A common system architecture includes three layers: (1) field hardware (e.g., level, flow, or rainfall sensors; valves or pumps; microcontrollers and wireless modems), (2) cloud services for data ingestion, storage, and applications, and (3) application logic for visualization, alerts, and automated control (Bartos et al. 2017).

Case studies demonstrate cost-effective configurations such as internet-controlled butterfly or gate valves, ultrasonic or pressure sensors, battery or solar power, and cellular telemetry, often installable at each site within a day once the control panel is pre-built elsewhere (Mullapudi et al. 2018); (Bartos et al. 2017). Utilities integrate these distributed nodes with SCADA/DSS platforms to coordinate storage, releases, and transfers under forecasted conditions (U.S. Environmental Protection Agency 2021).

6.1.4 Forecasting, Data, and Decision Support

Forecast-informed operations rely on robust data systems, effective assimilation methods, and intuitive operator tools. Cloud-based “subscriptions” and database triggers enable adaptive sampling and control while ingesting external forecasts for pre-storm drawdown (Bartos et al. 2017).

Planning should explicitly account for forecast uncertainty. Approaches such as Dynamic Over-flow Risk Assessment (DORA) assess overflow risk under probabilistic rainfall inputs, helping to establish conservative operational rules (Brasil et al., 2021). Forecast-Informed Reservoir Operations (FIRO) deployments formalize decision support systems (DSS) that rapidly process ensemble forecasts, synthesize watershed indicators, and present recommended releases within defined operational constraints. DSS implementations typically progress in phases, developing dashboards, forecast comparison tools, and integration with models such as HEC-ResSim and CWMS (Ralph et al. 2023).

Reliable automation depends on high-quality, trustworthy data, underscoring the need for data reconciliation and forecast skill evaluation before full implementation (Kerkez et al. 2022). Smart stormwater management systems operationalize these principles by continuously adjusting system behavior in response to changing forecasts. The ALCS retrofit to an existing stormwater pond in Edina, MN (Morningside Flood Infrastructure Project) is a recent, implemented example of a smart system that makes decisions based on current conditions and weather forecasts, and continuously adjusts and adapts to the changing conditions (Barr, 2022).

6.1.5 Operations, Maintenance, and Governance

Implementation continues beyond commissioning. The literature emphasizes ongoing maintenance, documentation (e.g., SOPs, post-event analyses), and operator training, alongside cybersecurity and interoperability planning (Kerkez et al. 2016); (U.S. Environmental Protection Agency 2021). Reliability and timely maintenance are critical, as system failures can worsen outcomes. Pragmatic monitoring approaches, such as low-cost level or temperature sensors support performance (Janke et al. 2022). Where advanced AI is applied, maintaining model interpretability and human oversight remains essential for operator trust and adoption (Bowes et al. 2021).

6.2 Minnesota-Specific ALCS Implementation

While the literature outlines a comprehensive, multi-phase process for ALCS implementation, experience from Minnesota ALCS projects shows that the pathway often looks slightly different in practice. Many of the same core phases remain relevant (planning, design, permitting, installation, and operation), but their sequencing, emphasis, and decision points have been adapted to fit Minnesota's regulatory frameworks, hydrologic conditions, and institutional structures. Through implementation of municipal-scale ALCS projects, we have identified a streamlined approach that reflects lessons learned from real-world constraints such as permitting complexity, interjurisdictional coordination, and seasonal construction limitations (Figure 6).

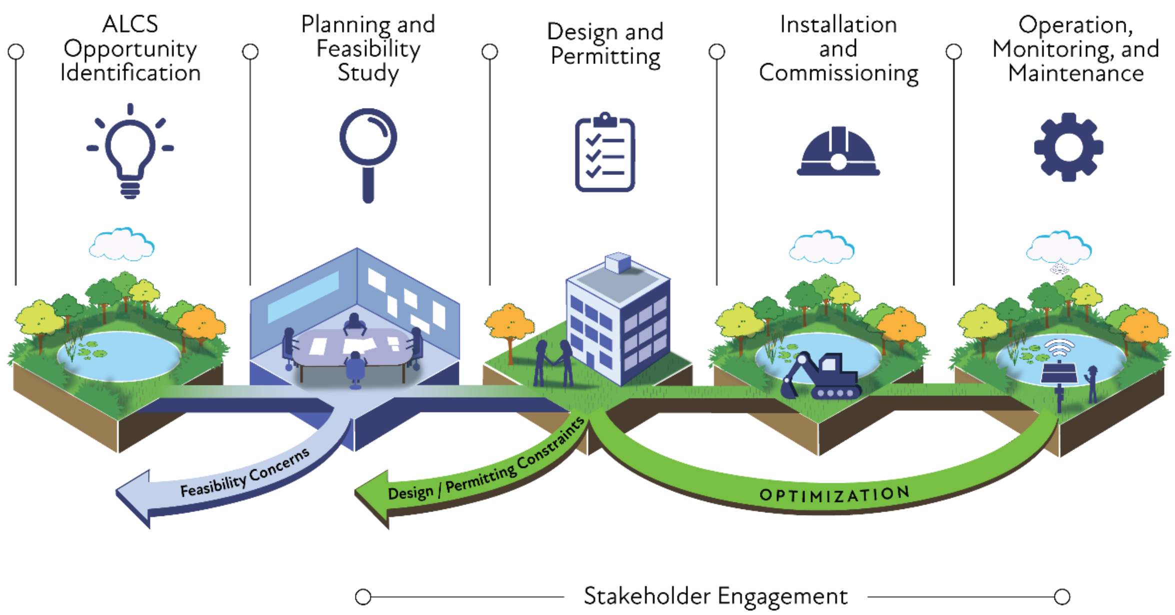


Figure 6 ALCS implementation process for Minnesota projects

The following subsections describe this Minnesota-specific framework, which maintains the foundational principles of the broader literature but simplifies them into a practical, five-phase process tailored to the state's regulatory and operational context. The five-phase implementation process is based on project examples within the City of Edina, MN, including one ALCS project that has been operational since August 2023, and several others currently in varying phases of the implementation process.

6.2.1 ALCS Opportunity Identification

Opportunities for implementing adaptive level control systems (ALCS) in Minnesota generally emerge through existing stormwater and surface water management planning processes. Public entities such as cities and watershed management organizations often identify areas of concern, such as localized flooding, downstream erosion, or water quality impairments, through prior hydrologic and hydraulic modeling or as part of their Surface Water Management Plans (SWMPs). These planning efforts frequently catalog infrastructure or subwatersheds where flood risk reduction, volume control, or pollutant load reduction goals are not being fully met.

For most public projects, the ALCS concept can be introduced once a problem area has already been defined. Historically, entities have focused on evaluating traditional best management practices (BMPs) such as detention ponds, infiltration systems, or outlet modifications to address these challenges.

However, as smart control technology becomes more accessible, there is growing value in considering ALCS as a complementary or alternative BMP during early project scoping. ALCS retrofits can often enhance the performance of existing systems by improving flood storage, optimizing drawdowns, or enhancing water quality benefits without requiring major new infrastructure.

For private entities, opportunity identification may follow a slightly different path, often driven by site-specific development needs. In most cases, however, some level of prior modeling or planning has already been completed, meaning that potential ALCS sites can be identified within the same decision framework used for evaluating other stormwater controls. Encouraging entities to screen ALCS options alongside traditional BMPs during feasibility and concept development ensures that adaptive control technologies are considered wherever they may provide added flexibility, performance, or cost efficiency.

6.2.2 Planning and Feasibility Study

The planning and feasibility phase establishes the foundation for a successful ALCS project. This stage focuses on engaging key stakeholders, evaluating project value, and defining the hydrologic and hydraulic setting in which the system will operate.

Stakeholder engagement is essential from the outset to clarify objectives, identify potential concerns, and align expectations. The specific stakeholders involved will vary by project, but engagement will often include impacted residents, neighborhood or community groups, lake associations, business owners, and other interested parties. A public engagement component is almost always recommended, and using multiple formats (e.g., online information, in-person or on-site meetings, surveys, Q&A sessions) can help reach a broader audience. Early coordination with permitting agencies (e.g., the Minnesota DNR, watershed management organizations, and local regulatory authorities including floodplain administrators) and with hydrologically connected entities such as upstream or downstream cities and adjacent watershed management organizations is also critical to project success.

Because many Minnesota waterbodies are designated public waters, one of the first steps is confirming jurisdictional oversight, including whether a site is classified as a DNR public water. Early meetings with agencies help identify “red flags,” align the project scope with regulatory expectations, and clarify permit pathways or environmental review requirements. In these cases, it is important to engage the DNR’s area hydrologist. Preparing at least conceptual design and preliminary performance estimates (e.g., peak-flow reduction, volume control, or water-quality benefits) before agency engagement facilitates more productive, informed discussions. Understandably, the less the proposed project is defined, the less feedback a permitting agency can provide early on during these discussions.

Ensuring thorough monitoring is also vital to project success. ALCS makes decisions (following detailed operation plans) based on conditions within the BMP, and system performance is best supported when upstream and downstream locations are also monitored (see Figure 1). Although upstream and downstream monitoring may not be a regulatory requirement for ALCS implementation, it provides significant benefits by improving understanding of watershed hydraulics and loading dynamics, strengthening operating plans, and increasing confidence in system performance. Monitoring data are essential for ALCS operation and for characterizing existing conditions that influence project objectives. Installing monitoring devices early in the planning and feasibility phase is important because the overall process may extend over months to years, and early data collection enhances planning, design, and permitting efforts. Water-level or discharge monitoring within the BMP itself is fundamental and should be implemented as early as possible. Furthermore, drawing on previous experience, it is advisable to implement continuous water level and/or flow monitoring, as well as water quality monitoring, at the following (non-exhaustive) locations in relation to the BMP where ALCS is under consideration:

- A carefully chosen location upstream of, and near to, the BMP. ALCS make decisions partially based on the expected runoff volume or flow rate that will flow into the BMP. Establishing a monitoring point upstream of the BMP can both inform future operations (part of the operating plan) and help calibrate runoff volume associated with storm events, improving decision-making ability.
- A practical site downstream, especially where regulations or possible impacts might need to be considered. For example, there may be a downstream nearby waterbody or stream/river where water level or water quality is critical. Some locations are shown on FEMA maps, others may have an established TMDL, and some locations have potential impacts to infrastructure or other environmentally sensitive areas. These locations will play a critical role in both the development and assessment of the operating plan, as well as in the subsequent verification of operational activities. In coordinated, distributed ALCS, downstream monitoring may even be part of the decision-making algorithm.
    - It is generally not recommended to monitor within downstream storm sewer pipes, as the water is typically contained and does not pose a significant risk to surface infrastructure. However, certain circumstances may warrant exceptions, and it is essential for the stakeholder group to identify these specific locations early during the planning and feasibility phase.
- When planning for stormwater or natural water systems that feed into downstream environments like streams or lakes, it's important to take significant tributaries into account. These large inflows may need to be included in the overall operating strategy. To improve monitoring, stations on these tributaries should be placed with both travel time and forecast needs in mind. For instance, if decisions must be made several hours before potential flooding, then monitors should be installed far enough upstream so that you have that advance notice, allowing for how long water takes to move along the tributary.
- Some consideration may also be needed for monitoring in the receiving water body, upstream of the BMP's discharge location (reference Figure 1). Understanding the conditions in the receiving environment, upstream of the discharge location can provide insight into how much water should be released by the BMP. If a large flood wave is observed in monitoring data upstream of the BMP discharge, then the operating plan may instruct the ALCS to reduce outflows for a time (if possible, based on other multi-objective factors) to let the flood wave go through and reduce the potential for downstream impacts.

A preliminary cost–benefit assessment should accompany early scoping to determine whether ALCS is a suitable and cost-effective solution compared with traditional best management practices (BMPs). This evaluation balances construction and operational costs against projected benefits such as flood-risk reduction, enhanced storage utilization, and water-quality improvement.

A site-specific feasibility analysis is then completed with Minnesota's regulatory and environmental context in mind. This analysis begins with defining the hydrologic and hydraulic system and identifying key loading constraints, such as nutrient and sediment inputs that may influence project objectives. Hydrologic and hydraulic modeling of baseline conditions and conceptual ALCS operations can then be used to quantify expected benefits and identify potential adverse impacts. Because ALCS represents a departure from traditional static outlet structures, project outcomes such as post-project peak flow rates, flow timing, and duration of peak flows will likely differ from those associated with a static outlet structure, particularly for larger storm or flood events. While many regulatory requirements explicitly address peak flow rates, they do not always account for potential benefits associated with modifying the timing and duration of peak flows. Therefore, feasibility analyses should evaluate not only changes in peak flow and discharge volume, but also how operational adjustments, such as pre-storm drawdowns, might influence downstream conditions, including erosion potential, and coinciding peak flows (Barr Engineering Co. 2025a). Ecological considerations are equally important, including for example maintaining baseflows, preventing excessive wetland drawdowns during critical times of the year, and limiting impacts from or to groundwater.

At the planning level, it is also important to acknowledge a common concern about forecast-based ALCS operations, specifically, what happens if the system predicts a storm that either doesn't happen at all or produces less precipitation than predicted? The nature of accurately predicting localized storm events is laden with uncertainties. Regulatory and stakeholder discussions often center on how quickly water levels would recover and whether temporary drawdowns could cause unintended effects. While these questions are best answered through detailed evaluation later in design, they should be recognized and discussed early to demonstrate awareness of site-specific hydrologic variability. Table 9 is a simple summary of possible non-ideal scenarios/considerations intended to address the questions "What if predictive discharge doesn't work right?" and "What could go wrong and what would be the impacts of it going wrong?".

Table 9 **Summary of scenarios and considerations for predictive ALCS outlets**

Storm Condition	Outlet Operation	Possible Resulting Impacts to Consider
Outlet controls DO function and outlet operates when directed to operate		
Storm Condition	**Outlet Operation**	**Possible Resulting Impacts to Consider**
Storm predicted, no/small storm occurs	Outlet operates due to predicted storm	• Outlet would draw pond (BMP) down, unless the outlet operation was interrupted. • This condition could have impacts on wildlife (requiring involvement and potential permitting requirements from the MNDNR). • Could leave a low or nearly-empty pond (BMP) until the next storm event. Could create aesthetic concerns
No storm expected, flash/large storm occurs	Outlet does not operate due to no storm prediction	• Outlet would not have time to draw the pond (BMP) down sufficiently, rendering the option ineffective for flood risk reduction. • Flooding would still occur as if the intended extra storage were not available; benefits unrealized.
Outlet controls DO NOT function (e.g., mechanical or electrical failure)		
Storm Condition	**Outlet Operation**	**Possible Resulting Impacts to Consider**
Storm predicted, no/small storm occurs	Outlet does not operate as it should	• No significant impact because no flooding occurs in the end. • Issue with outlet faulty operation may go unnoticed.
Storm predicted, storm occurs	Outlet does not operate as it should	• Outlet does not create additional storage for stormwater, even though the storm is predicted. • Flooding would still occur as if the intended extra storage were not available; benefits unrealized.
No storm predicted, no storm occurs	Outlet operates even though it should not	• Outlet would draw pond (BMP) down, unless the outlet operation was interrupted. • This condition could have impacts on wildlife (requiring involvement and potential permitting requirements from the MNDNR). • Issue with outlet faulty operation may go unnoticed.
Outlet controls NOT PERMITTED to operate due to full and/or flowing downstream conditions		
Storm Condition	**Outlet Operation**	**Possible Resulting Impacts to Consider**
Storm occurs	Outlet is not permitted to operate	• Outlet does not create additional storage for stormwater, even though the storm is predicted. • Flooding would still occur as if the intended extra storage were not available; benefits unrealized.

As the possible resulting impacts are considered, the magnitude of each potential impact can be weighed against the potential benefits during this planning and feasibility phase.

By the end of this phase, the project team should have a preliminary ALCS design, including a conceptual control strategy and infrastructure needs, and a design that appears technically sound, environmentally responsible, and sufficiently supported by key stakeholders to continue through the process.

An “off-ramp” exists at this stage in the process. At the conclusion of the feasibility stage, the team should assess whether ALCS remains an appropriate solution. If stakeholder engagement reveals limited support or lack of ownership clarity, if regulatory or technical barriers appear prohibitive, or if cost–benefit analyses indicate marginal value relative to other BMPs, the project may be better served by pursuing alternative approaches. Establishing this early off-ramp ensures that resources are directed toward projects with both technical merit and stakeholder alignment, strengthening overall program efficiency and long-term success.

6.2.3 Design and Permitting

The design and permitting phase transforms the conceptual ALCS developed during feasibility into a fully defined, permit-ready project. This stage includes detailed engineering design, modeling, development of the adaptive level control strategy, and close coordination with stakeholders and permitting agencies.

Stakeholder engagement continues throughout design. Early involvement of the project owner's operations and maintenance staff ensures that the system is practical to operate and maintain once constructed. Continued, regular communication with permitting agencies (e.g., Minnesota DNR, watershed management organizations, municipalities) helps identify potential concerns, align expectations, and streamline review.

In Minnesota, designs must explicitly address criteria in relevant regulations. For DNR Public Waters projects, state regulations (Minn. Stat. §103G and Minn. R. 6115) establish standards for outlet controls, including requirements to prevent "material upstream or downstream impacts" and to maintain stable normal water levels (ordinary high-water level, OHWL) except when intentionally drawn down under an approved plan. Watershed management organization rules typically require demonstration that a project will not adversely affect flood risk, channel stability, groundwater, or habitat. Likewise, when outlet structures are modified, rules often mandate no net increase in flood stage and showing that ALCS represents the minimal-impact alternative among feasible options (Barr Engineering Co. 2025a).

ALCS projects generally do not trigger a mandatory Environmental Assessment Worksheet (EAW), since they typically don't create large new impoundments or diversions. However, agencies will consider environmental effects through the permitting process. For example, the DNR will check for impacts on protected species or critical habitats (often requiring a natural heritage review if public waters are altered), and the watershed management organization may require assessment of water quality impacts (Barr Engineering Co. 2025a).

Detailed modeling refines the conceptual analyses completed during feasibility. Hydrologic and hydraulic models are advanced using site-specific data and design storms to confirm compliance with flood and flow standards. Depending on project goals, additional analyses may be performed to quantify benefits or assess potential subsurface impacts. Modeling results support a comprehensive engineering report or basis-of-design document, which typically includes pre- and post-project conditions (peak flows, flood levels, drawdown rates), rationale for the chosen control strategy, and an operations plan. Design documentation also includes structural details for retrofitted or new outlets and control devices, accounting for Minnesota's climate (e.g., ice loads and winter operations).

To date, Minnesota projects have relied on a rules-based control approach, which is preferred for permitting because it provides transparent, predictable operations. The control logic should define operating rules, triggers, and contingencies. If a technology vendor will supply hardware or software, early coordination ensures compatibility and integration planning.

Permitting begins once the design is complete enough to demonstrate regulatory compliance. Submittals typically include permit applications, modeling summaries, engineering drawings, and supporting analyses. Because ALCS projects often cross multiple jurisdictions, the permitting stage can be the longest, most complex, and therefore critical path. Agencies frequently request supplemental analysis or design refinements, so iterative dialogue is expected. The first ALCS project in a given geographic area can serve as a pilot that helps regulators interpret how adaptive outlet systems fit (or do not fit) within existing regulatory frameworks. Maintaining flexibility, such as willingness to include manual overrides or enhanced monitoring commitments, can facilitate approval and foster regulatory trust. With all required permits and approvals obtained, the project is ready to move into implementation.

An “off-ramp” also exists at this stage in the process. If, during design or permitting, significant regulatory barriers, ownership uncertainties, or operational concerns arise that cannot be resolved, the project team should reassess whether ALCS remains the most appropriate solution. Exploring alternative BMPs at this stage helps ensure resources are directed toward the most effective and feasible outcomes. Alternative BMPs are often required in permitting submittals anyway, to show the evaluation of multiple alternatives.

6.2.4 Installation and Commissioning

The installation and commissioning phase marks the transition from design to implementation. Construction and system deployment must be completed in full compliance with approved permit conditions and design specifications. In Minnesota, scheduling often accounts for seasonal restrictions, for example, in-water work windows to protect fish spawning (commonly March 15–June 15 for streams). Construction timing in Minnesota should also consider winter (frozen) versus summer (non-frozen) portions of the year. ALCS projects often require construction near and below the water level of existing BMPs, necessitating considerations for dewatering. Construction in the winter can often reduce, not eliminate, the need for dewatering, and may simplify the process.

Installation typically involves placing sensors, actuated controls (e.g., valves, gates, or pumps), telemetry units, and power systems. Given Minnesota’s climate, equipment may require added protection such as heaters, insulation, or weatherproof enclosures to ensure reliable year-round performance. During construction, close coordination among contractors, engineers, and inspectors helps verify that all components are installed according to approved plans and manufacturer requirements.

Once construction is complete, the system enters the commissioning stage. This includes field testing to confirm proper functionality of all sensors, actuators, and communication links. Functional tests, such as opening and closing valves, verifying sensor calibration, and conducting dry-run simulations, ensure that the ALCS responds correctly under controlled conditions. Where possible, commissioning may include a controlled trial during a storm event or simulated rainfall to observe real-world performance. Agency inspectors or project partners may attend to confirm that construction aligns with permit conditions and that the system operates safely and predictably. Commissioning also includes training for the owner’s operations and maintenance staff, ensuring they are familiar with system behavior, manual override procedures, and data monitoring tools.

During installation and commissioning, unexpected site conditions or performance issues may arise. For example, equipment malfunctions, inadequate communication coverage, or discrepancies between modeled and observed water-level responses. If these issues materially affect performance or compliance, the project team should pause implementation to reassess design parameters or operational logic before transitioning to full operation. Addressing these concerns early ensures that the ALCS performs reliably and maintains regulatory and stakeholder confidence.

6.2.5 Operation, Monitoring, and Maintenance

After commissioning, the ALCS transitions into the operations phase, guided by an adaptive management approach. Minnesota permits typically require a formal Operations and Maintenance (O&M) Plan, which outlines how the system will be operated, monitored, and maintained over time. The plan defines operating protocols for various conditions, such as when to initiate drawdowns or maintain seasonal level targets, as well as monitoring procedures (e.g., regular water-level and flow readings, or water-quality sampling when applicable). Maintenance tasks, including inspections, sensor calibration, and debris removal, should be performed according to a documented schedule to ensure consistent performance. As described prior, system malfunction due to lack of maintenance has the potential to result in worse conditions than the passive alternative, highlighting the importance of maintenance.

The project owner, often a city or watershed management organization, is responsible for training staff to manage the system safely and effectively. Training should cover routine operations, emergency protocols, and manual override procedures in the event of equipment failure or extreme weather events exceeding design capacity. Continuous data collection through remote telemetry enables real-time oversight, while periodic data reviews help verify that the ALCS is performing as intended. Regulatory agencies may require regular performance reporting, such as annual summaries documenting drawdown events, flood elevations, and any maintenance issues encountered.

Over time, the operating plan may be refined based on observed system behavior, performance data, or changing regulatory or environmental conditions. Adjustments, when made with agency coordination and approval, can improve system resilience and optimize performance without compromising compliance. The ultimate goal of this phase is long-term reliability, ensuring that flood risk is reduced and water-quality or ecological benefits are realized while considering unintended consequences.

It is during this phase that operational optimization may happen, or the operating plan may change due to additional coordinated ALCS throughout the system. As conditions change, and there is potential for optimization, the process can go back to the design and permitting stage, focused primarily on the control logic, rather than the hard infrastructure (Figure 6). This leaves room for continual improvement of the controls, and stormwater management outcomes.

It is also possible that, during operation, monitoring reveals recurring issues such as equipment malfunction, poor data reliability, or operational outcomes inconsistent with design expectations. In such a case, the project team should pause to reassess the control logic, infrastructure configuration, or maintenance strategy. In some cases, reverting to manual or semi-automated operation may be appropriate until system refinements are completed. Establishing a clear feedback loop between operations staff, engineers, and regulators ensures that emerging issues are addressed promptly, sustaining performance and maintaining public and regulatory confidence in ALCS systems.

7 Conclusions

There is a growing interest in ALCS within the stormwater management community, as well as an increasing demand for comprehensive understanding of the subject. Our research focused on summarizing the available literature, gaining a better understanding of the costs of retrofitting ALCS onto existing BMPs, and providing implementation strategies for how ALCS can be a viable retrofit to existing BMPs, with particular attention to applications and permitting within Minnesota. A set of presentation slides is included as Appendix B that can be used to share the report material with wider audiences in trainings, conferences, webinars, or other avenues where this work may be presented. Additionally, Appendix C includes the form used for potentially transferring Minnesota Stormwater Research Council funded projects to the Minnesota Stormwater Manual, for consideration by the Minnesota Pollution Control Agency.

The research conducted to date is extensive and overwhelmingly supports the consideration and use of ALCS in stormwater management. ALCS for stormwater has emerged to enhance flood risk reduction and water quality by actively managing storage and release across networks of assets. Studies consistently highlight its benefit in managing water quantity and flood risk, improving water quality and reducing downstream pollutant loading, and providing additional ecological co-benefits. Adding valves, gates, or pumps to existing stormwater facilities (retrofit) can extend hydraulic retention time, thereby promoting the capture of sediment-bound pollutants. Modulation of flows (hydrograph shaping) may reduce downstream erosion by limiting discharge rates as well as reduce flooding. Studies and municipal projects frequently prioritize flood metrics (e.g., flood levels, overflow volume, peak discharge, CSO counts), with water quality either as a secondary performance indicator or an indirect co-benefit. The imbalance is attributed to the relative maturity of level/rain sensing and actuation versus real-time chemical/biological monitoring; quality-focused implementations thus more often rely on proxies (e.g., turbidity) or modeled constituents. Despite the technology lagging in the water quality space, a recurring operational pattern among research and case studies is to emphasize water quality during small/frequent storms and emphasize flood control during larger events, demonstrating adaptive, multi-objective use across the event spectrum. ALCS can reliably deliver flood benefits now, while offering meaningful and growing water quality gains as sensing and data integration mature.

One of the significant benefits of ALCS is the ability to mechanically create dynamic storage. In developed settings where space is a premium, this provides a particular advantage and makes retrofitting existing stormwater assets with available dead storage most appealing. Retrofit mechanisms typically involve replacing or augmenting passive structures (orifices, weirs) with remotely operated valves, adding level sensors, and integrating controls with SCADA or cloud-based platforms. Across the literature, costs for adaptive level control systems range widely by scale (single-asset retrofits to city-wide programs), technology (open-source vs. commercial), and integration depth (sensing/telemetry only vs. full real-time control with optimization). However, it is readily apparent that flood management and water quality management benefits can be achieved through retrofitting at a fraction of the capital cost, compared to constructing new facilities, especially in developed settings. Operational and maintenance costs, however, will be higher with ALCS compared to passive outlet structures on a BMP. These ongoing costs need to be considered when planning, and when evaluating the cost-benefit over the long term.

Retrofitting ALCS to existing BMPs is occurring throughout the world, with significant implementation in developed, and built out regions, largely driven by the necessity to consider ALCS. Evidence overwhelmingly reflects urban and suburban contexts, with occasional references to rural siting. This common setting reflects the concentration of flood risk, aging infrastructure, and regulatory drivers in cities. Minnesota in particular has a number of ALCS either installed and operating, or under consideration. There are multiple projects with the Capitol Region Watershed District; the City of Edina has an installation as well as actively considering others; the Ramsey-Washington Metro Watershed District has multiple installations that are currently in various phases of transition from manual to more automated control; the Nine Mile Creek Watershed District and South Washington Watershed District are actively considering ALCS; and we recently learned of an installation that is currently in the design and permitting process in the City of Duluth.

Some states in the US have moved further along to the point of formal acceptance in state programs. The literature indicates that Maryland and California are two of the most prominent states accepting and approving ALCS in stormwater. The Maryland Department of the Environment (MDE) approved CMAC retrofits in both wet and dry ponds for meeting MS4 water quality requirements, and the Chesapeake Bay Program's Urban Stormwater Expert Panel also endorsed pollutant-removal credits for CMAC retrofits. It is interesting and important to note that Maryland and California are both coastal states.

One of the unique differences between coastal states versus inland states (such as Minnesota) is the ability to forecast precipitation. Coastal states that have large events driven by atmospheric rivers (west coast) or hurricane remnants (east coast) have an advantage in the ability to observe and forecast large rainfall events. Inland states where large rainfall events can be driven by convective storms are at a disadvantage because convective storms are much harder to predict. And this is especially true for smaller watersheds where time of concentration is short (i.e., hours or less). Research has been conducted on widespread, distributed and connected ALCS for optimizing flood management and water quality management, and found that in the upper Midwest, the ability to forecast events precisely enough to "optimize" is lacking. Currently, the technology may only be at a place to provide better results, rather than optimal results, particularly when leaning heavily on precipitation forecasts.

Outside of the challenges associated with precipitation forecasting, there are other barriers, some of which are regulatory. ALCS implementation often stalls on regulatory, permitting, and crediting hurdles that span standards, governance, environmental compliance, and institutional capacity. Regulatory bottlenecks largely reflect fragmented standards, complex permitting, data governance, institutional capacity, and statutory constraints. Across jurisdictions, regulation related to "smart" stormwater remains piecemeal, with unclear mandates and few incentives to adopt nontraditional solutions. Smart stormwater installations often trigger multi-agency review, with requirements beyond typical storm sewer permits. Early and sustained coordination with regulators and stakeholders is a must to streamline review.

A significant challenge beyond regulation is trust, which ultimately comes down to predictability and understanding of how the system operates and is intended to operate. Stronger operator involvement, training, intuitive dashboards, and transitional off-line or pilot operations are recommended to build confidence. One common theme heard from regulators and managers is the suggestion to use ALCS to make informed suggestions, which are sent in real-time to operators, who ultimately have decision and control rights. In this case, ALCS is not in an autopilot mode making decisions and taking action but is still utilizing the available information and capabilities of optimization to assist an operator in making better, active decisions.

Another challenge is associated with the data used to inform and control ALCS. Vulnerabilities exist when adjacent entities have unique systems that cannot operate together. Standardization is important for interoperability, especially as systems begin to cross jurisdictional boundaries. Cybersecurity is also a vulnerability. The consequences of malicious manipulation of an ALCS may be flood damage to infrastructure or release of pollutants from stormwater BMPs. These consequences may be incomparably low compared to cyberattacks at infrastructure such as nuclear plants or large dams or river diversion structures. Nevertheless, consequences exist, and therefore a vulnerability exists.

Although the literature highlights several challenges, the benefits gained from using ALCS are often shown to surpass both the costs and potential risks. As in any engineered system, there are potential modes of failure and conditions that can push a system past its design and function, yet on the whole, when the value outweighs the risk, the case can be made for implementation. One pathway that may be available for overcoming barriers is the need for updating management plans, control manuals, and operating plans. Triggers for updates may include external factors such as updates to precipitation data (such as the expected NOAA Atlas 15), or changes in zoning or other community management documents. These opportunities open the door for consideration and inclusion of ALCS as an acceptable strategy or BMP.

Additional research and analysis were conducted focused on the costs of ALCS, particularly in a situation where an outlet of an existing BMP is retrofitted to be active rather than passive. The analysis aimed to give planners and stormwater managers practical methods for estimating planning-level costs of an ALCS project. Drawing upon our experience with analysis, design, and construction of ALCS projects in Minnesota, we developed informed assumptions regarding design and construction. By estimating the initial capital cost for construction and implementation of an ALCS project, we found that retrofitting ALCS outlets to existing BMPs equipped with passive outlets enables increased stormwater storage volume in an efficient and cost-effective manner. While ongoing maintenance and operational costs for active outlets are higher than for passive outlets, the savings in initial capital expenses can outweigh these incremental additional annual expenses, even when considered over periods of 20 to 30 years.

Accordingly, our research team conducted an evaluation of overarching strategies applicable to initiating, executing, and completing an ALCS project. A review of the literature revealed common approaches and stages within this process. These findings were further substantiated by our experience in the state of Minnesota where we have designed, permitted, constructed, and are actively monitoring ALCS installations, with additional ALCS projects currently underway at new sites. We present a streamlined approach, providing guidance on all of the necessary considerations throughout the process to help prevent potential pitfalls and significant impacts on schedule and/or cost. In Minnesota, ALCS retrofits have so far proven feasible (although this conclusion is based on a limited number of projects) within existing permitting frameworks but require close coordination with agencies such as the Department of Natural Resources (Public Waters Work Permits), local watershed management organizations, and municipal stormwater authorities. Success depends on early engagement, transparent operating plans, and inclusion of manual override capabilities and monitoring commitments to build regulatory trust.

Given that this is a relatively new method for managing stormwater, and considering the established barrier of trust, it is understandable that this approach generates additional questions. The onus primarily rests on the proponent to substantiate that ALCS is capable of delivering the anticipated benefits, fully complying with all applicable permitting requirements, and will not give rise to adverse outcomes that may be of concern to regulators or other stakeholders. Until regulatory guidelines for ALCS retrofits are clearly established, obtaining permits is likely to present greater challenges compared to traditional passive outlet structures.

Considering the promising benefits, rising interest, and several gaps and challenges remaining in this area, we include recommendations for future research in the next section. A key challenge is demonstrating that active control, sometimes based on predictions, can operate effectively without resulting in unintended and undesirable consequences. This process requires thorough evaluation across a range of scenarios, in addition to clear communication with regulators and stakeholders to ensure their understanding of both the procedures involved and the control algorithm. As the algorithms increase in complexity, incorporating multi-dimensional dependencies and even autonomous decision-making, it becomes increasingly challenging to interpret and communicate these processes. Furthermore, a primary source of uncertainty identified in the literature, particularly for Minnesota, involves the complexities associated with managing uncertainties in weather forecasts. Current simulation model speed and computational resources appear insufficient for addressing uncertainties in real-time while also pursuing optimization goals. Further research is recommended in these areas. In the meantime, approaches can be taken to de-risk ALCS projects through scenario testing ahead of implementation, and developing comprehensive control plans, with review and approval by appropriate permitting agencies.

The research confirmed the initial hypothesis: ALCS can substantially improve the effectiveness of existing BMPs, achieving equivalent outcomes for a fraction of the cost of constructing new BMPs, particularly in developed urban and suburban areas. ALCS should be considered as one of the tools available for stormwater managers, engineers, and regulators in our collective efforts to improve and protect water resources in Minnesota.

8 Recommendations for Further Research

The research, which includes a literature review and an analysis of ALCS costs, identifies several areas of uncertainty and gaps that require additional study to enhance understanding and advancement of ALCS as a viable stormwater management tool. Some of these areas may be appropriate for consideration by the Minnesota Stormwater Research Council, while others may be more suitable for further investigation and development by other entities. The following list is arranged in order of priority, based on our findings from this research.

1. Noted throughout the research were the challenges with permitting and agency review, often associated with the lack of demonstration or pilot projects. **Small scale ALCS projects, fitted with additional sensors, primarily for the purpose of building, testing, analyzing, and improving the controls could pay off significantly in terms of building confidence in the technology and streamlining the design and review process.** This research, focused on small-scale testing, with a significant data collection component, may be well suited for the Minnesota Stormwater Research Council.

2. Hydrologic and water quality models are imperative to understanding and evaluating ALCS. As this field advances, ALCS implementation is expected to utilize more complex models, more parameters, and potentially even use models in real-time. To do this, as well as account for uncertainties, these models will need to be faster, both to produce results in real-time, short increments, and to evaluate large multi-dimensional spaces of operational possibilities for determining control plans. **Research is needed in computational power, distributed processing, and in other computational methods applied to hydrology, such as neural networks and various forms of machine learning.**

3. Most prominently, flood risk reduction (water quantity) and water quality improvements are the top benefits of ALCS. These have been analyzed and demonstrated in the literature. Other co-benefits exist, and the reporting on these varies. Some co-benefits may help manage aquatic vegetation, restore baseflow conditions, improve recharge to groundwater, or possibly benefit wildlife by modulating levels through various times of the year. There may also be negative consequences that are not yet well understood. **Further research in these areas will contribute to a deeper understanding of the various co-benefits and potential impacts that exist associated with ALCS.**

4. Noted throughout the literature were issues associated with cyber security, and interoperability. **Research and development could advance the ability for various programs, codes, and systems to engage with each other, communicating through the internet, to increase the connectedness and potentially effectiveness.** Research has suggested frameworks for developing a unified system, but it is unclear if that has been launched and is readily available. Additionally, while these systems increase in connectivity, the risk of cyber-attacks also increases. **Data and controls will need to be kept secure, and methods for security may need to be developed further.**

5. Multi-objective optimization of interconnected systems may be the future of ALCS. Finding the "best" solution, or at least a suite of actions that all results in similar desirable outcomes, would be beneficial for controlling ALCS. However, research suggests there is too much uncertainty in the fundamental inputs to these evaluations to reliably find the "best" solution. **Research could continue on the various methods for optimization (from other areas of study, such as**

“hedging” in economics, for example) while improvements are made on other important factors in parallel. This could enable optimization schemes and methods to be prepared when additional necessary breakthroughs occur.

6. Rainfall forecasts are seemingly the largest uncertainty, and potentially most influential uncertainty, in ALCS, particularly when it is prediction dependent. As noted, forecasting large rainfall events in the warm season, in the upper Midwest, is especially difficult, with low critical success indices when forecasting 24 hours prior to an event. While efforts are made to continually improve the ability to forecast rain events, likely by government agencies such as the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS), other research may benefit this industry. **Post-forecast corrections or bias corrections are one method for improving the accuracy of rainfall forecasts, and these or similar methods could be advanced to better inform prediction-dependent ALCS and the control algorithms.**

7. One of the other primary challenges with an ALCS project is buy-in from stakeholders, whether agencies, adjacent hydrologically connected organizations, or local residents. Recently, public engagement has been case-by-case, using a variety of means to communicate with the public, ranging from one-on-one, face-to-face discussions with individual homeowners, to large public meetings and rich, informative websites. **Research on social acceptance, and the means to get there, may inform and assist the community of owners, designers, and engineers who engage with people to discuss, explain, and promote ALCS as a viable option.**

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Appendix A

Technology Transfer: Literature Review Data

Individual articles have been provided electronically

#	Title	Authors	Year	Location	Conclusion	Key Takeaways	Quick Link (Online)	Category	Paper Relevance (High/Medium/Low)	Water Quality, Water Quantity or Both?
1	Deep Reinforcement Learning for the real time control of stormwater systems	Abhiram Mullapudi, Matthew J. Lewis, Cyndee L. Gruden, Branko Kerkez	2020	Simulated system based on Ann Arbor MI watershed	RL functions better when used for individual storage basins and les for more complex systems.	When RL was given more explicit guidance, there was an increase in performance but it requires a significant amount of computational resource. The controlled system outperfromed the uncontrolled system.	Deep reinforcement learning for the real time control of stormwater systems - ScienceDirect	Data Collection and Analysis	Medium	Both
2	Ecohydraulic-driven real-time control of stormwater basins	Dirk Muschalla, Bertrand Vallet, François Anctil, Paul Lessard, Geneviève Pelletier, Peter A. Vanrolleghem	2014	Simulation Study	RTC sytems are an effective solution for reducing TSS discharge and hydraulic stress in an urban river. Dynamic control was advantageous over static control.	Nine different static and dynamic simulated scenarios were analyzed by manipulating an outlet valve to increase retention time. There was a significant removal in suspended solids and hydraulic peaks were reduced by at least 50%. Overflow of the basin was avoided to reduce flooding.	Ecohydraulic-driven real-time control of stormwater basins - ScienceDirect	Case Study	Medium	Both
3	Effectiveness of Strategically Located Green Stormwater Infrastructure Networks for Adaptive Flood Mitigation in a Context of Climate Change	Muangsri, S., McWilliam, W., Lawson, G., & Davies, T.	2022	Lincoln, New Zealand	Adaptive flood mitigation does not necessarily include ALCS technology.	Adaptive flood mitigation is described as a planning strategy to identify stormwater infrastucture implementation.	Effectiveness of Strategically Located Green Stormwater Infrastructure Networks for Adaptive Flood Mitigation in a Context of Climate Change	Review	Low	Both
4	Evaluating Capability of Green Stormwater Infrastructure on Large Properties toward Adaptive Flood Mitigation: The HLCA+C Methodology	Muangsri, S., McWilliam, W., Lawson, G., & Davies, T.	2022	Lincoln, New Zealand	Adaptive flood mitigation does not necessarily include ALCS technology.	Adaptive flood mitigation is described as a planning strategy to identify stormwater infrastucture implementation.	Evaluating Capability of Green Stormwater Infrastructure on Large Properties toward Adaptive Flood Mitigation: The HLCA+C Methodology	Review	Low	NA
5	Exploring forecast-based management strategies for stormwater detention ponds	E. Gaborit, F. Anctil, G. Pelletier & P.A. Vanrolleghem	2016	Quebec City Canada	RTC offers a significant advantage in detention pond function specifically in dense urban areas limited by space.	RTC strategy vs. manual adjustment were applied both based on weather forecasted by Canadian global ensemble prediction system. Three different volumetric capacities were studied. RTC strategy performed better than the manual strategy.	Exploring forecast-based management strategies for stormwater detention ponds: Urban Water Journal: Vol 13 , No 8 - Get Access	Case Study	High	Both
6	Flood mitigation in coastal urban catchments using realtime stormwater infrastructure control and reinforcement stormwater infrastructure control and reinforcement learning	Benjamin D. Bowes, Arash Tavakoli, Cheng Wang, Arsalan Heydarian, Madhur Behl, Peter A. Beling and Jonathan L. Goodall	2021	Norfolk, Virginia	RL and RBC can improve stromwater infrastructure. It may not function as well on a more complex system and a focus on other variables.	focus on reinforcement learning (RL) versus modeled predictive control (MPC) and rule based control (RBC) RL achived nearly the same flood reduction 3% less than MPC and compared to RBC , RL learned quicker and reduced flooding by 19% higher , can control a simple system with potential on par of RBC	Flood mitigation in coastal urban catchments using real-time stormwater infrastructure control and reinforcement learning | Journal of Hydroinformatics | IWA Publishing	Data Collection and Analysis	High	Both
7	Hydrologic Impact Assessment of Land cover change and stormwater management using the hydrologic footprint residence	M.H. Giacomoni, R. Gomez, and E.Z. Berglund	2014	NA	The focus of the paper is on HFR or hydrologic footprint residence and explores the use of this concept as a more holistic approach to water management	No real references to adaptive level control systems	Hydrologic Impact Assessment of Land Cover Change and Stormwater Management Using the Hydrologic Footprint Residence | Request PDF	Data Collection and Analysis	Low	Water Quantity
8	Hydrologic processes regulate nutrient retention in stormwater detention ponds	Benjamin D. Janke, Jacques C. Finlay, Vinicius J. Taguchi, & John S. Gulliver	2022	Twin Cities, Minnesota	Maintaining storage volume is critical to manage flooding and nutrient loading. Controlled drawdown is another method mentioned to increase performance.	Nutrient retention was enhanced by nautral water loss. Ponds would perform better with increased storage and water loss. Low volume rentention resulted in net nutrient export.	Hydrologic processes regulate nutrient retention in stormwater detention ponds - ScienceDirect	Case Study	Medium	Water Quality
9	Inflow Prediction of Centralized Reservoir for the Operation of Pump Station in Urban Drainage Systems Using Improved Multilayer Perceptron Using Existing Optimizers Combined with Metaheuristic Optimization Algorithms	Lee E. H.	2022	Cheongju, Republic of Korea	Using SWMM models, different algorithms, and historic rainfall data this study looked at what algorithms had the least error when predicting historic flood inflows to a reservoir.	Multilayer perceptron (MLP) using an existing optimizer combined with an improved harmony. This is the system used improve inflow predictions. Technology could be used with real time prediction	Inflow Prediction of Centralized Reservoir for the Operation of Pump Station in Urban Drainage Systems Using Improved Multilayer Perceptron Using Existing Optimizers Combined with Metaheuristic Optimization Algorithms	Data Collection and Analysis	Medium	Water Quantity
10	Integrating model predictive control with stormwater system design; a cost-effective method of urban flood risk mitigation during heavy rainfall	Sun, L., Xia, J., & She, D.	2024	Wuhan, China	MPC provides potential cost saving of 5%-9% compared to rule based control and static control.Three models are used: the stormwater system model, the prediction process model, and the optimization model.	Integrating MPC is more cost-effective than expanding infrastructures for flood management as it notably increases the benefit contribution of controlled infrastructures at a modest cost.MPC outperforms static systems when there us limited infastructure size and extreme rainfall conditions. This study did not use real-world forecast data.	Integrating Model Predictive Control With Stormwater System Design: A Cost-Effective Method of Urban Flood Risk Mitigation During Heavy Rainfall - Sun - 2024 - Water Resources Research - Wiley Online Library	Case Study	High	Water Quantity
11	Model predictive control of stormwater basins coupled with real-time data assimilation enhances flood and pollution control under uncertainty	Oh, J., & Bartos, M.	2023	Austin, Texas	Study looks at MPC algorithm for stormwater detention ponds that determines the outlet valve control schedule needed to maximize pollutant removal and minimize flooding using forecasts of the incoming pollutograph and hydrograph. This study looks at TSS as the contaminant	Our approach handles both sensor measurement error and pollutant forecast uncertainty by fusing real-time turbidity data into the process model. The MPC can have multiple "rules" (Water quality, peak flows, volumes, settling time, etc.) and apply weight to each rule.	Model predictive control of stormwater basins coupled with real-time data assimilation enhances flood and pollution control under uncertainty - ScienceDirect	Data Collection and Analysis	High	Both
12	Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives	Webber, J. L., Fletcher, T., Farmani, R., Butler, D., & Melville-Shreeve, P.	2022	NA	Research of smart technologies for stormwater has increased significantly in the last 10 years.	-ALCS likely to grow with municipalites buying new water level, flow monitoring, and other stormwater sensors. -ALCS literature is primarily proof of concept modeling with limited real word studies	Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives - ScienceDirect	Review	High	Water Quantity
13	Nature-Based Solutions and Real-Time Control: Challenged and Oppotunities	José Brasil, Marina Macedo, César Lago, Thalita Oliveira, Marcus Júnior, Tassiana Oliveira and Eduardo Mendiondo	2021	Sao Paolo/ Unniversity of Texas	Green roofs can be used with RTC concept as a possible meas of water storage. Bioretention systems can benefit from saturation and storage throuhg processes such as denitrification. Road blocks with detention ponds include; mathematical models, forecasting system and cost for monitoring and transmitting data.	Property scale, green roofs were selected and at the street scale drainage system and bioretention. Detention basins were emained at the neighborhood and watershed scale. NBS (Nature Based Solutions)	Nature-Based Solutions and Real-Time Control: Challenges and Opportunities	Review	High	Both
14	Real time control of stormwater detention basins as an adaptive measure in mid size cities	Karine Bilodeau, Geneviève Pelletier & Sophie Duchesne	2018	Granby, Quebec Canada	Often easier to build detention basins downstream of developed areas or upstream of denser areas. Built next to receiving waters help the impact and delay runoff volumes after rainfall events. Further case studies need to be examined to valudate these positive results in other urban environments.	Simulations were based on a heavy precipitation year. Peak flows were reduced by an average of 46% with predictive RTC (Real Time Control) and downstream collector was used up to 22% less during rainfalls. Detention time reached desired period of 36h for water quality control for a majority of the rainfall events. Overall, RTC is a useful adaptation to changes in weather due to climate change.	Real-time control of stormwater detention basins as an adaptation measure in mid-size cities: Urban Water Journal: Vol 15 , No 9 - Get Access	Case Study	High	Both
15	Realising smarter stormwater management: A review of the barriers and a roadmap for real world application	Sweetapple, C., Webber, J., Hastings, A., & Melville-Shreeve, P.	2023	Exeter, UK	Improving smart stormwater technologies is an iterative process and with the technology being in its infancy it will take continuos iteration to continue improving. Technologies highlighted to be improved upon include stormwater system assets, asset sensing, data collection, data communication, data management	Identifies gaps in the current technologies but predicts that those gaps/limitations will continue to decrease and soci-economic barriers will be more of a roadblock	Realising smarter stormwater management: A review of the barriers and a roadmap for real world application - ScienceDirect	Review	High	Both
16	Smarter stormwater systems	Branko Kerkez, Cyndee Gruden, Matthew Lewis, Luis Montestruque, Marcus Quigley, Brandon Wong, Alex Bedig, Ruben Kertesz, Tim Braun, Owen Cadwalader, Aaron Poresky, and Carrie Pak	2022	South Bend Indiana	Trust must be maintaned with the data being gathered and used. Potential tension exists between who owns the infrastructure and which software is maintaining the system cooperation may need governing. Boarder community adoption is necessary, implementations must be shared.	Existing stormwater systems require significant investments to meet climate change challenges and rapid urbanization. Sensors and controllers can be a low cost solution. Transform the management from static to adaptive.	Smarter Stormwater Systems	Review	High	Both
17	The Potential of Knowing More: A Review of Data-Driven Urban Water Management	Eggimann, S., Mutzner, L., Wani, O., Schneider, M. Y., Spuhler, D., Moy de Vitry, M., Beutler, P., & Maurer, M.	2017	NA	As stormwater management becomes more data driven ALCS will become more widely used/accepted.	-ALCS allow for less infastructure while setting defined performance levels -Privacy is a concern with data-driven management (cyber security is important here) (More of a concern with waste/municipal water) -Spatially and temporal accuracy in rainfall data is important	The Potential of Knowing More: A Review of Data-Driven Urban Water Management | Environmental Science & Technology	Review	High	Both

#	Title	Authors	Year	Location	Conclusion	Key Takeaways	Quick Link (Online)	Category	Paper Relevance (High/Medium/Low)	Water Quality, Water Quantity or Both?
18	Model predictive control of urban drainage systems: A review and perspective towards smart real-time water management	Lund, N. S. V., Falk, A. K. V., Borup, M., Madsen, H., & Steen Mikkelsen, P.	2018	Technical University of Denmark	Four modeling compenets are reviewed: receding horizon principle, optimization model, optimization solver, internal MPC model	-Mutually interdependent model choices are required and dependent on the desired operating resolution -It is diffficult to compare different MPC methods because they have different evaluation schemes -Limited data that extends over a year or two of use	Full article: Model predictive control of urban drainage systems: A review and perspective towards smart real-time water management	Data Collection and Analysis	High	Water Quantity
19	Real-time control of urban headwater catchments through linear feedback; performance, analysis, and site selection	Wong, B. P., & Kerkez, B.	2018	Ann Arbor, MI	A synethetic study is performed on a watershed stormwater management model to analyze performance for retrofitting different numbers of storage nodes within the basin.	-Within a watershed ALCS is not necessary at all storage infastructure, desired perforamce outcomes can be achieved with 30% of storage infastructure being retrofitted -Author highlights the importance of performing real life studies	Real-Time Control of Urban Headwater Catchments Through Linear Feedback: Performance, Analysis, and Site Selection	Case Study	High	Water Quantity
20	Real time control of rainwater harvesting systems; the benefits of increasing rainfall forecast window	Xu, W. D., Fletcher, T. D., Burns, M. J., & Cherqui, F.	2020	Melbourne, Australia	A synethic study is performed and compares differnet performance goals: flood protection, supply maximization, longest discharge, streamflow preservation, conventional systems.	-Longer forecasting windows (7 days) allow for better preperation and water management as well as better management of flow regimes (natural flows) -Using long term forecasting helps mitigate error in the system from error in shortterm forecasting data through longer preperation time	Real Time Control of Rainwater Harvesting Systems: The Benefits of Increasing Rainfall Forecast Window - Xu - 2020 - Water Resources Research - Wiley Online Library	Data Collection and Analysis	High	Water Quantity
21	CSO reduction by integrated model predictive control of stormwater inflows; a simulated proof of concept using linear surrogate models	Lund, N. S. V., Borup, M., Madsen, H., Mark, O., & Mikkelsen, P. S.	2020	Technical University of Denmark	The efficacy of using ALCS in combined stormwater/sewer systems is assessed in this article	-Integrated model predictive control of stormwater inflows can reduce overflows, almost as much as disconnecting stormwater from the sewers	CSO Reduction by Integrated Model Predictive Control of Stormwater Inflows: A Simulated Proof of Concept Using Linear Surrogate Models - Lund - 2020 - Water Resources Research - Wiley Online Library	Case Study	High	Water Quantity
22	A smart predictive framework for system-level stormwater management optimization	Shishegar, S., Duchesne, S., Pelletier, G., & Ghorbani, R.	2021	Quebec City, canada	The optimization of dunamic data driven models and algorithms paired with RTC systems on watershed scale allow for improvements in both water quality and quantity.	Assess a system-level predictive RTC optimization/rule based algorithm -This algorithm provided a 59% mean reduction to peak flows and 21 hr increase in detention times. Compared to static controls	A smart predictive framework for system-level stormwater management optimization - ScienceDirect	Data Collection and Analysis	Medium	Both
23	Exceeding TMDL Requirements for Nutrient and Sediment Reductions in Maryland with CMAC	Opti	2024	Montgomery County, MD	Montgomery county retrofit four ponds with Optis CMAC (continuous monitoring and adaptive control). "Together, these four ponds generate 151.6 IACs toward Chesapeake Bay TMDL requirements, achieving over 95% cost savings compared to other water quality projects."	Maryland Department of Environment (MDE) approving Opti's CMAC for wet pond retrofits to meet MS4 permit water quality restoration requirements.	Opti Solution	Existing Infrastructure	Medium	Both
24	Retrofits of an existing stormwater pond with adaptive controls mitigates flooding and improves water quality of receiving waters	Opti, Jeremiah Johnson	2018	Beckley, WV	The client was experiencing flooding at a roadway. The detention pond upstream of the road was retrofit with an 18" valve to be used with CMAC. The pond reduced peak flow rates and flooding.	-system has been operating since 2016 -6X reduction in flood frequency -Provides warnings to first responders	Opti Solution	Existing Infrastructure	High	Water Quantity
25	Proactive stormwater design regulations mitigate flooding and reduce combined sewer overflows of the hudson river	Opti	2018	North Hudson Sewerage Authority (Hoboken, NJ)	A high density area in New Jersey was in need of a new approach to prevent combined sewer overflows and flooding. Several stormwater assets were put under Opti control. Minimized peak flows and saved capacity at the downstream treatment plant.	-$0.04/gal wet weather capture vs >$1.00/gal with passive controls -With CMAC a dention tank could be downsized 30% -75% flow reduction -95% savings (No info on what...)	Opti Solution	Existing Infrastructure	Medium	Water Quantity
26	Flood Mitigation in Historic Ellicott City, MD and Water Quality Improvements along the Anacostia River	Opti	2019	Howard County, MD	See key takeaways	-$14,000 a year in cost savings to landowners -4X retention time and water quality improvement -90% Peak flow reduction -Based on one year of data, Opti' adaptive control system outperformed traditional passive management by 2.3–3.9X.	Opti Solution	Existing Infrastructure	Medium	Both
27	LEED Platinum Building Saves >85% on OPEX and Stormwater Storage Space while Harvesting Rainwater to Provide Fresh Produce for Residents	Opti		New York City, NY	See key takeaways	-87% savings in operating expenses -88% space savings -Helped prepare quarterly reports with performance data (helps in achieving LEED certifications, etc.) -Storage and reuse	Opti Solution	Existing Infrastructure	Medium	Both
28	Stormwater Solutions for Transportation Projects	Opti		Maryland	Highlights the public-private partnerships in the Chesapeake bay and how they were leveraged for stormwater improvements.	Nature conservancy and Opti retrofit stormwater ponds at Walmarts. MDOT purchased water quality credits from Walmart	Opti Solution	Existing Infrastructure	Medium	Both
29	Supporting Economic Growth and Protecting the Environment	Opti	2023	Tampa Bay, Florida	See key takeaways	1-year statistics: +44% Nitrogen removal +56% Detention time +84% Flood attenuation	Opti Solution	Existing Infrastructure	Medium	Both
30	Smart watershed network management mitigates flooding and reduces combined sewer overflows to the Hudson River	Opti	2020	Albany, NY	See key takeaways	Adaptive controls were installed at a variety of stormwater assets with in a stormsewer system	Opti Solution	Existing Infrastructure	Medium	Both
31	Saving Millions in CAPEX, Sustainable OPEX, and LEED Points with Opti	Opti		Watertown, MA	Covers construction applications and space reductions	● 250,000 sq ft, LEED Gold certified, Class A Life Sciences Building ● Over $2M in CAPEX and ongoing OPEX savings over traditional approaches ● Stormwater reuse reduces municipal water costs	Opti Solution	Existing Infrastructure	Medium	Both
32	Casselberry is maximizing stormwater asset performance with Opti's continuous monitoring.	Opti		Casselberry, FL	See key takeaways	-A web based dashboard is used with the system -Reduced monitoring costs	Opti Solution	Existing Infrastructure	Low	Water Quantity
33	Meeting MS4 and Chesapeake Bay Program Compliance While Achieving 90% Savings on Phosphorus Reduction	Opti	2023	Lynchburg, VA	See key takeaways	$1,852/lb Phosphorus reduced Operating since 2017 Offsetting CAPEX with an existing BMP	Opti Solution	Existing Infrastructure	Medium	Both
34	Improved reliability of stormwater detention basin performance through water quality data-informed real-time control	Sazzad Sharior, Walter McDonald, Anthony J. Parolari	2019	Milwaukee Wisconsin	Active control driven by water quality information and detention time show promise in improving water quality compared to traditional controls	TSS control reduces system failure probability and TSS control may be more effective than rainfall dependent detention time control.	Improved reliability of stormwater detention basin performance through water quality data-informed real-time control - ScienceDirect	Existing Infrastructure	Medium	Both

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35	Shaping Streamflow Using a Real-Time Stormwater Control Network	Mullapudi, A., Bartos, M., Wong, B., & Kerkez, B.	2018	Basel, Switzerland	This article shows that a netwrok of internet connected sensors and valves can shape streamflow in large urban watersheds and allow for stormwater systems to meet there performance goals.	-Shows that intenet-connected stormwater control valves can shape streamflow in large urban watersheds. -Shows that ALCS can be used maintain downstream flow, rates and prevent sediment transport -All hardware, software, and project documentation is available at open-storm.org	Shaping Streamflow Using a Real-Time Stormwater Control Network	Case Study	High	Both
36	Application of Internet of Things (IoT) Technologies in Green Stormwater Infrastructure (GSI): A Bibliometric Review	Chen, T., Wang, M., Su, J., Ikram, R. M. A., & Li, J.	2023	Ann Arbor, Michigan	Interleaving of discharges provides an effective tool for empying upstream water retention basins wihtout introducing flashy conditions downstream.	This study reviews how a real world smart stomrwater system can be leveraged to shape streamflow in an urban watershed. characterizes the various waves released from upstream retention basins.	Application of Internet of Things (IoT) Technologies in Green Stormwater Infrastructure (GSI): A Bibliometric Review	Review	Medium	Both
37	Dynamic control of urban sewer systems to reduce combined sewer overflows and their adverse impacts	Rathnayake, U., & Faisal Anwar, A. H. M.	2019	Amsterdam	This algorithm is capable of minimizing pollution load.	Review of a model that can control gates dynamically with respect to time,	Dynamic control of urban sewer systems to reduce combined sewer overflows and their adverse impacts - ScienceDirect	Data Collection and Analysis	Low	Both
38	Stated preferences for smart green infrastructure in stormwater management	Meng, T., & Hsu, D.	2019	NA	Agencies are willing to pay more to reduce maintenance and construction cost.	Officials were survyed about their prefferred capabilities of green water infrastructure.	Stated preferences for smart green infrastructure in stormwater management - ScienceDirect	Review	High	Both
39	Stochastic water balance dynamics of passive and controlled stormwater basins	Parolari & Perline	2018	NA	Active control of stormwater flows allow land use and climate change adaptation.	Development of a new stochastic water balance model that provides analytical PDF's for water level, detention time and outflow.	Stochastic water balance dynamics of passive and controlled stormwater basins - ScienceDirect	Data Collection and Analysis	Medium	Both
40	Evaluating the Efficacy of Actively Managed Distributed Storage Systems for Peak Flow Reduction Using Spatially Uniform Design Storms	Riley Post, Felipe Quintero, and Witold F. Krajewski	2023	Iowa	Compared to passive systems outlet flows were reduced for all scenarios when using active controls. This article is related to 42 and 44	See conclusion	Evaluating the Efficacy of Actively Managed Distributed Storage Systems for Peak Flow Reduction Using Spatially Uniform Design Storms | Journal of Hydrologic Engineering | Vol 28, No 10	Data Collection and Analysis	High	Water Quantity
41	Investigating Utilization of Activated Distributed Storage Networks for Peak Flow Reduction Using Stochastic Storm Transposition	Riley Post, Felipe Quintero, Witold F. Krajewski, Daniel B. Wright	2024	Iowa	Flows were reduced for all rainfall events regardless of basin size, when comparing active to passive systems.	Stochastic Storm Transposition is a storm frequency analysis approach	Investigating Utilization of Activated Distributed Storage Networks for Peak Flow Reduction Using Stochastic Storm Transposition | Journal of Hydrologic Engineering | Vol 29, No 3	Data Collection and Analysis	High	Water Quantity
42	On the Optimized Management of Activated Distributed Storage Systems: A Novel Approach to Flood Mitigation	Post, R., Quintero, F., & Krajewski, W. F.	2024	Iowa	Control techniques reduce intensity and duration of flood events when compared to passive techniques. System utilizes less storage within a watershed than passive systems	Linear optimization released more water than genetic and partivle swarm optimization. This resulted in the metaheuristic approach having higher storage utilization	On the Optimized Management of Activated Distributed Storage Systems: A Novel Approach to Flood Mitigation	Data Collection and Analysis	High	Water Quantity
43	Can little ponds fight big floods?	Riley Post	2024	Iowa	This is a doctrate thesis that inludes articles 40 and 41.	See conclusion	Can Little Ponds Fight Big Floods? | Inside Higher Ed	Review	High	Water Quantity
44	Modeling Operations in System-Level Real-Time Control for Urban Flooding Reduction and Water Quality Improvement—An Open-Source Benchmarked Case	Jiada Li, Ryan Johnson, Steven Burian	2024	Ann Arbor, MI	System level controls provided peak depth, flood duration, and TSS reductions compared to static systems.	Sytem level control does not always outperform individual controls when alleviatiang flooding duration	Modeling Operations in System-Level Real-Time Control for Urban Flooding Reduction and Water Quality Improvement—An Open-Source Benchmarked Case	Case Study	High	Both
45	Bolivar Park Stormwater and Urban Runoff Capture Project	Jason Fussel & Richard Watson	2019	Southern California	This is an example of a system that is in use today and was installed and 2018. It is a good example of an active, succesful system with good data	-ALCS increased zinc reduction by 20% -Project was used for irrigation	Bolivar Park Stormwater and Urban Runoff Capture Project	Existing Infrastructure	High	Both
46	Flood Inundation Mapping & Alert Network (FIMAN)	North Carolina Floodplain Mapping Program	2024	North Carolina	Open access website that provides water level and rainfall data from, over 600 gauges across North Carolina. Gauge forecast data is integrated into the website. FIMAN also has inudation mapping showing impacted infrastucture, estimated damage costs, and flooding impacts to transportation assets.	FIMAN is setting a strong example for what municipalities can be doing with real-time sensors, data, and predictive modeling.	NC FIMAN	Other	High	Water Quantity
47	Digital Water lab at University of Michigan	Branko Kerkez et al.	2015	Michigan	Website provides videos, articles, and live data related to ALCS. Open-storm.org provides firmware, hardware, and software for ALCS	See conclusion	Digital Water Lab @ U-M	Review	High	Both
48	Glasgow's Smart Canal (2022)	Debbie Hay-Smith (AECOM)	2022	NA	ALCS used for creating a "smart canal" for flood control using sluice gates and stormwater ponds	Large scale example of ALCS in place.	Glasgow's Smart Canal	Existing Infrastructure	High	Both
49	SmartSWM System	Century Engineering	2021	Pennsylvania	Provides case studies and presentations of ALCS in place now	See conclusion	Home - SmartSWM	Review	High	Both
50	VIDEO: Maximizing Smart Stormwater Infrastructure for Public and Private Benefit	National Municipal Stormwater Alliance	2020	Ann Arbor, MI	Sandy Hertz with the Maryland DOT presents on a smart Pond project with OPTI.	See conclusion	Maximizing Smart Stormwater Infrastructure for Public and Private Benefit	Other	High	Both
51	Identification of stormwater control strategies and their associated uncertainties using Bayesian Optimization	Mullapudi, Abhiram and Branko Kerkez	2023	Ann Arbor, MI	-The article introduces the the first application of Bayesian optimization for control of stormwater systems. -The algorithm also quantifies rainfall uncertainity associated with real time controls	The BO algorithm is limited in its applicability now but as it used more it can be continuosly improved.	Identification of stormwater control strategies and their associated uncertainties using Bayesian Optimization	Data Collection and Analysis	Medium	Water Quantity
52	Measuring City-Scale Green Infrastucture Drawdown Dynamics Using Internet-Connected Sensors in Detroit	Brooke E. Mason, and Jacquelyn Schmidt and Branko Kerkez	2023	Detroit, Michigan	This study analyzes real time controls and drawdown dynamics for green infastructure	The features with the greatest impact on drawdown rates in the stuidy were the groundwater table, imperviousness , longitude, and drainage area to surface area ratio	Measuring city-scale green infrastructure drawdown dynamics using internet-connected sensors in Detroit	Case Study	High	Water Quantity
53	Generating interpretable rainfall-runoff models automatically from data	Dantzer & Kerkez	2023	Ann Arbor, MI	This method provides accurate interpretable rainfall-runoff models from precipiation and stage data. It provides a novel conceptual model of rainfall-runoff processess.	Exisiting models are not designed to digest large amount of real time data. Machine learning is able to digest this data but lacks interpretability. A new open source method automatically creates models that are interpretable.	Generating interpretable rainfall-runoff models automatically from data	Data Collection and Analysis	High	Water Quality
54	Improvement of phosphorus removal in bioretention cells using real-time control	Brooke E. Mason, Abhiram Mullapudi, Cyndee Gruden & Branko Kerkez	2022	Ann Arbor, MI	There is potential in real-time controlled bioretential cells, especially when conenring meeting water quality goals, particularily phosphorus.	An autonomous upgrade matched the pollutant treatment matched the performance of the baseline scenario in half the spatial footprint .	Improvement of phosphorus removal in bioretention cells using real-time control	Data Collection and Analysis	High	Both
55	An Automated Toolchain for Camera-Enabled Sensing of Drinking Water Chlorine Residual	Alyssa Schubert, Leah Pifer, Jianzhong Cheng, Shawn P. McElmurry, Branko Kerkez, and Nancy G. Love	2022	Ann Arbor, MI	Looks at an automated toolchain that processes photos of chlorine residual test strips.	See conclusion.	An Automated Toolchain for Camera-Enabled Sensing of Drinking Water Chlorine Residual | ACS ES&T Engineering	Data Collection and Analysis	Low	Water Quality
56	Editorial: Themed issue on data-intensive water systems management and operation	Branko Kerkez, Kris Villez, Eveline Volcke	2022	Ann Arbor, MI	In the face of climated change there should be a push to integrate more of this technology.	There is a massive opportunity to embrace emerging methods and technologies including artifical inteliigence, data analystics, low cost sensor hardware and cloud computing.	Editorial: Themed issue on data-intensive water systems management and operation (Journal Article) | OSTI.GOV	Other	Medium	Both
57	Wireless Sensors for Measuring Drinking Water Quality in Building Plumbing: Deployments and Insights from Continuous and Intermittent Water Supply Systems	Ernesto F. Martinez Paz, Meagan Tobias, Estefania Escobar, Lutgarde Raskin, Elizabeth F. S. Roberts, Krista R. Wigginton, and Branko Kerkez	2022	Ann Arbor, MI & Mexico City, Mexico	The value of real time control in drinking water facilities remains uncelar.	Real time control deployment in a drinking water system proved important in response to neighbnorhood scale elctroconductivity in Ann Arbor and water quality issues in Mexico City.	Wireless Sensors for Measuring Drinking Water Quality in Building Plumbing: Deployments and Insights from Continuous and Intermittent Water Supply Systems	Existing Infrastructure	Low	Water Quality

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58	pystorms: A simulation sandbox for the development and evaluation of stormwater control algorithms	Sara P. Rimer, Abhiram Mullapudi, Sara C. Troutman, Gregory Ewing, Benjamin D. Bowes, Aaron A. Akin, Jeffrey Sadler, Ruben Kertesz, Bryant McDonnell, Luis Montestruque, Jon Hathaway, Jonathan L. Goodall, Branko Kerkez	2021	Ann Arbor, MI	Psystorms allows users to quickly download and test psystorns abd various scenarios in only a few lines of code. Author desires code to lead to a community driven resource and integrate stormwater control simulations accordingly.	Although smart stormwater systems show promise there are still barriers for epxerts and novices to examine further.	pystorms: A simulation sandbox for the development and evaluation of stormwater control algorithms	Data Collection and Analysis	Medium	Both
59	Observability-Based Sensor Placement Improves Contaminant Tracing in River Networks	Matthew Bartos & Branko Kerkez	2021	Austin, TX	The use of this applied model should help practitioners deploy more effectiver riverine sensor networks for scientific and practical applications.	Paper reviews sensor placement strategy coupled with LTI system's Observability Gramian.	Observability-Based Sensor Placement Improves Contaminant Tracing in River Networks - Bartos - 2021 - Water Resources Research - Wiley Online Library	Review	Medium	Water Quality
60	Real time control schemes for improving water quality from bioretention cells	P. P. Persaud, A. A. Akin, B. Kerkez , D. T. McCarthy and J. M. Hathaway	2019	Knoxville, TN	Future research should include more hydrologic quantification of bioretention systems. Additionally the use of weather predicting software is critical, more studies need to focus on how well this prediciting software is performing and its optimization.	It may be possible to optimize storage time and/or soil moisture dynamics within bio retention cells through application of real time control. Results from a columm study suggest improvement on bioretention design but further optimization is required.	Real time control schemes for improving water quality from bioretention cells | Blue-Green Systems | IWA Publishing	Case Study	High	Water Quality
61	Autonomous Control of Urban Storm Water Networks Using Reinforcement Learning	Abhiram Mullapudi & Branko Kerkez	2018	Ann Arbor, MI	The stability and geralizability need to be durther exmained regarding real time control systems.	Reinforecement learning shows great potential in the operatiion of a urban storm water network but extensive research needs to be conducted to develop a fundamental understanding of the control robustness.	Autonomous Control of Urban Storm Water Networks Using Reinforce	Data Collection and Analysis	Medium	Both
62	Open storm: a complete framework for sensing and control of urban watersheds	Matthew Bartos, Brandon Wong, and Branko Kerkez	2017	Ann Arbor, MI	This open source platform has been created to realize the implementation of smarter water systems. it is intended to be a living document and anyone can participate.	Summarizes a comprehensive web based how to giude open-storm.org that empowers new comers to develop and deploy smart water systems. Two case studies demonstrate real world potential.	Open storm: a complete framework for sensing and control of urban watersheds	Case Study	High	Both
63	High-resolution hydrologic forecasting for very large urban areas	Hamideh Habibi, Ishita Dasgupta, Seongjin Noh, Sunghee Kim, Michael Zink, Dong-Jun Seo, Matthew Bartos and Branko Kerkez	2019	Arlington, TX	Hydrologic model forecasting can be optimized in parallel with ALCS, there are some data gaps that limit model accuracy.	-CASA WX Streamflow may be used for flash food forecasting and routine monitoring/prediction of streamflow -Hydrologic model run times can be optimized -A significant gap is th lack of real time water/flow and soil moisture data in urban catchments	High-resolution hydrologic forecasting for very large urban areas | Journal of Hydroinformatics | IWA Publishing	Data Collection and Analysis	High	Water Quantity
64	Using Sensor Data to Dynamically Map Large-Scale Models to Site-Scale Forecasts: A Case Study Using the National Water Model	Kevin J. Fries & Brando Kerkez	2018	Ann Arbor, MI	This article provides a method that combines large scale H&H model outputs wih sensor data to generate site level forecasts.	-Method doesn't require constant calibration of model or sensors -Can be used with short data histories (few months) -High applicablity in settings with changing land use such as urban areas	Using Sensor Data to Dynamically Map Large-Scale Models to Site-Scale Forecasts: A Case Study Using the National Water Model - Fries - 2018 - Water Resources Research - Wiley Online Library	Data Collection and Analysis	Medium	Water Quantity
65	A web-based decision support system for smart dam operations using weather forecasts	Shahryar Khalique Ahmad & Faisal Hossain	2019	Seattle, WA	This article provides an open-source platform that couple weathe forecasting with hydrologic modeling to optimize release decisions. Findings from the study	-Hydropower benefits can be maximized using weather forecasting -Uses numerical weather predictions models and artificial neural network models	A web-based decision support system for smart dam operations using weather forecasts | Journal of Hydroinformatics | IWA Publishing	Data Collection and Analysis	Medium	Water Quantity
66	The quiet revolution of numerical weather prediction	Peter Bauer, Alan Thorpe & Gilbert Brunet	2015	NA	As our computing abilities continue to advance over time so will our weather modeling.Today our 0-5 day weather forecasting is the most accurate with a forecasting skill over 90%. There are technological and scientific challenges that reduce weather forecasting accuracy.	Weather forecasting today is more accurate than ever especially for shorter time spans and weather forecasting ability will increase with time and advances in computing and scientific technologies.	The quiet revolution of numerical weather prediction	Data Collection and Analysis	Low	NA
67	Forecast Informed Reservoir Operations (FIRO)	Center for Western Weather and Water Extremes		NA	FIRO works to leverage improved weather/water forecasting to enable more effective management of reservoirs	FIRO links current research and science with existing reservoir operations and plans.	FIRO_Overview - Center for Western Weather and Water Extremes	Data Collection and Analysis	Low	Both
68	Lake Mendocino Forecast Informed Reservoir Operations	Jasperse, J.;Ralph, F. M.;Anderson, M.;Brekke, L.;Malasavage, N.;Dettinger, M. D.;Forbis, J.;Fuller, J.;Talbot, C.;Webb, R.;Haynes, A.	2021	Mendocino County, CA	Lake Mendocino used weather forecasting, weather and hydrologic modeling, and sensors to increase storage within the reservoir. This was the first FIRO project.	-They took a phased approach and will continue to update modeling practices as they improve with time -Storage was improved by 20% in 2019 compared to conventional practices -Included cost in the alternative analysis looking at the return on investment in forecast skill improvement	Lake Mendocino Forecast Informed Reservoir Operations Final Viability Assessment	Existing Infrastructure	High	Water Quantity
69	Prado Dam Forecast Informed Reservoir Operations Final Viability Assessment	Ralph, F. M. Hutchinson, A. Anderson, M. et al.	2023	Corona, CA	FIRO was used to maximize groundwater recharge for the Prado Dam while improving flood risk management and habitat	-With FIRO the dam could yield l 4-6,000 additional acre-ft of groundwater recharge -The dam is beginning to incorporate structural changes from the FIRO workplan and is scheduled for completion in 2029	Prado Dam Forecast Informed Reservoir Operations Final Viability Assessment	Existing Infrastructure	High	Water Quantity
70	Work plan for Yuba-Feather Forecast Informed Reservoir Operations	Ralph, F.. et al.	2021	CA	A new spillway is included in the design to leverage FIRO and allow for an additional 117,000 ac-ft of reservoir space.	-FIRO has potential to maintain water supply and improve flood risk management -FIRO alternatives reduce exceedance of key pool elev., outflows, and downsyream flows compared to existing operation -End of event storage, watter supply. Is generally increased	YF_workplan.pdf	Existing Infrastructure	Medium	Water Quantity
71	Work Plan for Seven Oaks Dam FIRO	Ralph, F.. et al.	2024	Highland, CA	Workplan details how FIRO will be used, and how/what will be used for forecasting, modeling, and runoff estimation,	See conclusion	SOD_FIRO_Workplan.pdf	Existing Infrastructure	Medium	Water Quantity
72	Work Plan for Howard Hanson Dam FIRO Work Plan	Ralph, M.. et al.	2024	King County, WA	Workplan details how FIRO will be used, and how/what will be used for forecasting, modeling, and runoff estimation,	See conclusion	FIRO_HowardHanson_Workplan.pdf	Existing Infrastructure	Medium	Both
73	Smart Data Infrastructure for Wet WEather Control and Decision Support	EPA	2021	Office of Wastewater Management	a very deatiled guide that covers just about all of our questions, especially since it includes numerous case studies	guidance on how to implement, how to develop and maintain the technology, beneficial application, level of control, guidelines for applying, data analysis, data management, data sharing, data validation, cost,	Smart Data Infrastructure for Wet Weather Control and Decision Support, March 2021	Review	High	Both
74	Key Challeneges for Smart Water	Gourbesville et al	2016	France	an alternative to more efficient water management	pertains to protection of the water cycle in the 21s centruy and how to better manage water use/flooding/future challenges, data sharing is critical	Key Challenges for Smart Water - ScienceDirect	Review	Medium	Both
75	Landscape elements affect public perception of nautre-based solutions managed by smart systems	Li et al.	2022	Michigan	This article details changes that smart systems introduce to the environment that can degrade landscape experiences for residents. Installation recommended in residential over commerical. Regular maintenance necessary to enhance public perception.	water level maintenance by smart systems may undermine residents views of stormwater ponds, land use contexts moderate the effects of water on perceptions, high water is percevied more positively in residential ponds, high and low water are percevied more positively in ponds with steep slopes, low water is percevied less positively in ponds surrounded by mowed turf.	Landscape elements affect public perception of nature-based solutions managed by smart systems - ScienceDirect	Review	High	NA
76	Efficient energy resource utilization in a wireless sensroy system for monitoring water quality	Olatinwo et al.	2019	NA	The study focused on various algorithm generated outputs to determine the optimal network paramteres	See conclusion	Efficient energy resource utilization in a wireless sensor system for monitoring water quality	Data Collection and Analysis	Medium	Water Quality
77	Uncertainties in Precipitation and Their Impacts on Runoff Estimates	Willmott, Roads, Fekete & Vorosmarty	2003	Newark, Deleware	There is variance in estimating precipitation depth depenfing on the model that is used. This translates to equal or greater variation on the runoff estimates from these precipitation datasets	-In wet regions error in precipitation translates to approximately the same error in runoff -In semidry regions errors in precipitation translate to greater error in runoff aproximation due to non-linear processes	Uncertainties in Precipitation and Their Impacts on Runoff Estimates in: Journal of Climate Volume 17 Issue 2 (2004)	Data Collection and Analysis	Medium	Water Quantity
78	Impact-Based Skill Evaluation of Seasonal Precipitation Forecasts	Nikraftar, Z., Mbuvha, R., Sadegh, M., & Landman, W. A	2024	NA	This article provides a framework to evaluate the skill of forecast models (focus is on tropical regions).	-Model performance varies significantly across regions and seasons -There are greater deficiencies in modeling severe precipitation events	Impact-Based Skill Evaluation of Seasonal Precipitation Forecasts - Nikraftar - 2024 - Earth's Future - Wiley Online Library	Data Collection and Analysis	Medium	Water Quantity

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79	Discrepancies in changes in precipitation characteristics over the contiguous United States based on six daily gridded precipitation datasets	Mallakpour et al.	2022	NA	There are significant variance in precipitation events acrosss data sets. It is important that multiple datasets be used to prevent bias.	-Six different daily gridded precipitation datasets in the US used in the study	Discrepancies in changes in precipitation characteristics over the contiguous United States based on six daily gridded precipitation datasets - ScienceDirect	Data Collection and Analysis	Medium	Water Quantity
80	Global Evaluation of Seasonal Precipitation and Temperature Forecasts from NMME	Roy et al.	2020	US	Results of this analysis demonstrate the need to use multiple models to improve precipitation forecasting	-Precipitation forecast skill is greatest at the initial lead time (month of intialization) and decreases for longer lead times. -Skill of precipitation forecasts is stongly dependent on region and season	Global Evaluation of Seasonal Precipitation and Temperature Forecasts from NMME in: Journal of Hydrometeorology Volume 21 Issue 11 (2020)	Data Collection and Analysis	Medium	Water Quantity
81	Hydrological Forecasts and Projections for Improved Decision-Making in the Water Sector in Europe	Samaniego et al.	2019	Europe	Combines hydrologic and precipitation models to help make better water resources decisions.	-Downsclaed models to a higher resolution -Evaluated the reliability and accuracy of forecasting	Hydrological Forecasts and Projections for Improved Decision-Making in the Water Sector in Europe in: Bulletin of the American Meteorological Society Volume 100 Issue 12 (2019)	Data Collection and Analysis	Medium	Water Quantity
82	Accounting For Climate Change in Post-Construction Stormwater Standards	Deborah Caraco, Karen, Cappiella, Paige Buzard, Lisa Fraley-McNeal, and Shohreh Karimipour	2024	Fulton, MD	Encourages the use of ALCS to maximize storage capacity and outflows. Also encourages Smart BMP technology for use with high precipitation and Drought. This technology is then recommended for most states. Notes are included in Table 2 (pg. 14)	See conclusion.	Accounting for Climate Change in Post-Construction Stormwater Standards - Center for Watershed Protection	Other	Medium	Both
83	Impacts of site real-time adaptive control of water-sensitive urban designs on the stormwater trunk drainage system	Meng, X., Li, X., Charteris, A., Wang, Z., Naushad, M., Nghiem, L. D., Liu, H., & Wang, Q.	2023				Impacts of site real-time adaptive control of water-sensitive urban designs on the stormwater trunk drainage system - ScienceDirect	Case study	High	Water Quantity
84	A data-driven improved fuzzy logic control optimization-simulation tool for reducing flooding volume at downstream urban drainage systems	Li, J.	2020		Paper looks at a specific model (Fuzzy logic control) and algorithm to be used with RTC. Water quantity focused		A data-driven improved fuzzy logic control optimization-simulation tool for reducing flooding volume at downstream urban drainage systems - ScienceDirect	Data Collection and Analysis	Medium	Water Quantity
85	Adapting Urban Infrastructure to Climate Change: A Drainage Case Study	Kirshen, P., Caputo, L., Vogel, R. M., Mathisen, P., Rosner, A., & Renaud, T.	2015		This is in the ASCE library. This article analyzes future stormwater infastructue and its applicability and adaptivity.		Adapting Urban Infrastructure to Climate Change: A Drainage Case Study | Journal of Water Resources Planning and Management | Vol 141, No 4 (ascelibrary.org)	Review	High	Both
86	Bioretention systems for stormwater management: Recent advances and future prospects	Vijayaraghavan, K., Biswal, B. K., Adam, M. G., Soh, S. H., Tsen-Tieng, D. L., Davis, A. P., Chew, S. H., Tan, P. Y., Babovic, V., & Balasubramanian, R.	2021		This paper cites a paper about adaptive level systems we have reviewed. It may look at other ALCS papers.		Bioretention systems for stormwater management: Recent advances and future prospects - ScienceDirect	Review	Low	Both
87	Calibration-free approach to reactive real-time control of stormwater storages	Liang, R., Maier, H. R., Thyer, M. A., Dandy, G. C., Tan, Y., Chhay, M., Sau, T., & Lam, V.	2022				Calibration-free approach to reactive real-time control of stormwater storages - ScienceDirect	Case study	High	Water Quantity
88	Improving the performance of stormwater detention basins by real-time control using rainfall forecasts	Gaborit, E., Muschalla, D., Vallet, B., Vanrolleghem, P. A., & Anctil, F.	2013		This focuses on the use of Real-time control (ALCS) with detention basins. Specifically "dry" basins.		https://www.tandfonline.com/doi/abs/10.1080/1573062X.2012.726229	Data Collection and Analysis	High	Water Quantity
89	Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience	Doberstein, B., Fitzgibbons, J. & Mitchell, C. Protect	2019				Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience | Natural Hazards (springer.com)	Review	Low	Both
90	Analytics and Optimization Reduce Sewage Overflows to Protect Community Waterways in Kentucky	Tao, D. Q., Pleau, M., Akridge, A., Fradet, O., Grondin, F., Laughlin, S., Miller, W., & Shoemaker, L.	2020	Kentucky	The Louisville MSD was established in 2006 and integrates sewer-monitoring data, weather forecasting, and network scale optimisation to maximise network capacity and treatment inflows. The scheme has resulted in a saving of over $200 million in capital costs through maximising network efficiency and reducing the need for stormwater storage facilities, as well as reducing operational and environmental costs through reducing sewer overflows by over 2-million gallons per year		Analytics and Optimization Reduce Sewage Overflows to Protect Community Waterways in Kentucky | INFORMS Journal on Applied Analytics	Existing Infrastructure	High	Water Quantity
91	Integrated Smart Water Management of the sanitation system of the Greater Paris region	Tabuchi, J. P., Blanchet, B., & Rocher, V.	2020		This case study details the development of a real-time control system (MAGES) in the Paris region designed to better control stormwater pollution caused by combined sewer overflows and to optimize the need for additional storage or treatment facilities. It is structured to outline the challenges facing the Greater Paris region water and sanitation networks, and the solutions provided by SIAAP, the public utility in charge of the treatment and transport of wastewater, over the past 20 years.		Integrated Smart Water Management of the sanitation system of the Greater Paris region: Water International: Vol 45 , No 6 - Get Access (tandfonline.com)	Existing Infrastructure	High	Water Quantity
92	Emerging investigators series: Building a theory for smart stormwater systems(Article)	Mullapudi, A., Wong, B. P., & Kerkez, B.	2017		Outlines how smart systems should be put together. Focusing on case studies for using smart sytems for nitrate load reductions		Emerging investigators series: building a theory for smart stormwater systems - Environmental Science: Water Research & Technology (RSC Publishing)	Review	High	Both
93	Smart Infrastructure: A Vision for the Role of the Civil Engineering Profession in Smart Cities	Berglund, E. Z., Monroe, J. G., Ahmed, I., Noghabaei, M., Do, J., Pesantez, J. E., Khaksar Fasaee, M. A., Bardaka, E., Han, K., Proestos, G. T., & Levis, J.	2020		Reviews current smart system technologies in the field of civil engineering not just stormwater		Smart Infrastructure: A Vision for the Role of the Civil Engineering Profession in Smart Cities | Journal of Infrastructure Systems | Vol 26, No 2 (ascelibrary.org)	Review	Medium	Both
94	Enhancing stormwater control measures using real-time control technology: a review	Xu, W. D., Burns, M. J., Cherqui, F., & Fletcher, T. D.	2021		Reviews current technologies and the future applicability at a larger scale		Enhancing stormwater control measures using real-time control technology: a review: Urban Water Journal: Vol 18 , No 2 - Get Access (tandfonline.com)	Review	High	Both
95	Real time control of biofilters delivers stormwater suitable for harvesting and reuse	Shen, P., Deletic, A., Bratieres, K., & McCarthy, D. T.	2020		Looks at using biofilters and RTC for E. coli, nutrients, and sediment. Specifically for stormwater reuse		Real time control of biofilters delivers stormwater suitable for harvesting and reuse - ScienceDirect	Case Study	High	Water Quality
96	A smart predictive framework for system-level stormwater management optimization.	Shishegar, S., Duchesne, S., Pelletier, G., & Ghorbani, R.	2021		Case study of RTC at a catchment scale		A smart predictive framework for system-level stormwater management optimization - ScienceDirect	Review	High	Both
97	'Rage against the machine'? The opportunities and risks concerning the automation of urban green infrastructure	Gulsrud, N. M., Raymond, C. M., Rutt, R. L., Olafsson, A. S., Plieninger, T., Sandberg, M., Beery, T. H., & Jönsson, K. I.	2018		Article evaluates the current and future risks of ALCS.		'Rage against the machine'? The opportunities and risks concerning the automation of urban green infrastructure - ScienceDirect	Review	High	Both
98	Implementation of IoT-Based Sensor Systems for Smart Stormwater Management	Altami, S. A., & Salman, B.	2022		Reviews the design and protoype implementation of an automated stormwater management system. The system aims to go beyond simple monitoring and allows actions to be taken automatically.		Implementation of IoT-Based Sensor Systems for Smart Stormwater Management | Journal of Pipeline Systems Engineering and Practice | Vol 13, No 3 (ascelibrary.org)	Case study	Medium	Water Quantity
99	Machine Learning-Assisted, Process-Based Quality Control for Detecting Compromised Environmental Sensors	Jacquelyn Q. Schmidt and Branko Kerkez	2023	Michigan	Article accesses the use of machine learning assisted QAQC of real time sensors.		Machine Learning-Assisted, Process-Based Quality Control for Detecting Compromised Environmental Sensors | Environmental Science & Technology	Data Collection and Analysis	High	Water Quantity
100	Extracting useful signals from flawed sensor data: Developing hybrid data-driven approaches with physical factors	Yang, C., Daigger, G. T., Belia, E., & Kerkez, B.	2020		Article looks at machine learning application for extracting useful data from flawed real time sensors data		Extracting useful signals from flawed sensor data: Developing hybrid data-driven approaches with physical factors - ScienceDirect	Data Collection and Analysis	Medium	NA
101	Balancing water quality and flows in combined sewer systems using real-time control	Troutman, S. C., Love, N. G., & Kerkez, B.	2020		Looks at dynamically controlling flows within a collection system for water quality benefits using an algorithm.		Balancing water quality and flows in combined sewer systems using real-time control - Environmental Science: Water Research & Technology (RSC Publishing)	Data Collection and Analysis	Medium	Both

#	Title	Authors	Year	Location	Conclusion	Key Takeaways	Quick Link (Online)	Category	Paper Relevance (High/Medium/Low)	Water Quality, Water Quantity or Both?
102	Real time controlled sustainable urban drainage systems in dense urabn areas	Kändler, N.; Annus, I.; Vassiljev, A.; Puust, R.	2020		Review of an effective RTC installation in Estonia		Real time controlled sustainable urban drainage systems in dense urban areas | Journal of Water Supply: Research and Technology-Aqua | IWA Publishing	Case study	High	Water Quantity
103	Potential and limitation sof modern equipment for real time control of urban wastewater systems	Campisano, A., Cabot Ple, J., Muschalla, D., Pleau, M., & Vanrolleghem, P. A.	2013		Review of the instruments/technologies necessary for RTC systems and their potential limitations		Potential and limitations of modern equipment for real time control of urban wastewater systems: Urban Water Journal: Vol 10 , No 5 - Get Access	Data Collection and Analysis	Medium	NA
104	Intergrated stromwater inflow control for sewers and green structures in urban landscapes	Lund, N.S.V., Borup, M., Madsen, H. *et al.*	2019		Support of the technology, article claims it is a path towards a more livable, resilient, sustainable city		Integrated stormwater inflow control for sewers and green structures in urban landscapes | Nature Sustainability	Case study	High	Water Quantity
105	Assessing and Optimizing the hydologic performance of Gre-Green infrastructure systems in response to climate change and non-stationary time series	Mo Wang, Ming Liu, Dongqing Zhang, Jinda Qi, Weicong Fu, Yu Zhang, Qiuyi Rao, Amin E. Bakhshipour, Soon Keat Tan	2023		Simulation based study to determine the performance of a hydrological drainage system in reponse to climate change		Assessing and optimizing the hydrological performance of Grey-Green infrastructure systems in response to climate change and non-stationary time series - ScienceDirect	Case study	Low	Water Quantity

#	Title	Authors	Question Anwsered 1-9	Question 1 - Purpose of ALCS Use	Question 2 - Primary Application	Question 3 - Location and Use Setting	Question 4 - States with Precedent for Approval	Question 5 - Regulatory and Other Barriers	Question 6 - Co-Benefits Beyond Water Quantity and Quality	Question 7 - Ownership and Operation	Question 8 - Modeling Software to Support ALCS	Question 9 - ALCS BMP Costs in Literature
1	Deep Reinforcement Learning for the real time control of stormwater systems	Abhiram Mullapudi, Matthew J. Lewis, Cyndee L. Gruden, Branko Kerkez	1, 2, 3	X	X	X						
2	Ecohydraulic-driven real-time control of stormwater basins	Dirk Muschalla, Bertrand Vallet, François Anctil, Paul Lessard, Geneviève Pelletier, Peter A. Vanrolleghem	1, 2, 3	X	X	X						
3	Effectiveness of Strategically Located Green Stormwater Infrastructure Networks for Adaptive Flood Mitigation in a Context of Climate Change	Muangsri, S., McWilliam, W., Lawson, G., & Davies, T.	1, 2, 3, 5	X	X	X		X				
4	Evaluating Capability of Green Stormwater Infrastructure on Large Properties toward Adaptive Flood Mitigation: The HLCA+C Methodology	Muangsri, S., McWilliam, W., Lawson, G., & Davies, T.										
5	Exploring forecast-based management strategies for stormwater detention ponds	E. Gaborit, F. Anctil, G. Pelletier & P.A. Vanrolleghem	1, 2, 3	X	X	X						
6	Flood mitigation in coastal urban catchments using realtime stormwater infrastructure control and reinforcement stormwater infrastructure control and reinforcement learning	Benjamin D. Bowes, Arash Tavakoli, Cheng Wang, Arsalan Heydarian, Madhur Behl, Peter A. Beling and Jonathan L. Goodall	1, 2, 3, 8	X	X	X					X	
7	Hydrologic Impact Assessment of Land cover change and stormwater management using the hydrologic footprint residence	M.H. Giacomoni, R. Gomez, and E.Z. Berglund	8								X	
8	Hydrologic processes regulate nutrient retention in stormwater detention ponds	Benjamin D. Janke, Jacques C. Finlay, Vinicius J. Taguchi, & John S. Gulliver	1, 2, 3	X	X	X						
9	Inflow Prediction of Centralized Reservoir for the Operation of Pump Station in Urban Drainage Systems Using Improved Multilayer Perceptron Using Existing Optimizers Combined with Metaheuristic Optimization Algorithms	Lee E. H.	1, 3, 8	X		X					X	
10	Integrating model predictive control with stormwater system design; a cost-effective method of urban flood risk mitigation during heavy rainfall	Sun, L., Xia, J., & She, D.	1, 3, 8, 9	X		X					X	X
11	Model predictive control of stormwater basins coupled with real-time data assimilation enhances flood and pollution control under uncertainty	Oh, J., & Bartos, M.	1, 2, 3, 8, 9	X	X	X					X	X
12	Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives	Webber, J. L., Fletcher, T., Farmani, R., Butler, D., & Melville-Shreeve, P.	1, 2, 3, 5, 8	X	X	X		X			X	
13	Nature-Based Solutions and Real-Time Control: Challenged and Oppotunities	José Brasil, Marina Macedo, César Lago, Thalita Oliveira, Marcus Júnior, Tassiana Oliveira and Eduardo Mendiondo	1, 2, 3, 5	X	X	X		X				
14	Real time control of stormwater detention basins as an adaptive measure in mid size cities	Karine Bilodeau, Geneviève Pelletier & Sophie Duchesne	1, 3, 6	X		X			X			
15	Realising smarter stormwater management: A review of the barriers and a roadmap for real world application	Sweetapple, C., Webber, J., Hastings, A., & Melville-Shreeve, P.	1, 3, 5	X		X		X				
16	Smarter stormwater systems	Branko Kerkez, Cyndee Gruden, Matthew Lewis, Luis Montestruque, Marcus Quigley, Brandon Wong, Alex Bedig, Ruben Kertesz, Tim Braun, Owen Cadwalader, Aaron Poresky, and Carrie Pak	1, 2, 3, 5, 7	X	X	X		X		X		
17	The Potential of Knowing More: A Review of Data-Driven Urban Water Management	Eggimann, S., Mutzner, L., Wani, O., Schneider, M. Y., Spuhler, D., Moy de Vitry, M., Beutler, P., & Maurer, M.	5, 6, 7					X	X	X		

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18	Model predictive control of urban drainage systems: A review and perspective towards smart real-time water management	Lund, N. S. V., Falk, A. K. V., Borup, M., Madsen, H., & Steen Mikkelsen, P.	5, 6, 8					X	X		X	
19	Real-time control of urban headwater catchments through linear feedback; performance, analysis, and site selection	Wong, B. P., & Kerkez, B.	1, 3, 8	X		X					X	
20	Real time control of rainwater harvesting systems; the benefits of increasing rainfall forecast window	Xu, W. D., Fletcher, T. D., Burns, M. J., & Cherqui, F.	1, 3, 6, 8	X		X			X		X	
21	CSO reduction by integrated model predictive control of stormwater inflows; a simulated proof of concept using linear surrogate models	Lund, N. S. V., Borup, M., Madsen, H., Mark, O., & Mikkelsen, P. S.	1, 3, 6, 8, 9	X		X			X		X	X
22	A smart predictive framework for system-level stormwater management optimization	Shishegar, S., Duchesne, S., Pelletier, G., & Ghorbani, R.	1, 3	X		X						
23	Exceeding TMDL Requirements for Nutrient and Sediment Reductions in Maryland with CMAC	Opti	1, 2, 3, 4	X	X	X	X					
24	Retrofits of an existing stormwater pond with adaptive controls mitigates flooding and improves water quality of receiving waters	Opti, Jeremiah Johnson	1, 2, 3, 4, 6	X	X	X	X		X			
25	Proactive stormwater design regulations mitigate flooding and reduce combined sewer overflows of the hudson river	Opti	1, 2, 3, 9	X	X	X						X
26	Flood Mitigation in Historic Ellicott City, MD and Water Quality Improvements along the Anacostia River	Opti	1, 2, 3, 4	X	X	X	X					
27	LEED Platinum Building Saves >85% on OPEX and Stormwater Storage Space while Harvesting Rainwater to Provide Fresh Produce for Residents	Opti	1, 3, 6, 7, 9	X		X			X	X		X
28	Stormwater Solutions for Transportation Projects	Opti	4, 7				X			X		
29	Supporting Economic Growth and Protecting the Environment	Opti	1, 2, 3	X	X	X						
30	Smart watershed network management mitigates flooding and reduces combined sewer overflows to the Hudson River	Opti	1, 2, 3, 9	X	X	X						X
31	Saving Millions in CAPEX, Sustainable OPEX, and LEED Points with Opti	Opti	1, 2, 3, 9	X	X	X						X
32	Casselberry is maximizing stormwater asset performance with Opti's continuous monitoring.	Opti	1, 3, 4, 7	X		X	X			X		
33	Meeting MS4 and Chesapeake Bay Program Compliance While Achieving 90% Savings on Phosphorus Reduction	Opti	1, 3, 6, 7, 9	X		X			X	X		X
34	Improved reliability of stormwater detention basin performance through water quality data-informed real-time control	Sazzad Sharior, Walter McDonald, Anthony J. Parolari	1, 2, 3, 5, 8	X	X	X		X			X	

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35	Shaping Streamflow Using a Real-Time Stormwater Control Network	Mullapudi, A., Bartos, M., Wong, B., & Kerkez, B.	1, 2, 3	X	X	X						
36	Application of Internet of Things (IoT) Technologies in Green Stormwater Infrastructure (GSI): A Bibliometric Review	Chen, T., Wang, M., Su, J., Ikram, R. M. A., & Li, J.	1, 3, 8	X		X					X	
37	Dynamic control of urban sewer systems to reduce combined sewer overflows and their adverse impacts	Rathnayake, U., & Faisal Anwar, A. H. M.	1, 3	X		X						
38	Stated preferences for smart green infrastructure in stormwater management	Meng, T., & Hsu, D.	5, 7, 9					X		X		X
39	Stochastic water balance dynamics of passive and controlled stormwater basins	Parolari & Perline	1, 2, 3	X	X	X						
40	Evaluating the Efficacy of Actively Managed Distributed Storage Systems for Peak Flow Reduction Using Spatially Uniform Design Storms	Riley Post, Felipe Quintero, and Witold F. Krajewski	1, 3, 8	X		X					X	
41	Investigating Utilization of Activated Distributed Storage Networks for Peak Flow Reduction Using Stochastic Storm Transposition	Riley Post, Felipe Quintero, Witold F. Krajewski, Daniel B. Wright	1, 3, 8	X		X					X	
42	On the Optimized Management of Activated Distributed Storage Systems: A Novel Approach to Flood Mitigation	Post, R., Quintero, F., & Krajewski, W. F.	1, 3, 8	X		X					X	
43	Can little ponds fight big floods?	Riley Post	1, 2, 3	X	X	X						
44	Modeling Operations in System-Level Real-Time Control for Urban Flooding Reduction and Water Quality Improvement—An Open-Source Benchmarked Case	Jiada Li, Ryan Johnson, Steven Burian	1, 2, 3, 8	X	X	X					X	
45	Bolivar Park Stormwater and Urban Runoff Capture Project	Jason Fussel & Richard Watson	1, 2, 3, 4, 5, 6, 9	X	X	X	X	X	X			X
46	Flood Inundation Mapping & Alert Network (FIMAN)	North Carolina Floodplain Mapping Program	1, 3, 4, 6, 7, 8	X		X	X		X	X	X	
47	Digital Water lab at University of Michigan	Branko Kerkez et al.	1, 2, 3, 8	X	X	X					X	
48	Glasgow's Smart Canal (2022)	Debbie Hay-Smith (AECOM)	1, 2, 3	X	X	X						
49	SmartSWM System	Century Engineering	1, 2, 3	X	X	X						
50	VIDEO: Maximizing Smart Stormwater Infrastructure for Public and Private Benefit	National Municipal Stormwater Alliance	1, 2, 3	X	X	X						
51	Identification of stormwater control strategies and their associated uncertainties using Bayesian Optimization	Mullapudi, Abhiram and Branko Kerkez	5, 8					X			X	
52	Measuring City-Scale Green Infrastucture Drawdown Dynamics Using Internet-Connected Sensors in Detroit	Brooke E. Mason, and Jacquelyn Schmidt and Branko Kerkez	1, 3, 8	X		X					X	
53	Generating interpretable rainfall-runoff models automatically from data	Dantzer & Kerkez	8								X	
54	Improvement of phosphorus removal in bioretention cells using real-time control	Brooke E. Mason, Abhiram Mullapudi, Cyndee Gruden & Branko Kerkez	1, 2, 3, 7, 9	X	X	X				X		X
55	An Automated Toolchain for Camera-Enabled Sensing of Drinking Water Chlorine Residual	Alyssa Schubert, Leah Pifer, Jianzhong Cheng, Shawn P. McElmurry, Branko Kerkez, and Nancy G. Love	1, 3	X		X						
56	Editorial: Themed issue on data-intensive water systems management and operation	Branko Kerkez, Kris Villez, Eveline Volcke	1, 2, 3	X	X	X						
57	Wireless Sensors for Measuring Drinking Water Quality in Building Plumbing: Deployments and Insights from Continuous and Intermittent Water Supply Systems	Ernesto F. Martinez Paz, Meagan Tobias, Estefania Escobar, Lutgarde Raskin, Elizabeth F. S. Roberts, Krista R. Wigginton, and Branko Kerkez	1, 3	X		X						

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58	pystorms: A simulation sandbox for the development and evaluation of stormwater control algorithms	Sara P. Rimer, Abhiram Mullapudi, Sara C. Troutman, Gregory Ewing, Benjamin D. Bowes, Aaron A. Akin, Jeffrey Sadler, Ruben Kertesz, Bryant McDonnell, Luis Montestruque, Jon Hathaway, Jonathan L. Goodall, Branko Kerkez	1, 2, 3, 8	X	X	X					X	
59	Observability-Based Sensor Placement Improves Contaminant Tracing in River Networks	Matthew Bartos & Branko Kerkez	1, 3, 8	X		X					X	
60	Real time control schemes for improving water quality from bioretention cells	P. P. Persaud, A. A. Akin, B. Kerkez , D. T. McCarthy and J. M. Hathaway	1, 2, 3, 5, 8	X	X	X		X			X	
61	Autonomous Control of Urban Storm Water Networks Using Reinforcement Learning	Abhiram Mullapudi & Branko Kerkez	1, 3	X		X						
62	Open storm: a complete framework for sensing and control of urban watersheds	Matthew Bartos, Brandon Wong, and Branko Kerkez	1, 2, 3, 5, 7, 8, 9	X	X	X		X		X	X	X
63	High-resolution hydrologic forecasting for very large urban areas	Hamideh Habibi, Ishita Dasgupta, Seongjin Noh, Sunghee Kim, Michael Zink, Dong-Jun Seo, Matthew Bartos and Branko Kerkez	8								X	
64	Using Sensor Data to Dynamically Map Large-Scale Models to Site-Scale Forecasts: A Case Study Using the National Water Model	Kevin J. Fries & Brando Kerkez	8								X	
65	A web-based decision support system for smart dam operations using weather forecasts	Shahryar Khalique Ahmad & Faisal Hossain	8								X	
66	The quiet revolution of numerical weather prediction	Peter Bauer, Alan Thorpe & Gilbert Brunet	8								X	
67	Forecast Informed Reservoir Operations (FIRO)	Center for Western Weather and Water Extremes	1, 2, 3	X	X	X						
68	Lake Mendocino Forecast Informed Reservoir Operations	Jasperse, J.;Ralph, F. M.;Anderson, M.;Brekke, L.;Malasavage, N.;Dettinger, M. D.;Forbis, J.;Fuller, J.;Talbot, C.;Webb, R.;Haynes, A.	1, 3, 7, 8, 9	X		X				X	X	X
69	Prado Dam Forecast Informed Reservoir Operations Final Viability Assessment	Ralph, F. M. Hutchinson, A. Anderson, M. et al.	1, 3, 4, 5, 7, 8, 9	X		X	X	X		X	X	X
70	Work plan for Yuba-Feather Forecast Informed Reservoir Operations	Ralph, F.. et al.	1, 3, 4, 5, 7, 8, 9	X		X	X	X		X	X	X
71	Work Plan for Seven Oaks Dam FIRO	Ralph, F.. et al.	4, 5, 7, 8, 9				X	X		X	X	X
72	Work Plan for Howard Hanson Dam FIRO Work Plan	Ralph, M.. et al.	1, 3, 4, 5, 6, 7, 8, 9	X		X	X	X	X	X	X	X
73	Smart Data Infrastructure for Wet WEather Control and Decision Support	EPA	1, 2, 3, 5, 7, 8, 9	X	X	X		X		X	X	X
74	Key Challeneges for Smart Water	Gourbesville et al	5, 7					X		X		
75	Landscape elements affect public perception of nautre-based solutions managed by smart systems	Li et al.	6						X			
76	Efficient energy resource utilization in a wireless sensroy system for monitoring water quality	Olatinwo et al.	5, 8					X			X	
77	Uncertainties in Precipitation and Their Impacts on Runoff Estimates	Willmott, Roads, Fekete & Vorosmarty	5, 8					X			X	
78	Impact-Based Skill Evaluation of Seasonal Precipitation Forecasts	Nikraftar, Z., Mbuvha, R., Sadegh, M., & Landman, W. A	5, 8					X			X	

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79	Discrepancies in changes in precipitation characteristics over the contiguous United States based on six daily gridded precipitation datasets	Mallakpour et al.	5, 8					X			X	
80	Global Evaluation of Seasonal Precipitation and Temperature Forecasts from NMME	Roy et al.	5, 8					X			X	
81	Hydrological Forecasts and Projections for Improved Decision-Making in the Water Sector in Europe	Samaniego et al.	5, 8					X			X	
82	Accounting For Climate Change in Post-Construction Stormwater Standards	Deborah Caraco, Karen, Cappiella, Paige Buzard, Lisa Fraley-McNeal, and Shohreh Karimipour	4				X					
83	Impacts of site real-time adaptive control of water-sensitive urban designs on the stormwater trunk drainage system	Meng, X., Li, X., Charteris, A., Wang, Z., Naushad, M., Nghiem, L. D., Liu, H., & Wang, Q.	1, 2, 3, 8	X	X	X					X	
84	A data-driven improved fuzzy logic control optimization-simulation tool for reducing flooding volume at downstream urban drainage systems	Li, J.	1, 2, 3, 8	X	X	X					X	
85	Adapting Urban Infrastructure to Climate Change: A Drainage Case Study	Kirshen, P., Caputo, L., Vogel, R. M., Mathisen, P., Rosner, A., & Renaud, T.	1, 2, 3	X	X	X						
86	Bioretention systems for stormwater management: Recent advances and future prospects	Vijayaraghavan, K., Biswal, B. K., Adam, M. G., Soh, S. H., Tsen-Tieng, D. L., Davis, A. P., Chew, S. H., Tan, P. Y., Babovic, V., & Balasubramanian, R.	1, 2, 3	X	X	X						
87	Calibration-free approach to reactive real-time control of stormwater storages	Liang, R., Maier, H. R., Thyer, M. A., Dandy, G. C., Tan, Y., Chhay, M., Sau, T., & Lam, V.	1, 2, 3, 5, 8	X	X	X		X			X	
88	Improving the performance of stormwater detention basins by real-time control using rainfall forecasts	Gaborit, E., Muschalla, D., Vallet, B., Vanrolleghem, P. A., & Anctil, F.	8								X	
89	Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience	Doberstein, B., Fitzgibbons, J. & Mitchell, C. Protect	1, 2, 3, 4	X	X	X	X					
90	Analytics and Optimization Reduce Sewage Overflows to Protect Community Waterways in Kentucky	Tao, D. Q., Pleau, M., Akridge, A., Fradet, O., Grondin, F., Laughlin, S., Miller, W., & Shoemaker, L.	1, 2, 3, 6, 8	X	X	X			X		X	
91	Integrated Smart Water Management of the sanitation system of the Greater Paris region	Tabuchi, J. P., Blanchet, B., & Rocher, V.	1, 2, 3, 4, 6	X	X	X	X		X			
92	Emerging investigators series: Building a theory for smart stormwater systems(Article)	Mullapudi, A., Wong, B. P., & Kerkez, B.	1, 2, 3, 8	X	X	X					X	
93	Smart Infrastructure: A Vision for the Role of the Civil Engineering Profession in Smart Cities	Berglund, E. Z., Monroe, J. G., Ahmed, I., Noghabaei, M., Do, J., Pesantez, J. E., Khaksar Fasaee, M. A., Bardaka, E., Han, K., Proestos, G. T., & Levis, J.	5					X				
94	Enhancing stormwater control measures using real-time control technology: a review	Xu, W. D., Burns, M. J., Cherqui, F., & Fletcher, T. D.	1, 2, 3, 5, 6, 9	X	X	X		X	X			X
95	Real time control of biofilters delivers stormwater suitable for harvesting and reuse	Shen, P., Deletic, A., Bratieres, K., & McCarthy, D. T.	1, 2, 3	X	X	X						
96	A smart predictive framework for system-level stormwater management optimization.	Shishegar, S., Duchesne, S., Pelletier, G., & Ghorbani, R.	8								X	
97	'Rage against the machine'? The opportunities and risks concerning the automation of urban green infrastructure	Gulsrud, N. M., Raymond, C. M., Rutt, R. L., Olafsson, A. S., Plieninger, T., Sandberg, M., Beery, T. H., & Jönsson, K. I.	1, 2, 3, 5, 6, 9	X	X	X		X	X			X
98	Implementation of IoT-Based Sensor Systems for Smart Stormwater Management	Altami, S. A., & Salman, B.	2, 8		X						X	
99	Machine Learning-Assisted, Process-Based Quality Control for Detecting Compromised Environmental Sensors	Jacquelyn Q. Schmidt and Branko Kerkez	8								X	
100	Extracting useful signals from flawed sensor data: Developing hybrid data-driven approaches with physical factors	Yang, C., Daigger, G. T., Belia, E., & Kerkez, B.	8								X	
101	Balancing water quality and flows in combined sewer systems using real-time control	Troutman, S. C., Love, N. G., & Kerkez, B.	1, 2, 8	X	X						X	

#	Title	Authors	Question Anwsered 1-9	Question 1 - Purpose of ALCS Use	Question 2 - Primary Application	Question 3 - Location and Use Setting	Question 4 - States with Precedent for Approval	Question 5 - Regulatory and Other Barriers	Question 6 - Co-Benefits Beyond Water Quantity and Quality	Question 7 - Ownership and Operation	Question 8 - Modeling Software to Support ALCS	Question 9 - ALCS BMP Costs in Literature
102	Real time controlled sustainable urban drainage systems in dense urabn areas	Kändler, N.; Annus, I.; Vassiljev, A.; Puust, R.	1, 3	X		X						
103	Potential and limitation sof modern equipment for real time control of urban wastewater systems	Campisano, A., Cabot Ple, J., Muschalla, D., Pleau, M., & Vanrolleghem, P. A.	8								X	
104	Intergrated stromwater inflow control for sewers and green structures in urban landscapes	Lund, N.S.V., Borup, M., Madsen, H. *et al.*	2, 3, 6		X	X			X			
105	Assessing and Optimizing the hydologic performance of Gre-Green infrastructure systems in response to climate change and non-stationary time series	Mo Wang, Ming Liu, Dongqing Zhang, Jinda Qi, Weicong Fu, Yu Zhang, Qiuyi Rao, Amin E. Bakhshipour, Soon Keat Tan	1, 3, 6, 9	X		X			X			X

Appendix B

Technology Transfer: Baseline Presentation Slides

Adaptive Level Control Systems

Maximizing Stormwater Pond Functionality

Cory Anderson, PE

Sarah Stratton, CFM

November 2025

BARR®

Acknowledgements

This project was supported by the Minnesota Stormwater Research Program administered by the University of Minnesota Water Resources Center. Financial support was provided through an appropriation from the Clean Water Fund established by Minnesota Clean Water Land and Legacy Amendment and from the Minnesota Stormwater Research Council. The council is supported with financial appropriations from many watershed districts and organizations, cities, and private industry. Visit the website at wrc.umn.edu/msrc to see the list of these financial partners.

For more information about the program, visit the website at wrc.umn.edu/stormwater

For more information about the Minnesota Clean Water, Land and Legacy Amendment, visit https://www.legacy.mn.gov/about-funds

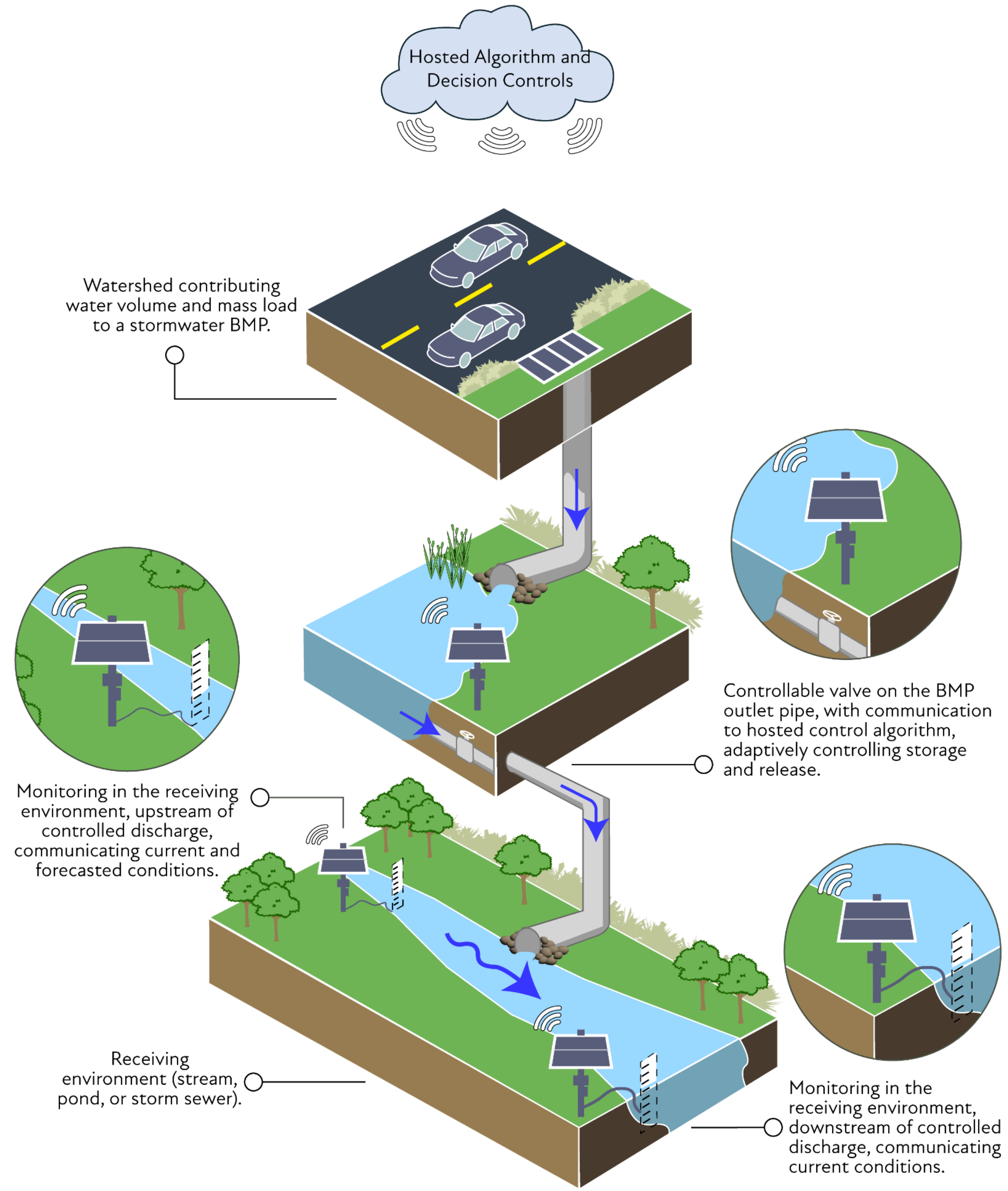
Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the Water Resources Center or the Minnesota Stormwater Research Council.

Contents

Background:
What is ALCS?

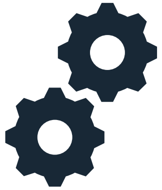
What is ALCS?

- Adaptive
- Level
- Control
- System



Similar Technology or Alternative Names

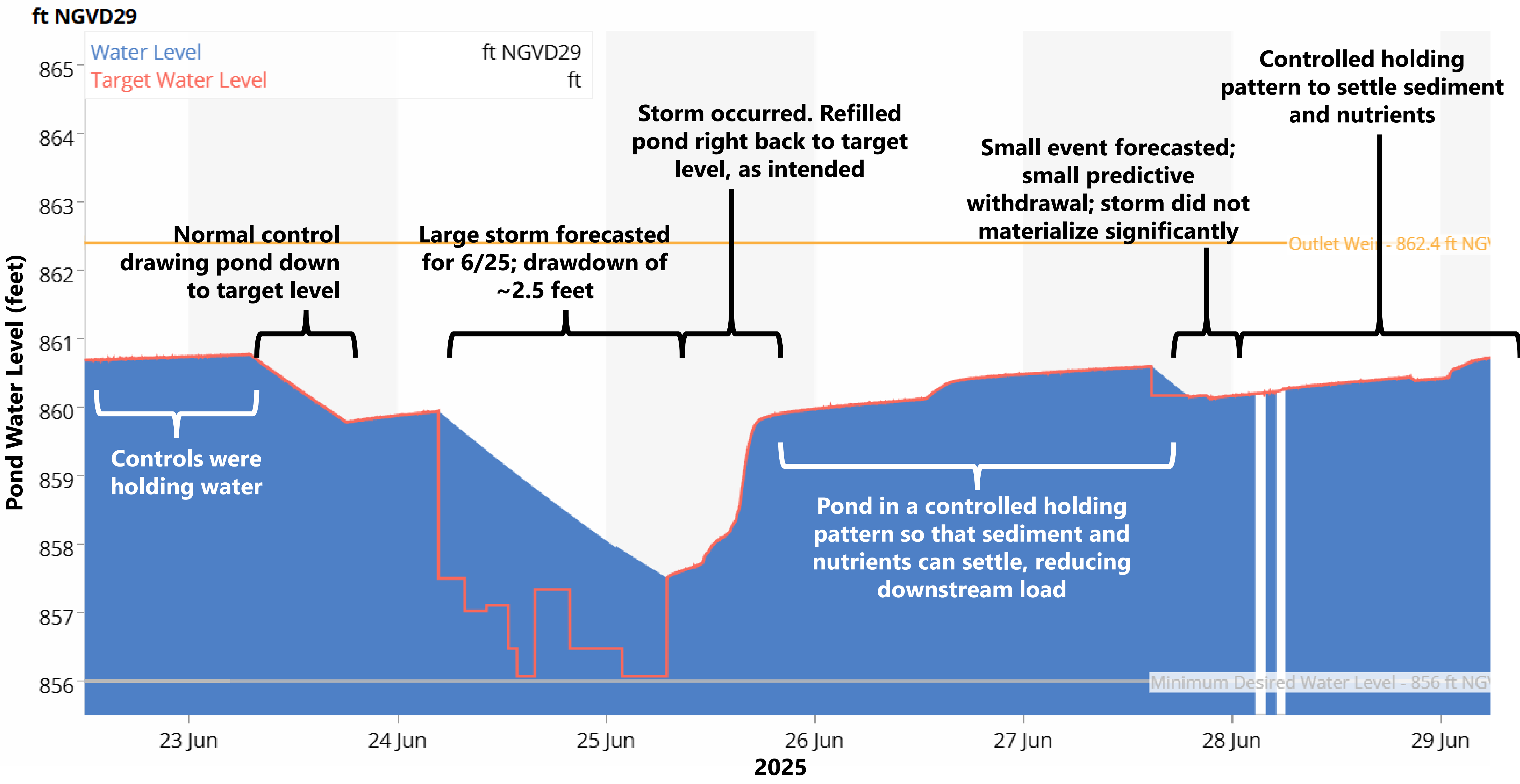
Real-Time Control (RTC)



Continuous Monitoring and Adaptive Control (CMAC)

Smart Infrastructure

Forecast Informed Reservoir Operations (FIRO)



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Weber Pond, City of Edina, MN (Morningside Flood Infrastructure Project)

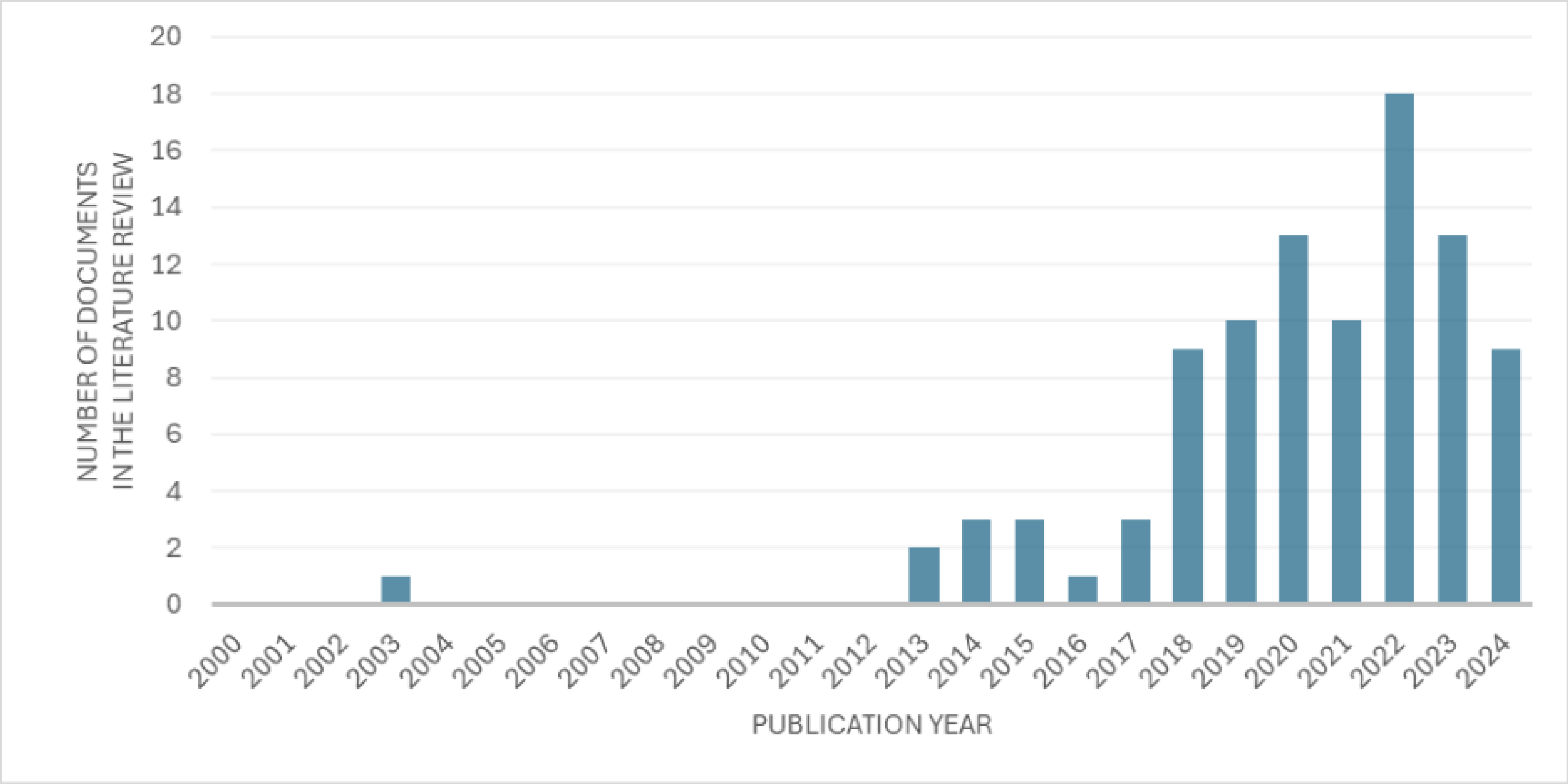
Literature Review
Research Questions

Research Questions

- Purpose of ALCS use
- Primary application: retrofits or new construction?
- Location and use setting
- States with precedent for approval
- Regulatory and other barriers
- Co-benefits beyond water quantity and quality
- Ownership and operation
- Modeling software to support ALCS
- ALCS BMP costs in the literature

Literature Review

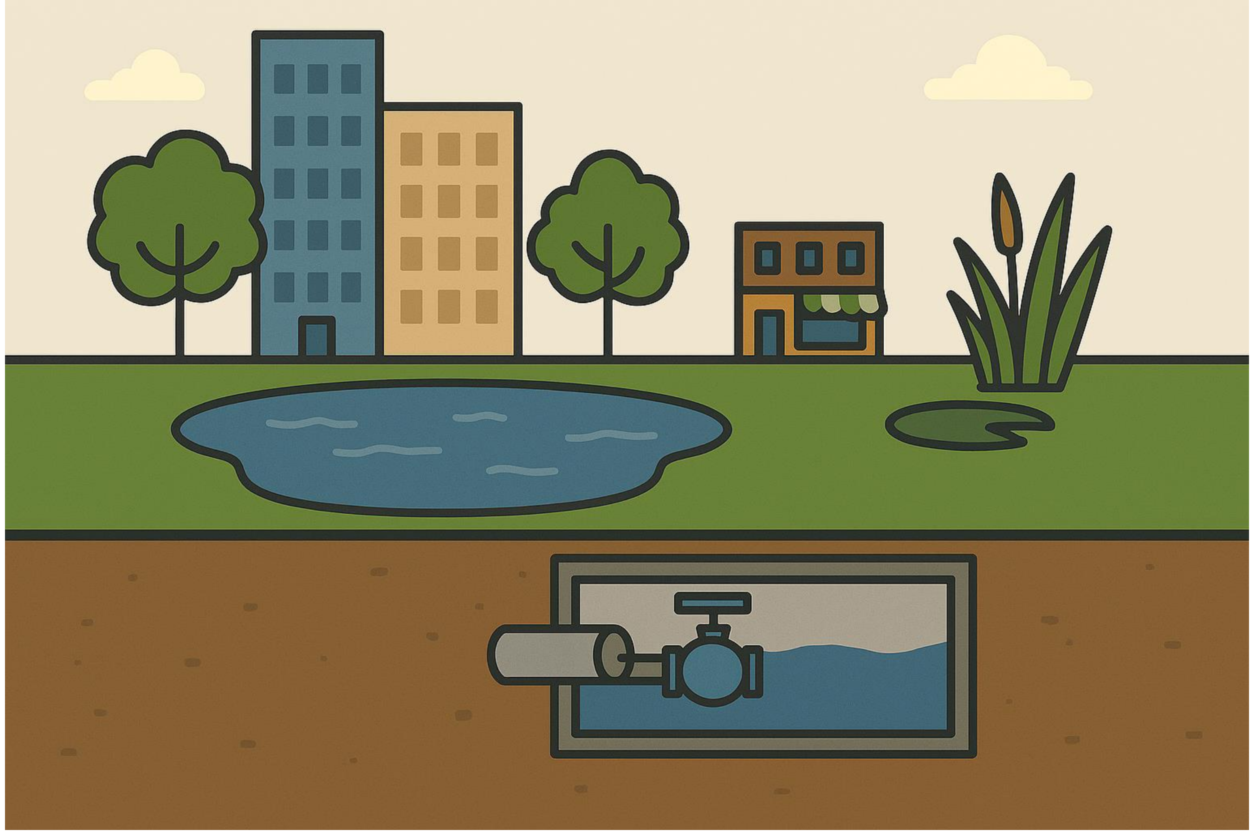
- Internet Search for ALCS-Related Phrases
- 105 Documents Identified and Referenced



Question 1 – Purpose of ALCS Use

- Dual Purpose
- Multi-Objective Operation
- Technology Adoption
- Operational Patterns
- System Level Benefits

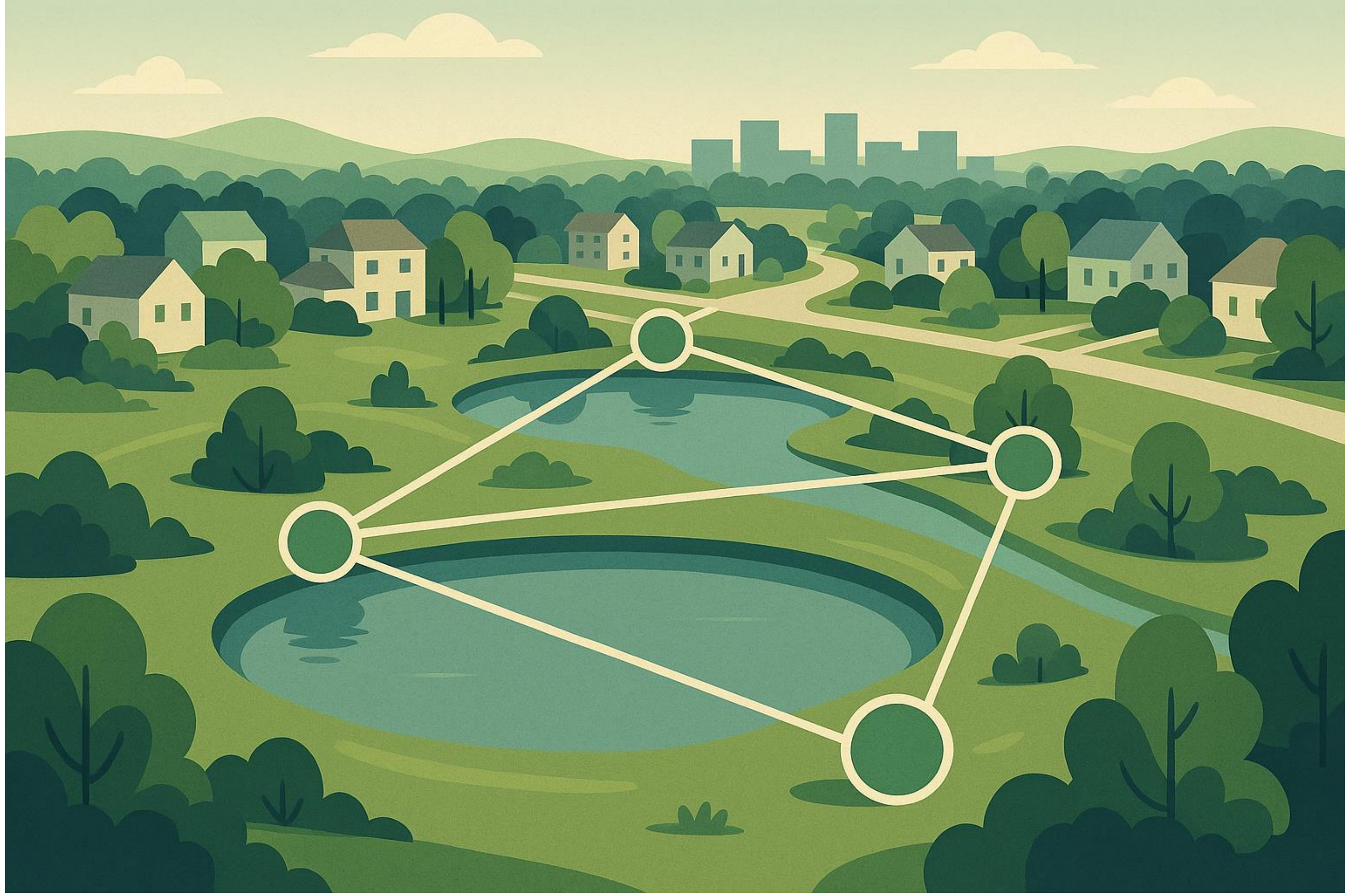
Question 2 – Retrofits or New Construction?



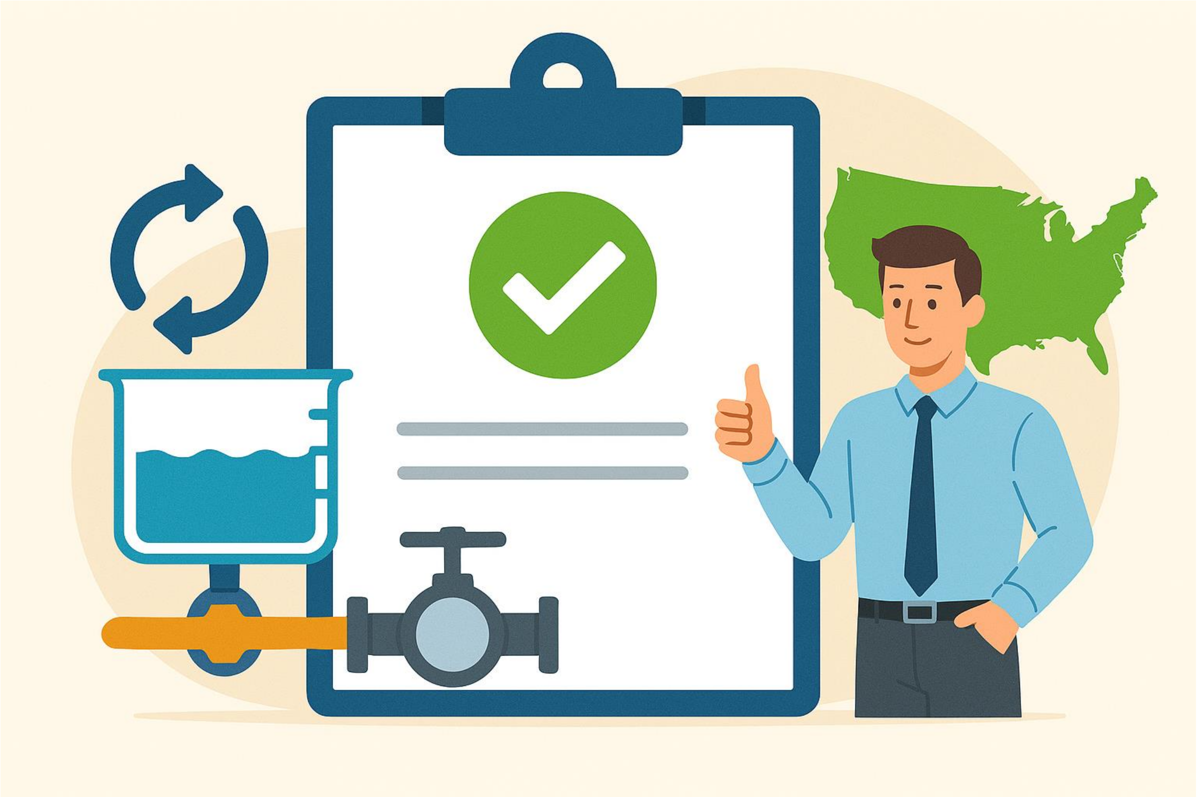
- Retrofits Dominate
- Typical BMPs for Retrofits
- Retrofitting Benefits
- New Construction Applications

Question 3 – Location and Use Setting

- Urban and Suburban Focus
- Scalable Applications
- Watershed-Scale Potential
- International Uptake



Question 4 – States with Precedent for Approval



- Regulatory Acceptance in Key States
- Pathways to Approval
- Role of Trust and Predictability
- Growing Catalog of Case Studies
  - EPA Report

Question 5 – Regulatory and Other Barriers

- Regulation, Governance & Permitting Complexity
- Institutional Capacity & Operator Trust
- Interoperability & Standardization
- Data Uncertainty & Computation Power
- Data Privacy & Cybersecurity
- Public Perception & Design-Mediated Acceptance
- Pathways to Overcome Barriers

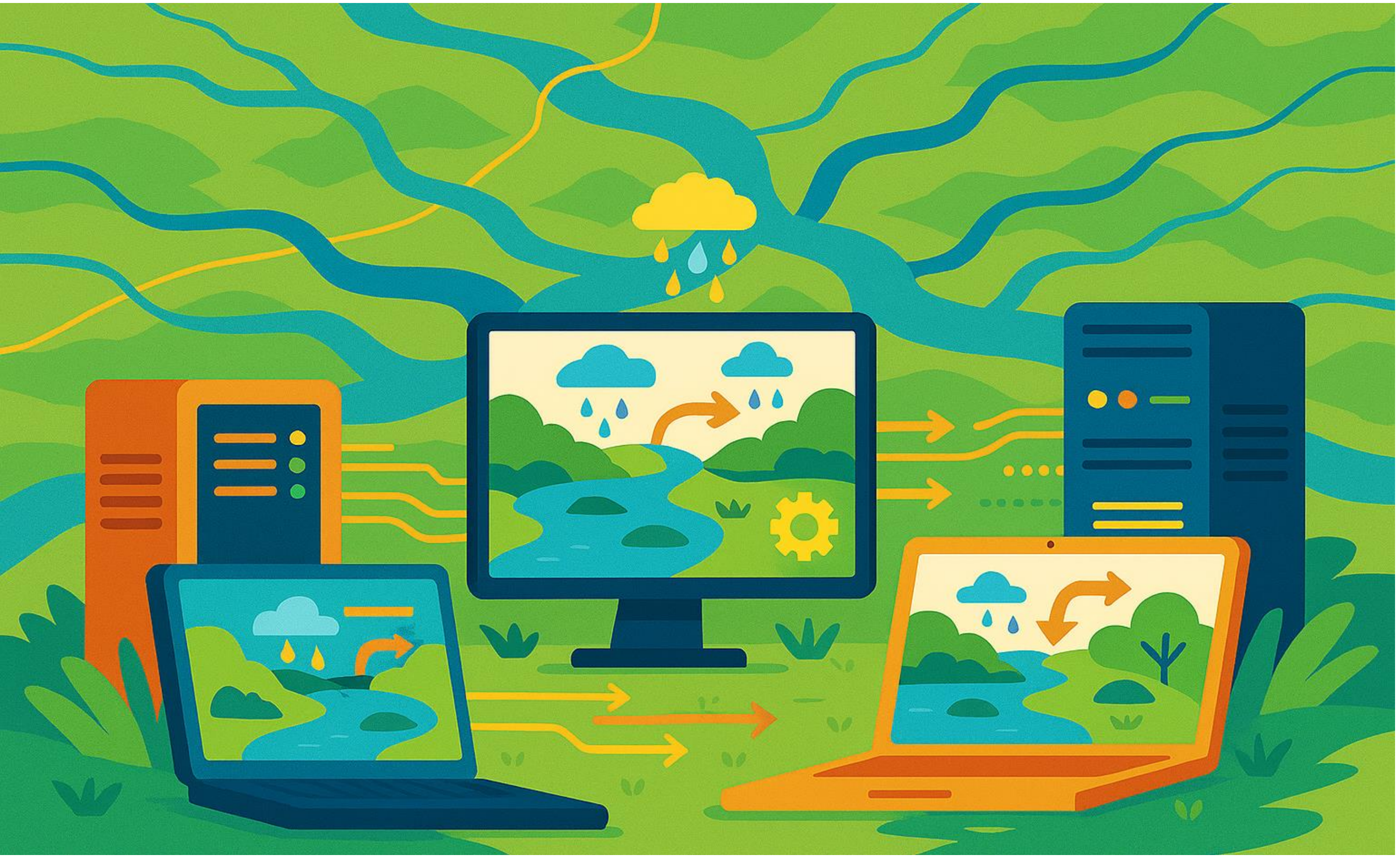
Question 6 – Co-Benefits

- Environmental Co-Benefits
- Operational Advantages
- Economic and Social Gains

Question 7 – Ownership and Operation

- Defined Ownership & Responsibility
- Central Role of Operators
- Heightened Maintenance Needs
- Organizational Capacity

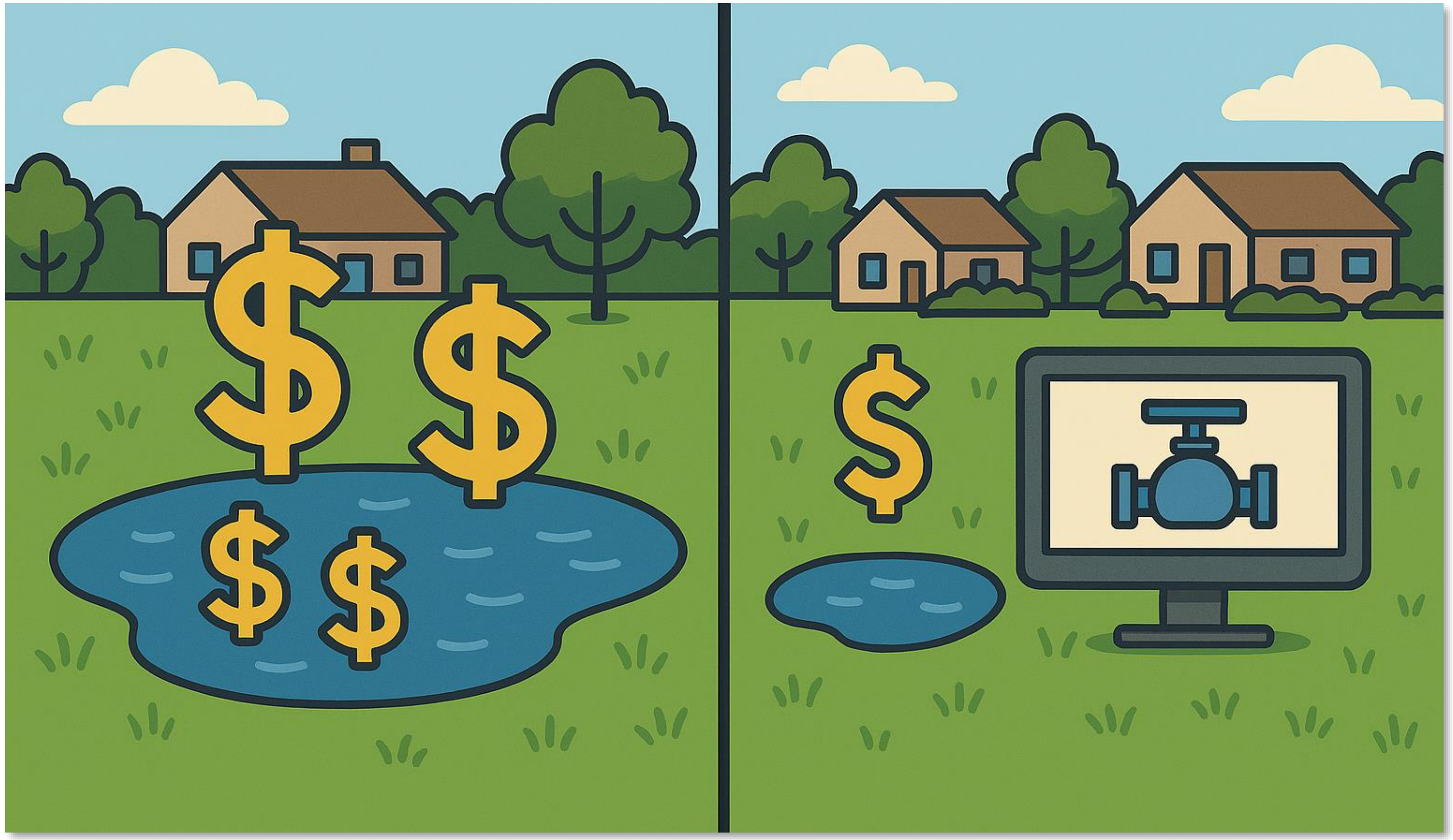
Question 8 – Modeling Software



- Tool Selection
- Real-Time Capability
- Model Speed & Computational Power
- Emerging Technologies

Question 9 – Costs in Literature

- Capital Cost Savings
- Operational Costs
- Life Cycle Analyses



Cost Estimating

Cost-Estimating Purpose

- Estimate Capital and Operating Expenses during Planning
- Provide a Point of Comparison to other BMPs
- Facilitate Consideration of ALCS in Planning

Basic Assumptions for Planning-Level Cost Estimates

- Existing BMP (wet pond or lake); existing outlet
- Proximity to streets and storm sewer
- Drawdown depths are limited
  - Controls infrastructure size in the vertical dimension
- Drawdown time (forecast horizon) is limited to 12-24 hours
- Discharge rates are limited to capacity of downstream infrastructure

Basic Assumptions for Planning-Level Cost Estimates

- Cost of purchasing land not included…not needed
- Construction limits set by size of structure
- Construction duration
- Minor dredging required
- One time and ongoing costs for smart infrastructure

Planning Level Cost Estimate for Construction – Gate Option

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$426,000	$780,000
20	$436,000	$889,000
30	$455,000	$974,000
40	$465,000	$1,081,000
50	$476,000	$1,176,000
60	$509,000	$1,285,000
70	$516,000	$1,379,000
80	$532,000	$1,487,000

These cost ranges are based on estimated ranges in units costs and in quantities;
at planning level, the accuracy range of -50%/+100% should be applied to these costs

Planning Level Cost Estimate for Construction – Valve Option

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$542,000	$806,000
20	$591,000	$843,000
30	$615,000	$869,000
40	$662,000	$930,000
50	$770,000	$1,054,000

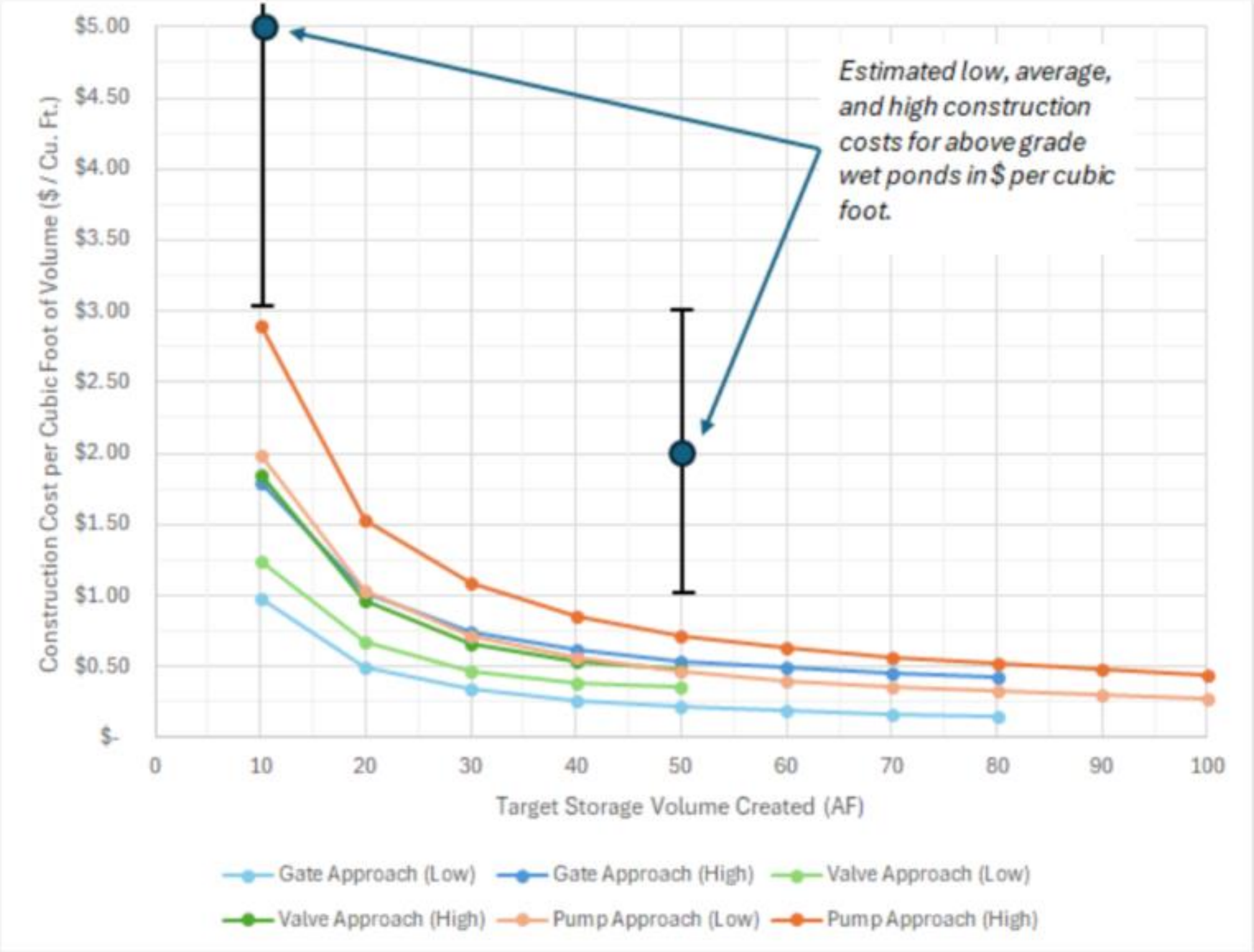
These cost ranges are based on estimated ranges in units costs and in quantities;
at planning level, the accuracy range of -50%/+100% should be applied to these costs

Planning Level Cost Estimate for Construction – Pump Option

Total Storage (AC-FT)	Anticipated Cost, Low End, $ USD	Anticipated Cost, High End, $ USD
10	$864,000	$1,263,000
20	$903,000	$1,340,000
30	$941,000	$1,417,000
40	$980,000	$1,495,000
50	$1,019,000	$1,572,000
60	$1,056,000	$1,656,000
70	$1,095,000	$1,736,000
80	$1,135,000	$1,810,000
90	$1,172,000	$1,888,000
100	$1,211,000	$1,898,000

These cost ranges are based on estimated ranges in units costs and in quantities;
at planning level, the accuracy range of -50%/+100% should be applied to these costs

Planning Level Cost Estimate for Construction – Comparison



Planning Level Cost Estimate for Construction – Comparison

Retention Storage BMPs	Installation	Low Typical $/cf Volume	Average Typical $/cf Volume	High Typical $/cf Volume
Underground Storage	underground	14	21	28
Above Grade Wet Ponds (Large, ~50 ACFT)	above ground	1	2	3
Above Grade Wet Ponds (Medium, ~10 ACFT)	above ground	3	5	10
Above Grade Wet Ponds (Small)	above ground	10	15	50
Green Infrastructure BMPs	**Installation**	**Low Typical $/cf Volume**	**Average Typical $/cf Volume**	**High Typical $/cf Volume**
Rainwater Garden (infiltration)	above ground	13	18	22
Rainwater Garden (biofiltration)	above ground	16	21	27
Enhanced Media Filter	above ground	21	24	27
Stormwater Planters	above ground	21	27	34
Tree Trench (infiltration, filtration)	above ground	35	53	70
ALCS BMPs	**Installation**	**Low Typical $/cf Volume**	**Average Typical $/cf Volume**	**High Typical $/cf Volume**
Actuated Gate Weir (Medium, ~10 ACFT)	retrofit	0.98	1.38	1.79
Actuated Gate Weir (Large, ~50 ACFT)	retrofit	0.22	0.38	0.54
ALCS Pump Station (Medium, ~10 ACFT)	retrofit	1.98	2.44	2.90
ALCS Pump Station (Large, ~50 ACFT)	retrofit	0.47	0.59	0.72
ALCS Pump Station (Very Large, ~100 ACFT)	retrofit	0.28	0.36	0.44
Actuated Valve (Medium, ~10 ACFT)	retrofit	1.24	1.55	1.85
Actuated Valve (Large, ~50 ACFT)	retrofit	0.35	0.41	0.47

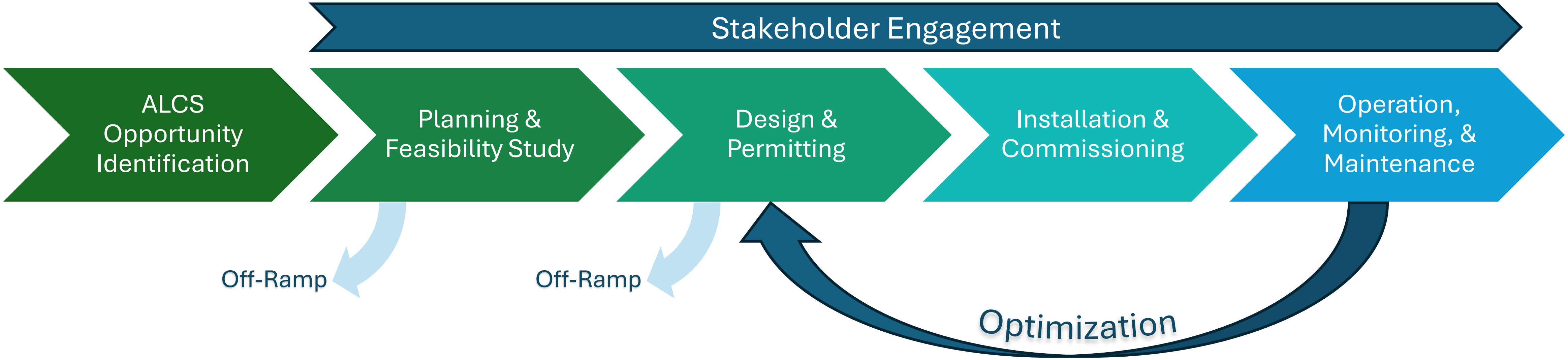
Other Cost Considerations

- Land Acquisition
  - Needed or Not
  - Substantial Cost Savings with ALCS
- O&M Costs
  - Maintenance, Subscriptions, and Repairs
- Engineering, Design, and Permitting
  - Engineering and Design
  - Permitting

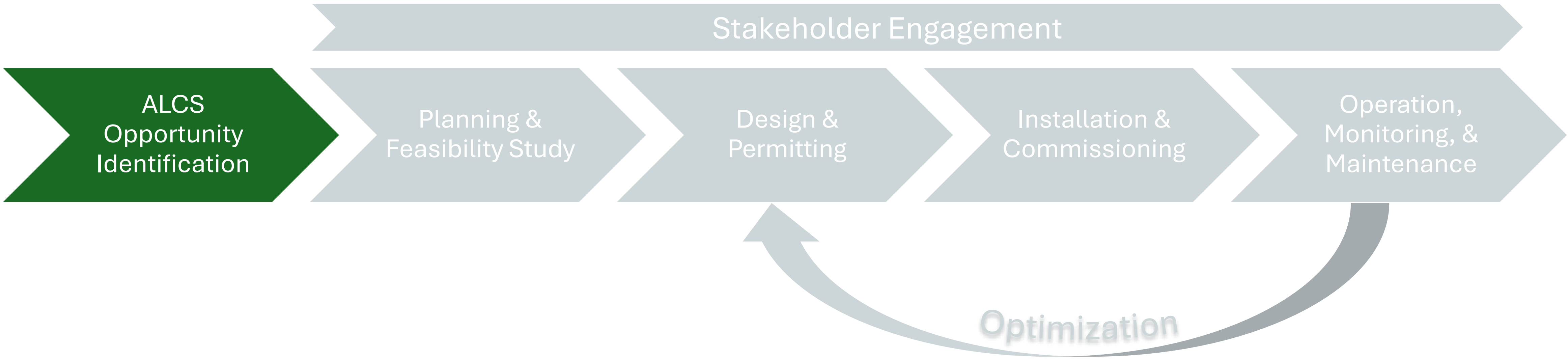
Implementation Strategies

Minnesota Specific

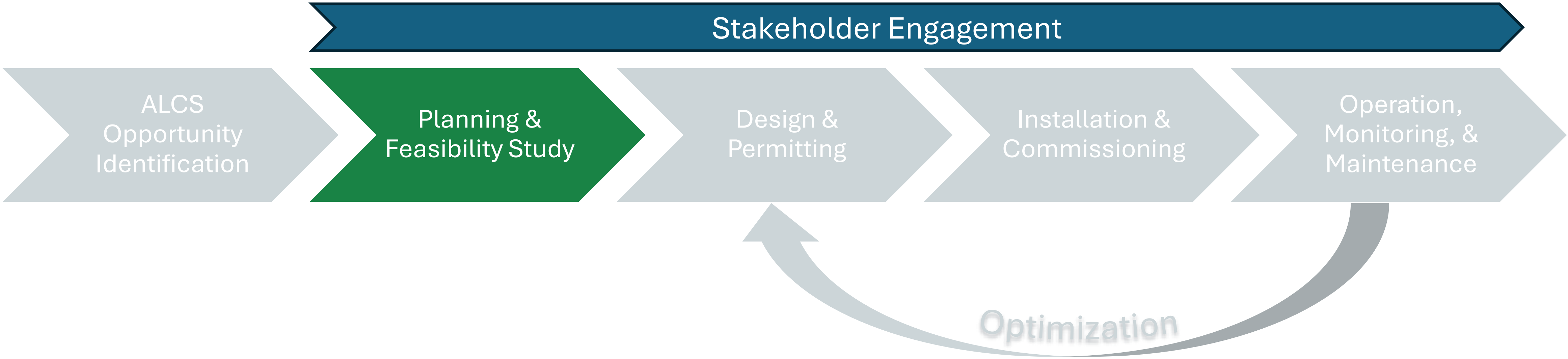
Process for ALCS Implementation



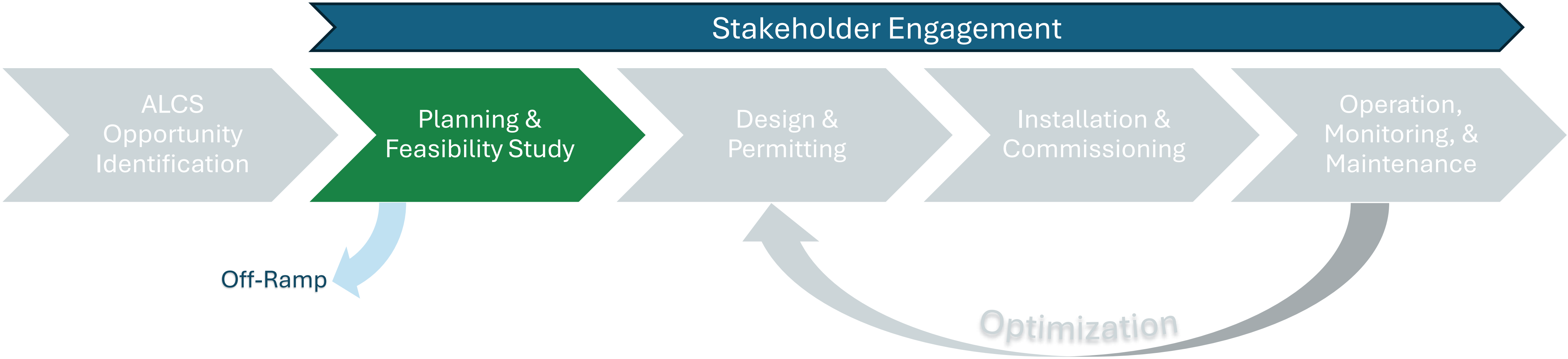
Process for ALCS Implementation



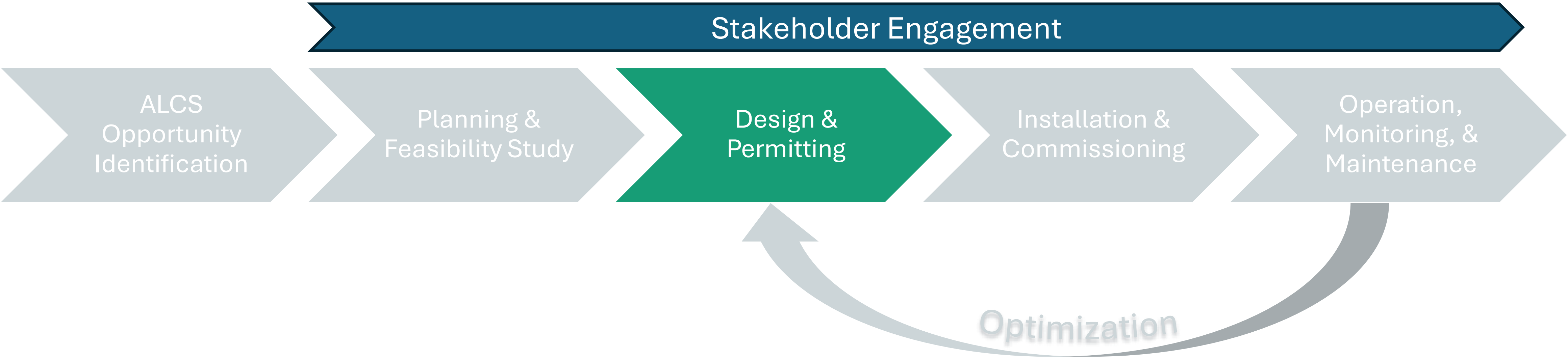
Process for ALCS Implementation



Process for ALCS Implementation



Process for ALCS Implementation



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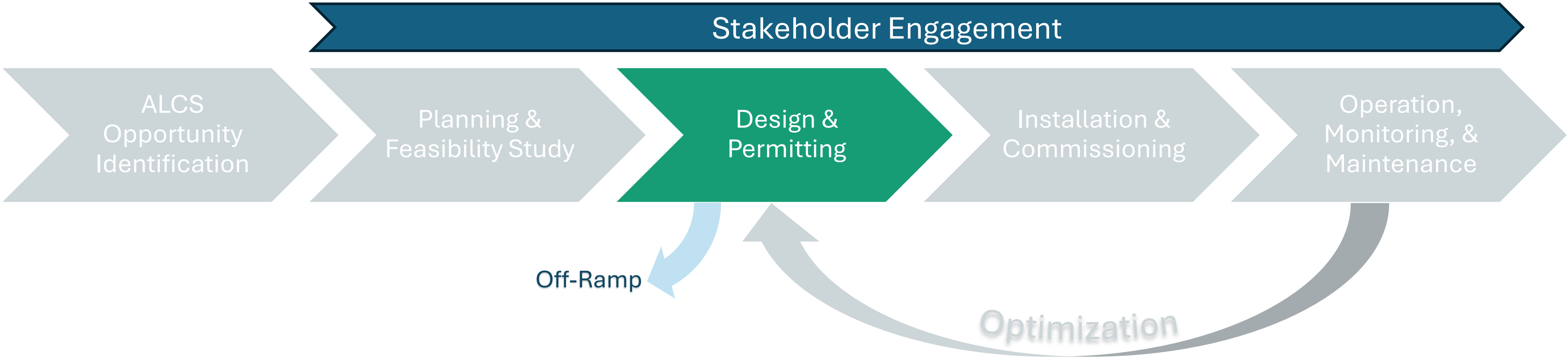

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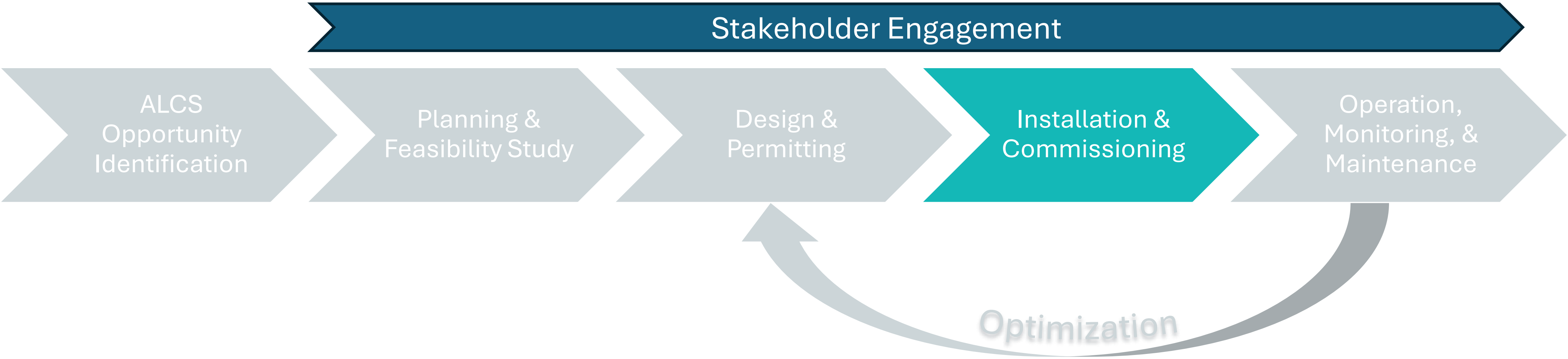

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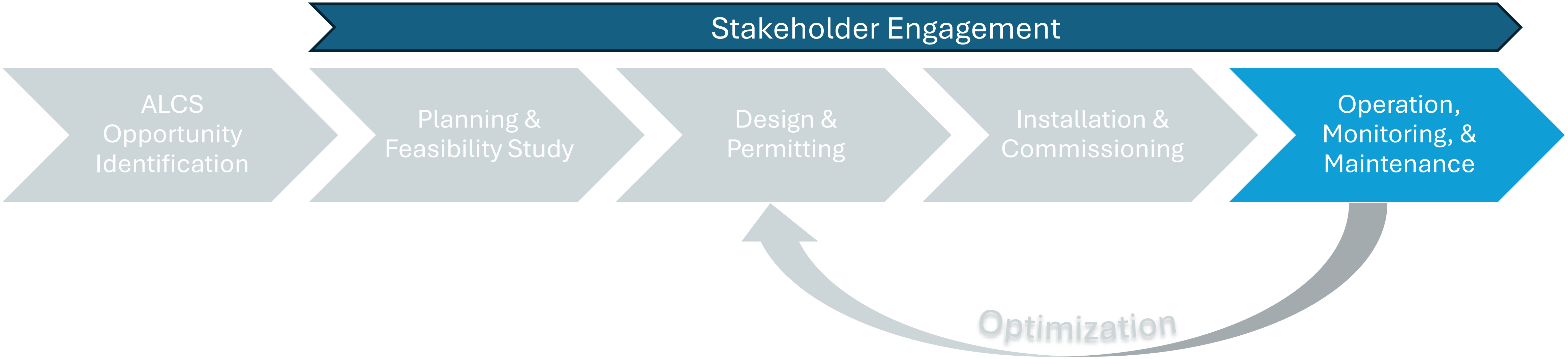
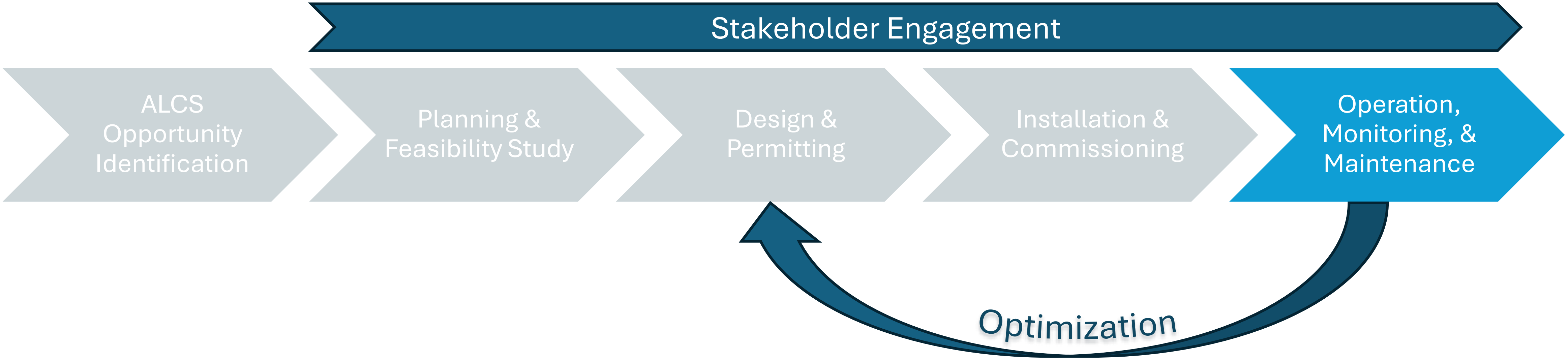
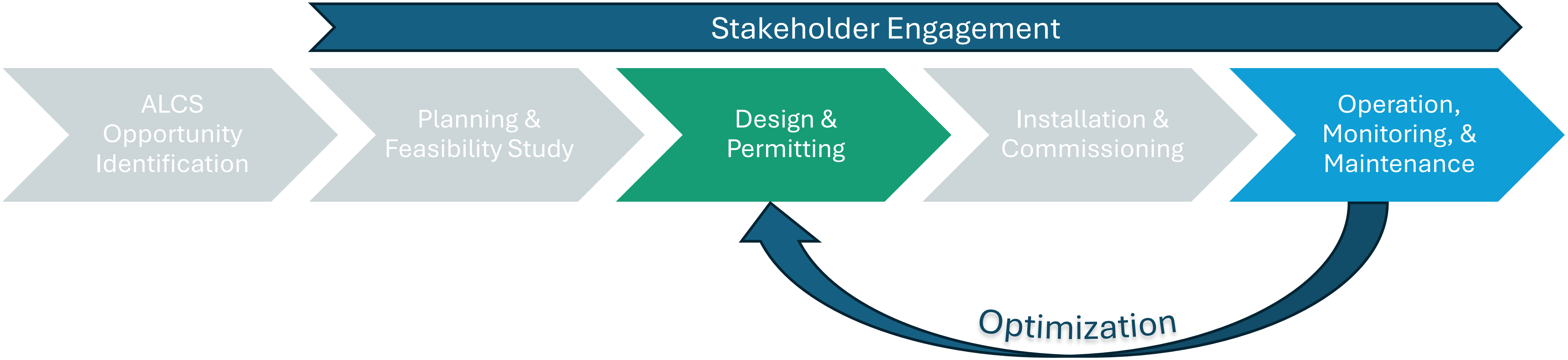


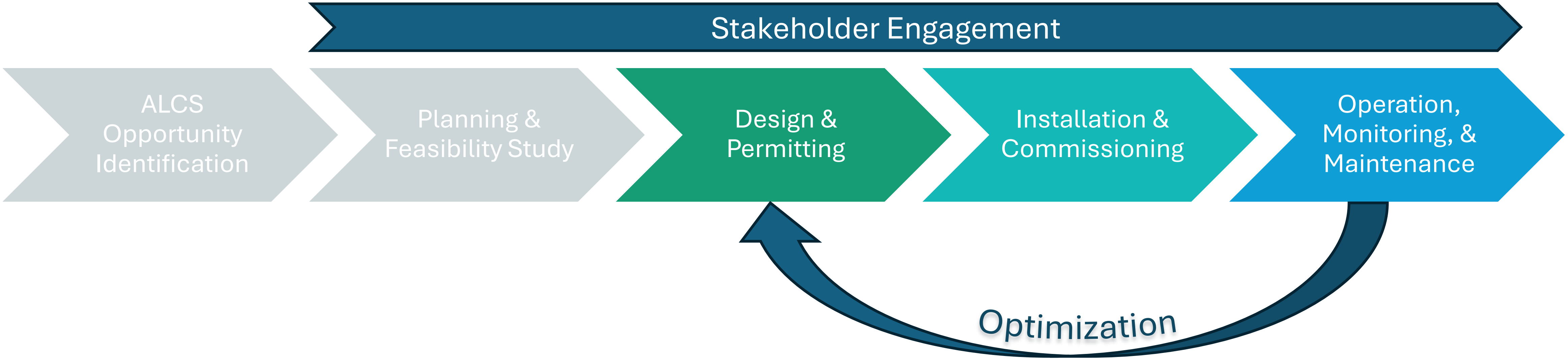
Process for ALCS Implementation



Process for ALCS Implementation



Process for ALCS Implementation



Project Examples

To be included on a presentation-by-presentation basis, depending on the target audience, and with permission from clients

Thank you

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Sarah Stratton, CFM

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Appendix C

Technology Transfer: Recommendations for ALCS Inclusion in Minnesota Stormwater Manual Guidance

Technology Transfer of Minnesota Stormwater Research Council Funded Projects to the Minnesota Stormwater Manual

Introduction

The Minnesota Pollution Control Agency (MPCA) administered Minnesota Stormwater Manual (Manual) is the premier source of information on stormwater management in the State of Minnesota. The University of Minnesota Water Resources Center (WRC) and the Minnesota Stormwater Research Council (MSRC) fund priority research on stormwater management and is an important means to develop new information for the Manual.

Stormwater research results may may be included in the Manual on a case-by-case basis, as determined by the MPCA. WRC & MSRC funded projects are required to include a technology transfer plan, many which indicate their results may be included in the Manual. The MPCA and WRC have developed these guidelines and form to collect and provide information on a research project so that the agency may evaluate if the findings should be incorporated into the Manual.

Instructions

Part I is to be completed by researchers of WRC-MSRC funded projects and should also be included in the final report deliverable, most likely as an appendix. WRC staff will forward this information to the MPCA for consideration.

Part II is informational and describes some considerations the MPCA will make to determine whether the proposed information may be integrated into the Manual. The amount of information and vetting necessary by the MPCA will vary depending on the nature of the material, extent of the results and recommendations, and potential concerns (e.g. discrepancies with existing information, differences with regulatory requirements, interactions with other regulatory jurisdictions, potential to create other impacts, or other potential concerns).

WRC-MSRC funded research projects for which the work might be considered for inclusion into the manual, should provide the information described in Part I and include it as an appendix with the submission of the final report.

Part 1: Information requested from MSRC researchers

1. Research Project Overview

This form is an appendix to the research report, titled *Adaptive Level Control Systems, Research on Maximizing Stormwater Pond Functionality*, published November 2025. The executive summary is in the research report. Principal investigators were Cory Anderson, PE, and Sarah Stratton, CFM, Barr Engineering Company. Additional members of the research team from Barr Engineering Company were: Carter Moffitt, Katie Kramarczuk, Jack Jarvela, and Matt Metzger, PE.

2. Practices or Topics of Relevance

This research is most relevant to traditional Best Management Practices (BMPs) that normally hold water such as lakes, reservoirs, wet ponds, cisterns, underground storage vaults. This research could also apply to other BMPs that do not normally hold water (dry basins, rain gardens, tree trenches, etc.) by having the small outlet become controllable to open and close, but this is a far less common application.

3. Benefit and Need

The main purposes of the research were to: summarize the current state of understanding on this topic, provide a thorough, yet quick means to estimate costs during the planning and feasibility stage of the implementation process, and to provide insight and guidelines for evaluating, designing, permitting, constructing, and maintaining an ALCS, particularly in the state of Minnesota. There is increasing attention on this topic, with a growing number of stormwater managers and engineers evaluating this method as a cost-effective and practical best management practice that has previously received limited consideration. Results are most useful to stormwater managers, BMP owners, regulators, and engineers. This work may enhance the Manual's guidance by contributing essential content, thereby encouraging greater consideration of ALCS and providing solid guidance. .

4. Technical Advisory Committee or Panel (TAC or TAP?)

A formal TAC or TAP was not convened specifically for this research. However, this research built on the experience of the Principal Investigators through multiple related projects, where TACs and TAPs have been convened. For example:

- For the City of Edina's work on ALCS, Ross Bintner (Engineering Services Manager) from the City of Edina convened the following people to keep them informed and gather feedback: Chad Millner (Director of Engineering) from the City of Edina; Julie Long (City Engineer), Jack Distel (Water Resources Specialist), and Bryan Gruidl (Water Resources Manager) from the City of Bloomington; Chad Donnelly (Assistant Utility Superintendent) and Mattias Oddsson (Water Resources Engineer) from the City of Richfield; Erica Sniegowski (District Administrator) and Zach Stafslien (Regulatory Program Manager) from Nine Mile Creek Watershed District; Cory Anderson (Senior Water Resources Engineer), Sarah Stratton (Senior Water Resources Scientist), Louise Heffernan (Senior Water Resources Engineer) and Janna Kieffer (Senior Water Resources Engineer) from Barr Engineering Co.; Wes Saunders-Pearce (former North Metro Area Lead Hydrologist) and Jeff Weiss (Floodplain and Surface Water Engineer) from the Minnesota DNR.
- For the Nine Mile Creek Watershed District's work on ALCS, Erica Sniegowski (District Administrator) and Zach Stafslien (Regulatory Program Manager) from Nine Mile Creek Watershed District convened the following people to keep them informed and gather feedback: Ross Bintner (Engineering Services Manager) and Jessica Vanderwerff Wilson (Water Resources Manager) from the City of Edina; Jack Distel (Water Resources Specialist) and Bryan Gruidl (Water Resources Manager) from the City of Bloomington; Mattias Oddsson (Water Resources Engineer) and Kristin Asher (Public Works Director) from the City of Richfield; Eric Vogel (Water Resources Engineer), Eric Waage (Directory of Emergency Management), and Kris Guentzel (Land and Water Supervisor) from Hennepin County; Phil Olson (City Engineer), Sarah Schweiger (former Water Resources Engineer), Chris Long (Assistant City Engineer), and Leslie Yetka (Natural Resources Manager) from the City of Minnetonka; Patrick Sejkora (Water

Resources Engineer) from the City of Eden Prairie; Nick Tiedeken (Hydrologist), Jason Swenson (MS4 Principal Engineer), and Katherine Kowalczyk (Metro Water Resources Engineer) from the Minnesota DOT; Wes Saunders Pearce (former North Metro Area Lead Hydrologist) from the Minnesota DNR; Eric Klingbeil (Assistant City Engineer) from the City of Hopkins; Amy Timm (Watershed Project Manager) and Miranda Nichols (Central Watershed Unit Supervisor) from the Minnesota Pollution Control Agency; Jennifer Dullum (Board Conservationist) from the MN Board of Water and Soil Resources; Brian Vlach (Senior Manager of Water Resources) from the Three Rivers Park District.

5. TAC or TAP Result Review

As mentioned above, there was no formal TAC or TAP for this specific research. However, responses from the TACs and TAPs for the City of Edina and Nine Mile Creek Watershed District have been appreciative and interested in the discussions about ALCS. The main area of concern has been around the ability for rainfall forecasts to accurately predict storms, and what may happen as a result of false positives where a storm is forecasted, storage volume is released to lower water levels, and the storm does not occur as expected and the water level stays low for an extended time. Additional questions about potential for erosion in Nine Mile Creek (as an example) have been addressed via research on sediment transport capacity as part of an ALCS project for the City of Edina and shared with their TAC.

6. Which of the following do the research and results apply to?

Select all that might apply in your opinion.

- X Design guidance technical information
- ☐ Installation (construction) guidance technical information
- ☐ Inspection, operation, and maintenance guidance technical information
- ☐ Tool(s)
- X Case study or demonstration/pilot project
- ☐ Uncertain
- X Other (explain) – *Cost Estimating, and Implementation Strategies to Aid in Process*

7. Which best describes the relevance of the results to existing Manual information?

Select the one best option in your opinion or leave unanswered if you are unsure.

- X The results provide new technical information not currently in the Manual.
- ☐ The results augment existing technical information in the Manual.
- ☐ The results suggest a change or replace existing technical information in the Manual.
- ☐ None of the above or other (explain)

8. Identify specific manual page(s), location on the page(s), and links where you think this information should be incorporated.

The Manual is in process of being updated from the version 3 wiki format to a new online format as version 4. This beta version of the new Manual is referenced here.
Description of ALCS as a retrofit to BMPs should likely be included alongside the structural BMPs:
Structural stormwater Best Management Practices | Minnesota Stormwater Manual
Pages that talk about retrofit suitability would also be a good place to include this research:
Overview for stormwater ponds | Minnesota Stormwater Manual
The research also focuses on cost estimates, and the Manual could benefit from including the cost estimates for ALCS documented in the research report. Places in the Manual could be on pages such as:
Cost-benefit considerations for stormwater ponds | Minnesota Stormwater Manual

9. Description of New or Updated Information Proposed for Inclusion

The most relevant information from the research report is likely the description of ALCS in Section 2, the cost information in Section 5, and the guidance on implementation in Section 6. Information on the implementation may be well suited for the Manual in this page:
Design guidance for stormwater BMPs | Minnesota Stormwater Manual

Part II: Informational only; MPCA considerations

Section not required