A framework for making economic evaluations of control improvement projects in urban drainage systems

A modified cost-benefit analysis approach

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Master of Science Thesis

TU Delft
Delft University of Technology

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MASTER OF SCIENCE THESIS

For the degree of Master of Science in Civil Engineering at Delft University of Technology

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November 19, 2013

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Acknowledgements

I would like to thank my graduation committee for their support and guidance through the preparation of this thesis. Your diverse areas of interest and expertise relating to the topic of my research helped me to see many perspectives of decision-making processes and control improvement projects in urban drainage systems. I hope that this thesis reflects your valued input.

I am grateful to the officials and engineers of the projects in Quebec, South Bend, Tokyo, Hoeksche Waard and Messel, who took the time to discuss their projects with me and provided additional data and information.

I would also like to recognize my office mates in 4.84, Marijn, Bouke, Emma, Nadine, Stephanie, Wouter, Tim and Maarten, for the really wonderful – though terribly messy – work environment in “The Henhouse”. Bedankt voor de lessen in de Nederlandse taal, humor en cultuur. I hope I never again have to use most of the words or jokes you taught me, but the food, drinks, laughs and chats have made these months erg gezellig.

To my friends in Delft and at home, thank you all for your support and good company.

Sadie McEvoy

Delft

November 2013

Abstract

A framework has been developed for making economic evaluations of control improvement projects (CIPs) in urban drainage systems. The framework uses a modified cost benefit analysis approach to combine best economic practices with pragmatic limitations on benefit valuation. The framework aims to standardize evaluations to ensure that projects are assessed correctly and produce useful information for further understanding. Foremost, the framework is a practical way of providing relevant information to advise decision-makers on investments in CIPs.

Around the world, many cities with combined sewers are currently facing the need to improve their urban drainage systems to meet new water quality standards and address growing challenges from urbanization and climate change. Costly infrastructure expansions are the traditional way of increasing system capacity to reduce combined sewer overflows (CSOs). An alternative approach, however, is to better use the infrastructure that already exists.

Most urban drainage systems are controlled by structures and operational rules that do not optimize or integrate the sewer, wastewater treatment plant and surface waters. Using advanced control schemes to do this can improve system performance with less capital investment. As water managers begin considering control improvement as a way to reduce CSO emissions, these projects need to be evaluated and compared to conventional infrastructure solutions. Economic assessments play an important role in such processes, but these are not straightforward to make and there is no established standard. This thesis aims to provide a practical framework for making economic evaluations of CIPs in urban drainage systems, in order to inform decision makers.

A literature review was made to establish the present status of control applications in urban drainage systems, as well as current theories in economic valuation of water resources and project evaluation techniques. Eleven cases from North America, Europe and Japan were then studied to gain insight into how assessments are being made and projects are being implemented in practice.

The findings of the literature reviews indicate that the current lack of standards for evaluating CIPs has led to inconsistencies in how projects are assessed and the way that costs and performance results are reported. This makes it difficult to analyse and compare projects. One key problem is that, in most cases, control improvement is part of a wider project that includes elements of optimization, control and infrastructure expansion. The performance results and costs, however, are reported holistically, making the contribution of the control difficult to determine. Another problem is that the different starting points and control potential of projects are not made clear in the evaluations. This makes the results ambiguous and misleading.

In order be usable, the framework must conform to practical limitations. One significant constraint is the lack of a reliable way to value the benefits of CIPs in economic terms. Another constraint is a lack of motivation to make comprehensive economic assessments, since decision-makers are mainly motivated to meet a regulatory standard and not to optimize their investment. Finally, the framework must address the difference in the timing of investments for control and infrastructure projects, since the upfront costs associated with CIPs can be offputting.

The framework suggests a modified cost benefit analysis (CBA) approach to standardize economic evaluations in a practical way. The main features are:

1. Least cost analysis (LCA).
    a. A special case of CBA, in which benefits are not valued, because they are the same for every alternative. This is appropriate because regulation as the main driver of CIPs means that the performance (benefits) of all viable alternatives must be the same.
    b. This avoids the difficult task of valuing benefits in economic terms.
2. A two-step assessment.
    a. The purpose of the first step is to rationalize the upfront costs of investigating whether a control improvement option should be included in the project alternatives.
    b. The purpose of the second step is to compare project alternatives with comparable performance levels, using a least cost analysis.
3. A categorized and marginal approach.
    a. Three categories are identified in CIPs: optimization, control and capital improvement. The purpose of the categories is to isolate the costs and performance results attributable to the control aspects of a project.
    b. Five benchmark control levels are identified to measure the marginal performance gains for the incremental improvements in control. The purpose of the marginal approach is to minimize the bias in reported costs and results due to different starting points and control potential. The marginal approach may also help identify points of diminishing return (in performance results) for investment in control.

The framework offers a pragmatic standard for making economic evaluations of control improvement projects, in order to inform decision makers.

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1 Introduction

In built-up areas, the space available for rainwater infiltration is decreased, leading to rapid runoff processes and increased flood risks. In many urban centres a single-pipe network is used to collect both wastewater and storm water for transportation to a treatment plant. When the capacity of these combined sewers is exceeded, however, relief structures discharge the runoff and sewage directly to surface waters (Figure 1). In addition to untreated domestic and industrial wastewater, the storm water also contributes to the pollution caused by these combined sewer overflows (CSOs). Urban runoff may contain a host of pollutants like oil, pesticides, heavy metals, grease and fecal coliform from pet and wildlife waste (Viessman 2005). Minimizing CSOs, therefore, is important for improving surface water quality.

Legislation, such as the US Clean Water Act and the EU Water Framework Directive, is pushing many cities to find ways of reducing CSO emissions. Costly infrastructure expansions have long been the way of increasing system capacity to reduce overflows. An alternative approach, however, is to better use what already exists. Presently, most urban drainage systems are controlled by structures or operational rules that do not adapt to factors such as the heterogeneity of rainfall distribution and runoff in a catchment, or to changing conditions within the system. This commonly leads to the occurrence of overflows at some locations, while capacity remains in others. There is further potential for optimization by integrating the management of the sewer with the wastewater treatment plant (WWTP) and receiving surface water body (M. Schütze, A. Campisano, et al. 2004) (Zacharof, Butler, et al. 2004) (Breinholt, et al. 2008).

As early as the 1970s, more integrated and dynamic control options were being researched and initiated in the United States and Europe. Despite promising theoretical results, aspirations for improved control were stymied by poor

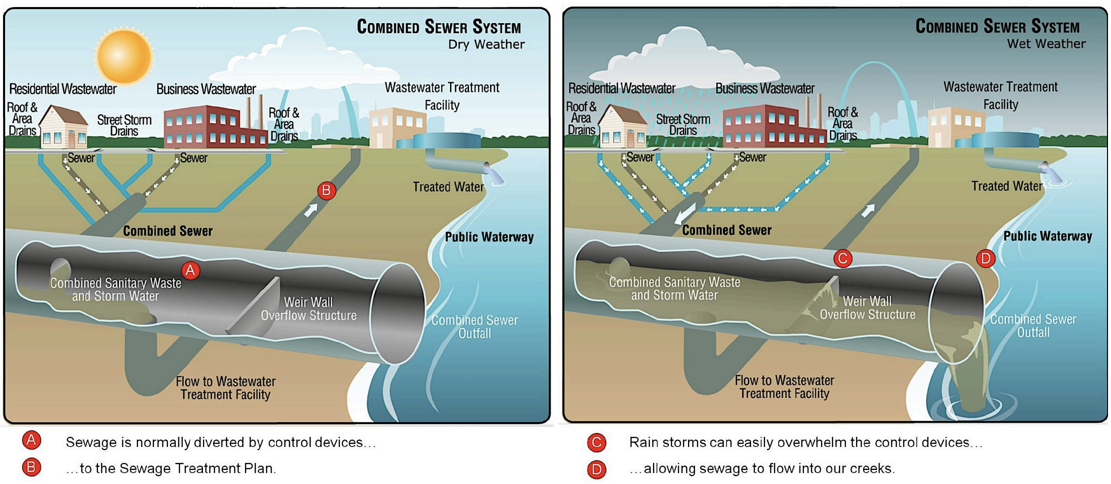

Figure 1 Typical combined sewer operation in dry and wet weather conditions (MSD 2009)

reliability of sensors, gate motors and communication systems, slow computers, limited availability and accuracy of hydrological and hydraulic models and the inadequate ability of control systems to react to emergency situations (Pleau, et al. 2005). In recent years, however, interest in improved control of urban drainage systems has been growing, for three key reasons:

1. The hardware and software technologies they rely on are now widely available and affordable (Pleau, et al. 2005).
2. Increasingly stringent surface water quality regulations are spurring pollution control projects in cities worldwide.
3. There is enthusiasm for integrated approaches to water resources management (M. Schütze, A. Campisano, et al. 2004).

As water managers and decision makers begin considering control improvement as a way to reduce CSO emissions, these projects will need to be evaluated and compared to conventional infrastructure expansions. Economic assessments play an important role in such processes, but these are not straightforward to make. While there are well-established methods and values for appraising traditional infrastructure projects, there are no such standards for control improvement. Several features make these evaluations challenging:

First, the timing of investments is different for traditional infrastructure and control improvement projects. In order to assess the feasibility of control, a certain level of system data and models are needed. If these do not already exist, there are upfront costs to investigate whether a control option should be included as a project alternative. These investments must be made when there is still uncertainty about whether control will be a promising solution. By comparison, checking the feasibility of infrastructure projects can be done with relatively straightforward calculations based on design standards. Investments for infrastructure projects, therefore, are only needed when there is more certainty in the preferred alternative. Table 1 illustrates the difference in timing of investments for three basic project steps.

Table 1 Level of uncertainty in solution and timing of investments for control and infrastructure alternatives at key project steps

Project step	Level of certainty	Investment for infrastructure	Investment for control
Identify alternatives	*Low*	*Low*	*High*
Evaluate alternatives	*Moderate*	*Moderate*	*Moderate*
Implement chosen alternative	*High*	*High*	*Low*

Second, when comparing traditional infrastructure and control improvement projects, there is a large difference in the costs, but also in what they “purchase”. Many of the benefits attributed to control improvement, such as greater operational flexibility, are not easily comparable to the actual increases in system capacity that most infrastructure expansions achieve. These differences make comparing control improvement and traditional infrastructure projects complicated.

1.1 Research objective

The goal of this thesis is to provide a practical framework for making economic evaluations of control improvement projects in urban drainage systems, in order to inform decision makers.

To meet this objective, the following research questions and sub-questions were developed:

1. What is the best way to make economic evaluations of control improvement projects in urban drainage systems?
    a. How can the benefits of preventing overflows be valued?
    b. What are the best current practices in economic evaluations of projects involving water resources?
    c. Can the costs and benefits of control improvement be standardized and expressed as functions of overflow volume?
2. What practical considerations are important for a usable framework?
    a. What real-world limitations are there for making economic evaluations of control improvement projects?
    b. How are control improvement projects being evaluated in practice?
    c. What are the primary motivations for implementing control improvement projects?
    d. How can the upfront costs of considering control improvement solutions be rationalized?

1.2 Research approach

Addressing these questions consisted of three basic steps:

1. A literature review to gain a foundation in the necessary theory and current practices of control in urban drainage systems, cost benefit analysis and economic valuation of water resources.
2. A review of documented control improvement projects to gain insight into how evaluations are made and projects are implemented in practice.
3. Developing a framework that combines the relevant aspects of economics, engineering and practical information in a way that can be applied to evaluate projects and inform decision-making.

1.3 Research scope

This study aims to develop a framework that is both usable and in line with best economic practices. Beyond a literature review, however, determining economic values for ecological and water quality benefits is outside the scope of this thesis. Such studies warrant their own research and require the specialized skills of economists and ecologists.

1.4 Thesis outline

The succeeding chapters of this thesis present the framework and the research that supported it. Following this introduction, Chapter 2 provides more detail on control and urban drainage systems. Chapter 3 is an overview of techniques for making economic valuation of water resources and project evaluations. Chapter 4 is a review of control improvement projects documented in literature, with implications for the framework. Chapter 5 presents the framework and Chapter 6 the conclusions and recommendations.

For readers with a background in control of urban drainage systems and economic evaluation of water resources, the following sections highlight the findings of this research:

- **Section 3.1.4** draws conclusions from the literature review on economic valuation methods for water resources.
- **Section 3.2** provides a discussion of project evaluation techniques and the selection of a special case of cost benefit analysis for the framework.
- **Section 4.3** presents the findings of the literature review on documented control improvement projects.
- **Section 4.5** presents the implications of the project review findings for the framework.
- **Section 5.1** introduces the framework and provides justification for the approach.
- **Chapter 6** gives the conclusions and recommendations from the research.

2 Control in urban drainage systems

This chapter summarizes the relevant information on control in urban drainage systems from the literature review. The aim of this chapter is to provide a foundation of understanding about the systems that the framework evaluates later in the thesis. Section 2.1 provides terminology and a basic introduction to control in sewer applications. Section 2.2 gives a background on urban drainage systems. Section 2.3 describes current practices in urban drainage and the context of control improvement projects.

2.1 Control systems

Control requires four components: (1) sensors for the measurement of process variables, (2) actuators to adjust the process, (3) controllers to determine what the actuators need to do and (4) some communication system to link sensors, controllers and actuators. These prerequisites can be met by many means, from simple human actions, to complex automated systems. There are several ways to categorize control systems based on *where* control decisions are made, *who* makes the decisions, *what* is being controlled and *how* the decisions are made in relation to time. Different terminology, however, is used for control of different types of systems. In sewer applications, the meaning of some terms conflicts with their meaning in control theory, which can lead to confusion. For the purposes of this thesis, the following definitions, which are defined for such purposes by the US Environmental Protection Agency (EPA 2006, 45-46), will be used.

With respect to *where* the control decisions are made:

- **Local control** – is when both sensor(s) and controller are located at the actuator site and control decisions are determined based on local information.
- **Remote control** – is when the controller is located away from the actuator and control decisions may be based on information from other parts of the system.

With respect to *who* makes the control decision and action:

- **Manual control** – is when an operator takes the control decision.
- **Supervisory control** – is when an operator at a central control location monitors a system operated under local control and may override decisions or remotely adjust settings of local controllers.
- **Automatic control** – is when a computer program takes the control decision without input from the operator[1].

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[1] There are structures that use the laws of physics to realize a control algorithm without involving a computer. See for example EPA 2006, page 11.

With respect to *what* an algorithm is controlling, or the physical scope:

- **Local algorithms** – control single sites, independent of other system facilities.
- **Central algorithms** – control multiple sites in the sewer in a coordinated way, based on the overall status of the system. This definition combines both the “regional” and “system-wide” terms used by EPA (2006), as well as “global algorithms”, a common name found in literature.
- **Integrated algorithms** – simultaneously control aspects of the sewer and WWTP processes together.

With respect to *how* the decision is made in time:

- **Static control** – is when fixed structures (such as weirs with set crest-heights) are used for control.
- **Reactive algorithm** – is when measured (past or current) values are used as input for the control decision.
- **Predictive algorithm** – is when forecasted, as well as past and/or current, values are used as input for the control decision.

The term ‘real time control’, or RTC, is often used to describe automatic systems in which the controller responds to current or predicted conditions almost immediately. Within the control community, however, RTC has a special meaning that does not apply to sewer applications[2]. Therefore, the term RTC is not used in this thesis.

2.2 Urban drainage systems

The domestic and industrial activities concentrated in urban areas produce wastewater that, if left untreated, can cause environmental pollution and direct risks to human health. Sanitary sewers are used to transport wastewater, via piped networks, away from urban centres to WWTPs. After purification, the treatment plant effluent is discharged to receiving surface waters. In addition to wastewater, however, storm water flows also cause problems in urban areas. When rain falls (or snow melts) on natural surfaces, some precipitation will infiltrate to the groundwater, some will evaporate or be used in transpiration by plants, and some will run off the surface. The relative proportions of these flows depend, in part,

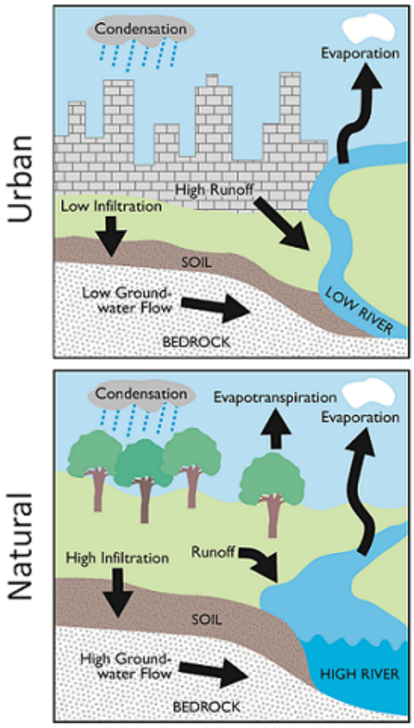

Figure 2 Water cycle for urban and natural catchments (Cities 2013)

[2] Specifically “RTC” is reserved for processes in which the calculation and implementation of multiple control actions is subject to such stringent timing constraints that satisfying them becomes an integral part of the control problem, due to limits on actuator response speed and calculation times. An example would be the control system of an inherently unstable airplane

on the nature of the surface. In built-up environments, where artificial surfaces predominate, a higher portion of precipitation becomes runoff, which can lead to flooding, inconvenience and property damage. Figure 2 illustrates differences between natural and urban water cycles. The storm water runoff may contain contaminants from artificial surfaces and rain, creating further risk to human health and the environment (Butler and Davies 2011). Storm water, therefore, is also collected and transported away from urban centres. There are two means for achieving this:

1. In separated sewers storm water and wastewater are collected and transported in different piped networks. The storm water is typically released directly to a surface water body, while the wastewater goes to the WWTP for purification, before also being discharged to surface water.
2. In combined sewers storm and wastewater are collected together and treated at a WWTP, before being discharged to surface waters.

Figure 3 schematizes a separated and combined sewer system.

While there has been a push toward separated systems, the traditional combined sewers are still more common (Butler and Davies 2011) and are the type dealt with in this thesis. In combined systems the sewer and WWTP must be sized to accommodate both runoff and wastewater, despite the fact that, most of the time, storm water is not present. Since runoff can be as high as 100 times wastewater flows, it is not economically feasible to provide capacity throughout the sewer and in the WWTP for all potential scenarios. The solution is to provide relief structures that divert flows above a certain level directly to the surface water, creating combined sewer overflows (CSOs) (Butler and Davies 2011).

2.3 Control of urban drainage systems

The term 'urban drainage system' refers to the sewer network(s), WWTP(s) and receiving surface water(s) that serve an urban or semi-urban area. Despite the fact that these elements are part of a system, they are mostly operated independently from one another – and, in many parts of the world, are managed by different agencies (M. Schütze, A. Campisano, et al. 2004).

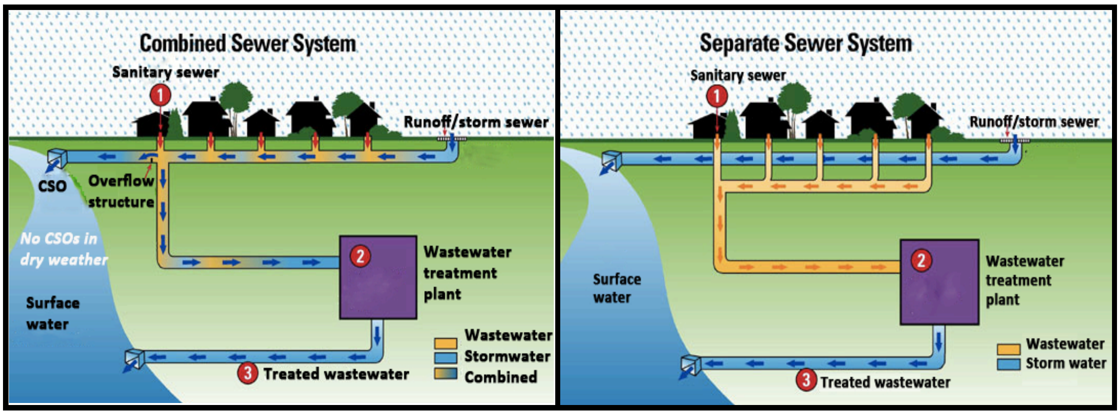

Figure 3 Simplified examples for separated and combined sewer systems (Winnipeg 2008)

2.3.1 Current operation and control practices in urban drainage systems

The sewer system

Combined sewers consist of a series of pipes from residences, businesses and stormwater collectors that connect to larger pipelines, which convey wastewater and runoff to WWTPs. In addition to transportation, sewers provide in-system storage capacity. Within the sewer, there usually exists a combination of pumps and structures, such as weirs and gates to control flow. The structures can be fixed or moveable and the pumps may be of on/off or variable speed type. These sewer elements are typically controlled locally, by fixed operational rules or settings. In many cases, adjustments are only made during the installation and testing phases of the system, or seasonally (EPA 2006). The conditions in the sewer, however, change often, due to factors such as heterogeneous rainfall distribution, different types of rainfall events and system blockages. This means that, most of the time, operation and storage in many sewers is not optimized (M. Schütze, A. Campisano, et al. 2003).

In many sewers, there are minimal measurements made of water level, flows and CSO events, which indicate a system's operating status and performance. In these instances, CSO occurrence, volume and duration may be unknown, based on estimates, or rely on visual observation (Engelhard, De Toffol and Rauch 2008).

The wastewater treatment plant

WWTPs are designed with specific hydraulic and organic load capacities to ensure a high quality effluent for good surface water quality. Fluctuations in influent flows and organic loads are undesirable, as they create inefficiencies and may result in degraded treatment (Viessman 2005). Internal process controls are widely used in WWTPs, but these are rarely connected to the conditions of the sewers or the surface waters. This means that WWTP operations are usually not optimized in terms of system-wide factors like intake flows and using potential excess capacity in the plant as storage (M. Schütze, A. Campisano, et al. 2004) (Rauch and Harremoes 1999).

The surface waters

Surface waters receive the effluent from urban drainage systems' CSOs and WWTPs. When overflows occur, they may be less preferable in some locations than others, based on the surface water quality or potential for human contact. With the types of control currently used in most sewers, however, the discharge location is largely determined by the rainfall patterns and the current status of the sewer, during an event (Rauch and Harremoes 1999).

To best gauge the performance of an urban drainage system, the receiving surface water quality, levels and flows should be measured. In practice, however, such measurements are rare. Instead, auxiliary performance indicators, like CSO volumes and frequency are used to estimate impacts on water quality (Zacharof, Butler, et al. 2004) (Rauch and Harremoes 1999).

There are several problems with the current paradigm of operations and control in urban drainage systems:

First, most sewers and WWTPs are not used as efficiently as possible, leading to preventable pollution of the receiving waters. Unnecessary pollution can come from CSOs that would be avoided or minimized by better operation, or those that occur in sensitive areas and could be rerouted to preferred locations. In addition to overflows, WWTP effluent is another source of potential pollution. Inefficient operation of a sewer can lead to shock loads and large fluctuations in a plant's influent, which damage treatment processes and result in a lower quality effluent being discharged to the receiving water body (Zacharof, Butler, et al. 2004).

Second, the performance of urban drainage systems is not being measured. The sewer performance is often based on estimated or reported overflow occurrences, volumes or frequencies. In turn, these values are combined with assumptions of pollutant concentrations and constituency in the overflow water to estimate impacts on surface water quality. In reality, pollutant loads vary, as do the quantity and quality of the receiving waters, making the impacts of CSOs difficult to predict (M. Schütze, A. Campisano, et al. 2004) (DWA 2005). Since the good quality of the receiving waters is a chief goal of urban drainage systems, direct measurement of metrics such as dissolved oxygen and ammonia concentration should be made. Overflow events themselves, should also be measured directly, to determine the actual performance of the sewer (Vanrolleghem, Benedetti and Meirlaen 2005).

In addition to the shortcomings of current practices in urban drainage, there are further drivers for change. Many urban areas are now facing worn out or undersized sewer systems, as well as growing challenges from climate change and urbanization. At the same time, advances in the fields of water management and environmental sciences have prompted a move toward more integrated approaches to water resources management. This can be seen in institutional changes, such as the European Union's Water Framework Directive, as well as increasing regulation of the environment and natural resources (Breinholt, et al. 2008) (M. Schütze, A. Campisano, et al. 2003).

2.3.2 Opportunities for improved control in urban drainage systems

Traditional ways of improving urban drainage systems have focused on expansions, such as separating the storm and sanitary sewers, building new storage facilities, increasing the pump and treatment plant capacities, or improving infiltration and retention to reduce runoff. These options, however, are costly and complicated by the often-limited available space in cities (Breinholt, et al. 2008). In many urban drainage systems, it is clear there is room for improvement by optimizing the existing infrastructure. Moving toward more centralized, automated control systems, therefore, is increasingly being considered as an alternative or supplement to conventional capital improvement projects. With the necessary hardware and software now available and affordable, improved control seems to offer interesting benefits (Pleau, et al. 2005).

In most cases, the objective of improving control is to increase the system's performance while minimizing high cost capital investments. Control at an advanced level, such as an automatic integrated system, aims to optimize the sewer and WWTP together to minimize pollution of surface waters. This may be achieved by reducing CSOs through better use of storage and pump capacities, by routing unavoidable overflows to least sensitive locations, or by integrating operation of the sewer and processes in the WWTP (Rauch and Harremoes 1999) (Breinholt, et al. 2008). Auxiliary benefits of better control are increased understanding of how the urban drainage system works and the flexibility to make operational changes based on different conditions (Schütze and Haas 2010) (DWA 2005). Each of these attributes of improved control has the potential to reduce system costs. In addition to minimizing the need for expensive construction, lower operation costs may be realized through more efficient use of pumps, WWTP processes and maintenance activities (Breinholt, et al. 2008) (DWA 2005). A better understanding of the existing system may also inform future investment and design decisions.

The theoretical benefits of control improvement projects in urban drainage systems seem promising. Different systems, however, will have different existing infrastructure, control potential and objectives. Currently, there is no standard for evaluating control solutions or for comparing them to traditional infrastructure alternatives. This makes it difficult for decision-makers to consider control projects as viable options (Schütze, Erbe, et al. 2008).

3 Economic evaluations in water management

This chapter summarizes the findings of the literature review on methods for making economic evaluations of control improvement projects. Section 3.1 provides an overview of techniques for making economic valuations of water resources and concludes that there is no practical and reliable method for doing so. Section 3.2 introduces relevant project evaluation methods and explains the selection of a special case of cost benefit analysis as the preferred approach for assessing control improvement projects. Section 3.3 provides details on cost benefit analysis and useful modifications for control improvement projects.

3.1 Economic valuation theory and methods

In order to make economic assessments of control improvement projects, the relevant costs and benefits need to be valued. Costs and benefits can be identified as two basic types: marketable and non-marketed. The former are relatively straightforward to estimate using market prices for goods and services. For control improvement projects, costs should all be of the marketable type. Additionally, some benefits, such as energy savings and more efficient operation and maintenance, may be valued using market prices. Other benefits, however, are more complicated. Since the aim of control improvement projects is pollution abatement, the primary benefits to be gained relate to water quality and environmental health. These types of benefits are non-marketed, making them difficult to represent in the same units as cost (i.e. money). Special techniques are needed to convert such benefits into economic terms. Making these valuations for water resources is particularly complicated by the fact that water is not a normal economic good (Agudelo 2001) (Griffen 2006) (Merrett 1997). As a commodity, water has special characteristics, such as its provision as both a flow and a store, its status as a mostly, but not always, public good, its bulkiness and its high mobilization costs. Furthermore, the value of water varies in both space and time, since demand and availability change by season and location (Savenje 2002).

The purpose of this section is to review possible methods for valuing the potential benefits to water resources from control improvement projects.

3.1.1 Types of water values

The total economic value (TEV) of the goods and services provided by water is the sum of its use and non-use values. Water's use values can be further identified as being of direct or indirect type:

- **Direct use values** are those that involve the consumptive or productive use of the water resource itself. Direct use values can be public or private goods[3] and are generally the most straightforward to evaluate.
- **Indirect use values** are those that support human life or welfare through services provided by the natural resource. These are always public goods and are therefore more difficult to evaluate.
- **Non-use values** are those derived from the knowledge that the resource exists, the option to use it, or the desire to bequest it to future generations. These are always public goods and difficult to quantify in monetary terms.

(Dharmaratna and Gangadharan 2011).

Figure 4 Schematizes the TEV of water resources and some of the different types of values.

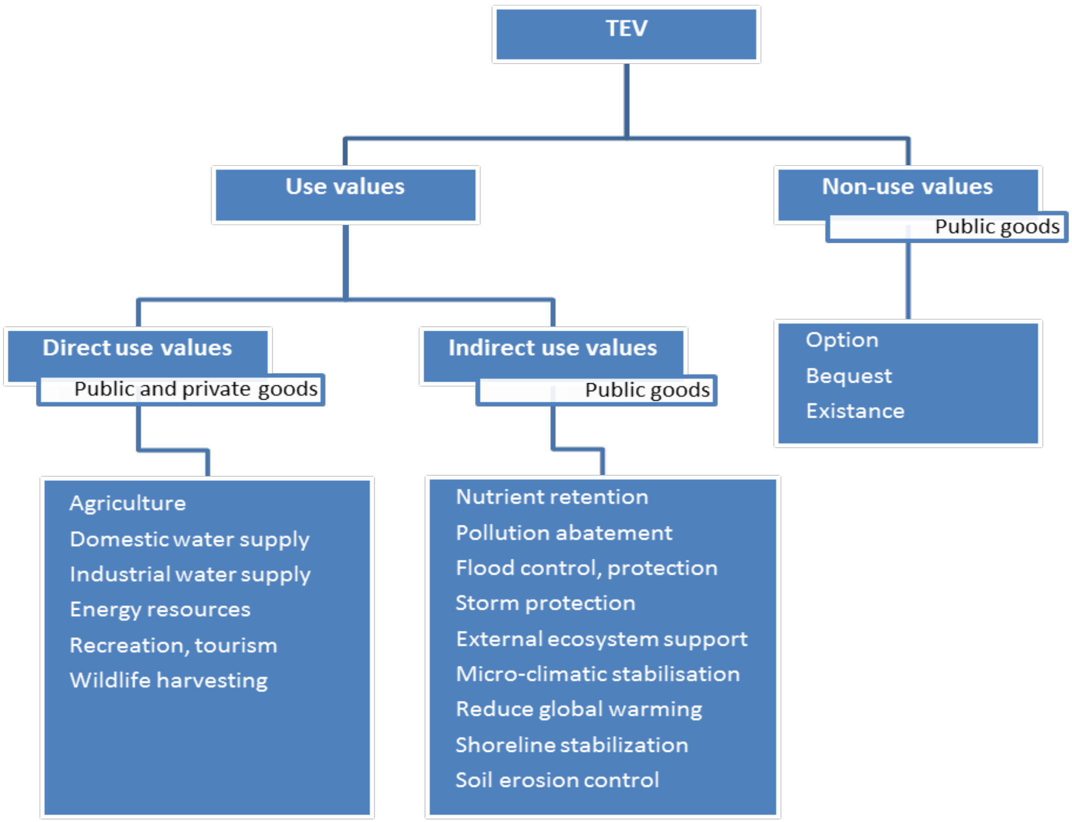

Figure 4 Different types of values of water resources

In most cases, water has public good characteristics, which are difficult to value, since they are not traded in markets. In cases of direct use when water has private good characteristics and is traded, it is often subject to market failures. Issues include imperfect competition or monopolies (common in water supply), imperfect information, lack of property rights, and externalities (Birol, Koundouri and Kountouris 2008). Despite the evident challenges, it is important

[3] Public goods are defined as those that are non-excludable and non-rival. Private goods are those that are excludable and rival.

that the full resource value is considered in water management decisions (Agudelo 2001). Therefore, various techniques have been developed to quantify water's market and non-market values. A brief summary of the most relevant methods is provided below. More detail can be found in the large body of literature on this topic.

Methods for valuing water can be broadly categorized as those that use revealed preferences and those that use stated preferences.

3.1.2 Revealed preference methods for valuing water resources

Revealed preference methods look at direct, indirect or surrogate market data in which the goods and services of the natural resource is explicitly or implicitly traded. Revealed preference techniques, therefore, have the benefit of being based in market data, but they cannot be used to estimate non-use values.

Direct market valuation

Direct market valuation can be used when a good or service is traded in a market, or when a resource is an important input to a marketed good or service and variation in the quality or quantity of the resource contributes measurably to the value of the good or service in the market. Direct market methods of valuation, therefore, are only possible for direct uses of water that are traded in a market (see Table 2). Additional disadvantages of direct market valuation methods are that they are limited to the current market situation and cannot provide the TEV of water, since non-use values are not captured and prices are often subject to market distortions (Birol, Koundouri and Kountouris 2008). Two direct market valuation techniques are:

Market price method (MP) – this method relies on the market price of the resource to reflect its value. In reality, the market price is rarely equal to the TEV of water (Agudelo 2001). Shadow pricing can be used to try to correct for market failure (Snell 1997).

Production function method (PF) – when a natural resource is input to the production of a marketed good, the production function can be used to determine the change in the value of the resource by changes in the buyers' and sellers' gains from exchange (Agudelo 2001).

Indirect market valuation

In cases where goods and services are not available in a competitive market, a market price cannot be used to value the benefits provided by the natural resource. However, some financial information can be used to indirectly estimate the value of the goods and services. Like direct market valuation, indirect methods can only be used to appraise use values. Therefore, the TEV cannot be captured using these techniques. Another drawback shared by all indirect methods is the need to determine the relationship between the financial information and the factors being analysed (Dharmaratna and Gangadharan 2011). This requires values by indirect market techniques to be estimated in two stages: First, analysts use data to identify the physical impact of environmental changes. Second, market prices are applied to estimate the dollar values of those impacts. There are several indirect market techniques, as described below:

Replacement cost method (RCM) – this method values the cost of replacing damaged assets, including environmental ones. This approach assumes substitutability of goods and services, that the damage can be measured and that the value of the environmental asset in concern is not greater than the replacement costs (Dharmaratna and Gangadharan 2011).

Averting expenditure method (AEM) – this method is based on the idea that individuals will respond to an increase in degradation of inputs or environmental resources to avoid adverse impacts. For example, households will change their behavior to avoid exposure to contaminants in water supply by purchasing bottled water. Important limitations of this approach are that consumers may undertake more than one risk averting behavior and they may receive additional benefits that are not captured (Birol, Koundouri and Kountouris 2008).

Net factor income approach (NFI) – this method measures the net benefit to a firm of producing a good after subtracting the cost of other inputs from the total revenue (Dharmaratna and Gangadharan 2011). For example, changes in water quality can be measured by the changes in the costs of purifying water.

Cost of illness method (COI) – this method measures the benefits of pollution abatement or the reduction in harm to environmental assets by estimating the possible saving in expenses resulting from illness. This approach may not consider the actual disutility of sick people and will not account for the defensive or averting expenditures that individuals may have taken to protect themselves (Dharmaratna and Gangadharan 2011).

Dose response method (DRM) – this method measures the effect of ecosystem changes by determining the subsequent changes in production costs of goods. There are several significant limitations to this technique, among them the difficulty in determining the causal dose-response relationship when there are a variety of factors that may not be easily identified or separated. Additionally, this method does not account for policies or measures that have already been taken to minimize environmental impacts. Generally, DRM is used to identify the cause-effect relationship of an environmental impact and another method, such as RCM is used to value the effect (Akesbi 2006).

Surrogate market valuation

In some cases, a surrogate or proxy market can be used to observe behaviour in order to estimate a willingness to pay (WTP) for the goods and services of a natural resource. This estimation represents the value of, or the benefits derived from, the environmental resource. Two prevalent techniques are the hedonic pricing and the travel cost methods (Birol, Koundouri and Kountouris 2008).

Hedonic pricing method (HPM) – this method is based on the theory that the value of an asset is derived from the values of its characteristics. HPM uses variation in property prices, for example, to reflect relevant characteristics, such as size, crime rates and environmental features, like surface water quality. This method of valuation requires a lot of assumptions, such as household awareness of damages to the ecosystem or natural resource. If respondents are not aware of the links between the environmental attribute in question and their property, then the value they reveal will not be reflected in property prices. Hedonic pricing requires a large amount of data and very high costs of obtaining precise information. (Agudelo 2001)

Travel cost method (TCM) – this method is used to estimate use values associated with ecosystems or sites to which people travel for recreation, such as hunting, fishing, hiking, boating or watching wildlife. TCM is based on the premise that the time and travel cost expenses that people pay to visit a site represent the value of access to the site. Thus, peoples' WTP to visit the site can be estimated based on the number of trips that they make at different travel costs (Griffen 2006). The method can be used to estimate the economic benefits or costs resulting from changes in access costs for a recreational site, elimination of an existing recreational site, addition of a new recreation site and changes in environmental quality at a recreation site. Limitations of TCM are that defining and measuring the opportunity cost of time is complicated (a visit to a site may be part of a longer or multipurpose trip), only a site's users are represented in the data and substitute sites yield information on the value of characteristics in addition to the value of the site as a whole. (Dharmaratna and Gangadharan 2011)

3.1.3 Stated preference methods for valuing water resources

Stated preference techniques aim to capture consumer preferences for goods and services on a hypothetical market; they can be used for direct, indirect and non-use values of water resources. Achieving valid and reliable results from stated preference techniques, however, is challenging (Dharmaratna and Gangadharan 2011).

Contingent valuation (CVM) – The purpose of CVM is to elicit individuals' WTP for changes in the quantity or quality of non-marketed environmental resources. This method involves the preparation of surveys with the aim to construct a fictitious market in which individuals will be able to respond as realistically as possible. The surveys are conducted to collect preferences, from which a demand curve for the non-marketed good is estimated. The surveys often use hypothetical scenarios and are vulnerable to survey respondents not understanding, not responding or not disclosing their true WTP for the environmental good. Therefore, careful and skilled design and implementation of the surveys is crucial to producing valid results. This makes CVM expensive, time consuming and difficult to do correctly (Dharmaratna and Gangadharan 2011). Further, there are many types of bias that may skew the results, including information bias, non-response bias, yea-saying bias, design bias, strategic (free-riding) bias, hypothetical bias and embedding effects (Birol, Koundouri and Kountouris 2008). It is argued by some economists that, despite its popularity, even when CVM is undertaken with great skill and care, the results are still not viable or reliable (Diamond and Hausman 1994).

Choice modelling valuation (CM) – This technique, sometimes called Choice Ranking or Choice Experiment, also uses surveys, however, respondents are not asked to make a single direct comparison between a particular environmental change and money payment. Instead, respondents are asked to make a series of choices between alternative environmental "shopping baskets", one of which is the status quo. In this way the environmental resource is defined in terms of its attributes and levels of these attributes. In other words, CM enables the estimation of the value of the environmental resource as a whole and estimation of the implicit values of its features (Bateman, et al. 2006). This, and increased response rates when compared to CVM, are notable advantages of CM (Dharmaratna and Gangadharan 2011). This method also reduces several of the potential biases in CVM (Birol, Koundouri and Kountouris 2008). Disadvantages are the high cost, skill and time requirement to produce a data set, which will still be far from perfect (Dharmaratna and Gangadharan 2011).

Benefits transfer (BT) – This method estimates the value of a resource by using the results of studies on similar resource sites. A transfer can be made of mean unit values, adjusted unit values or of the demand function. The benefit of this method is the ability to estimate order-of-magnitude values for likely costs and benefits (Agudelo 2001). This technique has the considerable challenge of finding two goods or sites with all of the same site and user specific characteristics. Additionally, existing studies may be difficult to find or be inappropriate or inadequate for the needs of the current evaluation. Extrapolation of results beyond the characteristics of the initial study may also be a problem (Dharmaratna and Gangadharan 2011). It is important to remember the imperfect nature of the original values that are used in BT, as well. Transferring such values to another site further reduces their validity and reliability (Diamond and Hausman 1994).

Participatory economic valuation (PEV) – This method uses a group of stakeholders to discuss the values of ecosystem goods and services together. The theory is that public discussion should lead to more socially equitable and politically legitimate outcomes. However, group valuations are better suited as a complement rather than a replacement for individual economic valuation methods. Limitations of PEV are group members who may be uninformed or unwilling to share their views and information. Additionally, dominant group members or peer pressure can lead to bias or invalid results (Dharmaratna and Gangadharan 2011).

3.1.4 Conclusions on economic valuation

While the costs and some benefits of control improvement projects may be relatively straightforward to estimate using market prices, the benefits to water resources are harder to value. Despite the multiple techniques for doing so, each has significant drawbacks and complications. In addition to inherent uncertainty in the values produced by most methods, the TEV of water will vary in time and space. This makes it difficult and costly to develop reliable economic values that capture the benefits from pollution control in surface waters.

The implications of these findings for evaluating control improvement projects are:

1. Since the primary benefits of control improvement projects involve water resources, combinations of valuation methods will be needed to capture the TEV of the benefits.
2. To make economic valuations of the environmental and water quality benefits from control improvement projects will mean:
   - Significant on-site measurements to determine project impacts.
   - Specialized economists to implement appropriate valuation techniques.
   - Considerable time and financial resources.
3. Even if valued carefully, economic estimations of benefits to water resources will be subject to bias and uncertainty.

Table 2 summarizes different values of water resources and the economic valuation methods that may be appropriate for estimating them. Refer to Birol, Koundouri and Kountouris (2008); Ruijgrok (1999); Dharmaratna and Gangadharan (2011) for details on how to apply the techniques.

Table 2 Economic values of water resources and possible valuation methods

TEV component	Valuation method*
Direct use values	
Irrigation for agriculture	PF, NFI, RCM, MP
Domestic and industrial water supply	PF, NFI, RCM, MP
Energy resource (hydro, fuel, wood, peat)	MP
Transport and navigation	MP
Recreation	HPM, TCM, CVM, CM
Wildlife harvesting	MP
Indirect use values	
Nutrient retention	RCM, AEM
Pollution abatement	RCM, COI, AEM
Flood control and protection	RCM, MP
Storm protection	RCM, PF
External ecosystem support	RCM, PF
Micro-climatic stabilisation	PF
Reduced global warming	RCM
Shoreline stabilisation	RCM, AEM
Soil erosion control	PF, RCM
Non-use values	
Option–potential future direct and indirect uses	CVM, CM
Option–future value of information of biodiversity	CVM, CM
Biodiversity	CVM, CM
Cultural heritage	CVM, CM
Bequest, existence, altruistic value	CVM, CM

**Acronyms refer to Production Function (PF), Market Prices (MP), Net Factor Income (NFI), Replacement Cost (RCM), Cost of Illness (COI), Travel Cost Method (TCM), Hedonic Pricing Method (HPM), Contingent Valuation Method (CVM), and Choice Modelling Method (CM), Avoided Expenditure Method (AEM).*

3.2 Economic evaluation techniques and practices

While there are different criteria on which to evaluate projects, this thesis focuses on economics. Cost benefit analysis (CBA) is a tool that can be used to help decision makers in their task of distributing limited financial resources between potential projects, by testing whether the returns on a project exceed the costs, or by ranking alternatives using quantitative economic metrics. The idea of a successful CBA, therefore, is to support informed decisions with economic justification (Griffen 2006). This method has long been used in water resources projects around the world; in fact, many governments and organizations, such as the United States and World Bank, require CBA for the projects they fund (Kalman and Lund 2000) (Birol, Koundouri and Kountouris 2008). For these reasons, CBA was considered a promising technique for evaluating control improvement projects.

In CBA the total costs and benefits of a project are expressed in a common unit of measure, aggregated over time and then compared to each other in several possible ways, called indicators. These indicators can be used to inform decisions of investment type: whether or not to proceed with a project, or of design type: which alternatives to proceed with (Snell 1997). Both kinds of questions are relevant to control improvement projects.

A key advantage of CBA is that a project's costs and benefits can be directly compared, since they are valued in the same unit. The indicators make it simple to judge multiple projects in a rational and straightforward way. Additionally, CBA's history in water resources planning makes the method familiar to most engineers and water managers. This has led to a large body of related research and literature that is can be helpful to practitioners (Kalman and Lund 2000) (Birol, Koundouri and Kountouris 2008). The most notable disadvantage of using CBA for control improvement projects is that benefits must be valued in economic terms. This is a difficult task and may result in some benefits, especially those related to water quality, not being properly captured. Another problem is that indicators can give an over-simplified view of projects. Decision-makers may not understand the subjectivity and uncertainty of the values used to create the indicators, and indicators themselves can be manipulated, either by accident or on purpose (Snell 1997).

It is clear from Section 3.1 that there is no straightforward way to make reliable economic valuations of water quality benefits. This poses a problem for using CBA to evaluate control improvement projects. There are a number of alternative evaluation techniques, however, that have been developed to handle project benefits in different ways. These alternatives, as described below, were also reviewed as options for the framework.

3.2.1 Types of economic evaluations

Variations on CBA - There are three special cases of CBA:

- **Least Cost Analysis** (LCA) is applicable when alternatives have identical benefits. In this instance only the costs need to be compared. The obvious advantage is that benefits do not need to be valued. This makes comparing different project alternatives straightforward. The major disadvantage of LCA is that some alternatives may have additional benefits or drawbacks that are not captured in the evaluation. Also, the actual return on investment is not expressed (Snell 1997).

- **Cost Effectiveness Analysis** (CEA) is used when benefits are expressed in a different unit than costs. In this case, the costs and benefits are each quantified and the cost per unit of benefit is determined for different alternatives. Advantages of this method are that a straightforward indication of return on investment is given and that benefits do not need to be converted into economic terms. A disadvantage is that the value of the benefits may not be fully understood by decision-makers. Additionally, if there are different types of benefits, they need to be expressed in a common unit (Snell 1997).
- **Incomplete CBA** is a form of assessment described by both Griffen (2006) and Snell (1997), in which a CBA is prepared as completely as possible and simply accompanied by a list of intangible or unquantifiable impacts. Advantages are that some of the benefits are quantified and compared to costs, in a common unit of measure. A disadvantage is that it may not be clear what is, or is not, included in the benefit values. Also, indicators based on incomplete benefit valuation may be misleading. Decision-makers are likely to prefer the simple indicators of the CBA and ignore the accompanying list, which is more difficult to evaluate (de Haan and de Heer 2012).

Dual analysis techniques – This type of evaluation quantifies the costs for a project but lists the benefits qualitatively. The benefits may be listed or detailed in an Environmental Impact Assessment. The advantages of this type of evaluation are that: environmental benefits are accounted for; difficult economic valuations are not needed; and decision-makers have to consider the inherent value of water resources. Disadvantages to this type of assessment are: they are not well-suited to inform design decisions; the value of environmental benefits are determined by decision-makers who may not be qualified to make such judgments; and preference may be given to projects with the lowest cost, since there is no straightforward comparison of benefits. This method has been used successfully by Merrett (1997).

Scorecards and multi-criteria analysis – This method consists of two parts:

1. Scorecards, which aim to represent the impact of different alternatives on a set of project criteria; and
2. A multi-criteria analysis (MCA), which standardizes the scores and ranks alternatives using assigned weights.

Advantages of this method are: criteria and results with different units can be compared in a straightforward way; quantitative and qualitative values can be presented together; environmental benefits can be accounted for; and difficult economic valuations of benefits are not needed. Disadvantages of this method, however, are: the use of scores and weights add subjectivity to the results; the influence of scores and weights may not be clear to decision-makers; weights make the results specific to a point-of-view or stakeholder group; the approach is not well-suited to inform design decisions; and MCA is not a strictly economic evaluation (de Haan and de Heer 2012).

Alternative valuation technique **–** Ruijgrok (1999) proposes making evaluations by comparing economic costs to different types of benefit values that may better capture their TEV. Specifically, Ruijgrok combines economic, psychological and ecological values, for representing different functions of the natural resource. Advantages of this technique are: it tries to capture the inherent value of environmental benefits, without converting them to economic terms; it tries to quantify benefits that are considered unquantifiable or intangible in other methods; and it accounts for environmental benefits explicitly. Disadvantages are: difficult valuations must be made, which require specialized skill and significant time to implement correctly; results are subject to many types of bias; the evaluation requires the comparison of three different units of measure and four factors (costs, economic benefits, psychological benefits and ecological benefits); and the method is basically untested.

3.2.2 Selecting an evaluation method

The alternatives to CBA discussed above, share several interesting advantages worth mention. The first is that they attempt to value environmental and intangible goods and services on their own merits, instead of converting them to an uncertain value with a convenient unit of measure. This addresses more honestly the fact that monetizing water resources can be misleading. As Ludwig (2000) contends, there are serious flaws in the idea of economic valuation of water. Among his strongest arguments is that the inherent assumptions of substitutability and rationality are not valid. In essence, valuation assigns a price to a resource that, in many cases, cannot be compensated through purchase or substitution. Therefore, using a qualitative or alternative measure of a water resource may be more representative of its true value. The second interesting benefit of alternative assessment methods is that by not providing a straightforward indicator for projects, decision-makers must grapple more directly with the true complexities of water resources management. One serious drawback to mixing qualitative and quantitative values, however, is ambiguity in what is included in each part of the analysis. In many cases, benefits may be listed as negative costs, or vice versa, making even the quantified portions of an analysis misleading. This can be problematic, as decision-makers may be drawn to the straightforward numbers and give less consideration to how they were developed or understanding the qualitative aspects.

It is clear that, despite some interesting benefits of alternative analysis techniques, there is no escaping the complexity, uncertainty and subjectivity that plagues CBA in water resources projects. In short, there is no alternative to CBA with an overwhelming advantage in the accuracy of results or the ease of analysis. Despite its imperfections, CBA does provide a rational assessment of a project's relevant costs and benefits. In the end, whether these costs and benefits are quantified or not, any decision will be based on weighing and comparing these two aspects. One argument for CBA is that it makes explicit how everything is valued. When valuation is not straightforward, an economist may be better fit to determine values than a decision maker who lacks the germane expertise. Another argument, perhaps more pragmatic than meritorious, is the wide acceptance and use of CBA in the water resources field. This institutional entrenchment has resulted in a large and international body of literature, reference projects and experts. Additionally, it means that many potential control improvement projects will have to make a CBA to meet organizational requirements. For these reasons, CBA was determined to be the preferred and most practical option for the framework. Findings from the project review in Chapter 4 show that most control improvement projects meet a set of conditions, which make the special case of LCA appropriate (see Chapter 5). This circumvents the greatest remaining argument against the use of CBA – the need to value benefits related to water resources.

It is worth noting that while CEA seems a good option, it is not well-suited to control improvement. As will be shown in Chapter 4, projects result in benefits of many different types. This means there is no straightforward way to show the cost per unit of benefit. Additionally, it will be seen that, in practice, the benefits to water resources are not being measured and there is no incentive to do so.

3.3 Cost benefit analysis

In this section, an overview of the steps to complete a CBA is provided, with comments on the modifications for LCA and control improvement projects.

3.3.1 Types of cost benefit analysis

There are three types of CBA: financial, economic and social. **Financial CBA** only considers financial costs and benefits, which are measured in terms of money. **Economic CBA** considers the economic values of costs and benefits, some of which may not be represented by financial prices. This occurs when costs and benefits are non-market goods and services, or when they are undervalued on the market. **Social CBA** adjusts values beyond what an efficient market would achieve, in order to reflect social or political priorities and ideals. In both social and economic CBA values are typically given in a currency to make them comparable to financial prices.

Since CBA can inform both investment and design-type decisions, it can be used at different phases of a project (Snell 1997). An ex-ante CBA can be used in pre-feasibility and feasibility stages to determine which alternatives or basic design options are worth pursuing. In the design and implementation phases, CBA can be used to optimize a project. Finally, when a project is no longer meeting performance goals or current needs, CBA can be used to decide whether or how to rehabilitate or improve it. Ex-post appraisals can be made to assess past actions and profit from hindsight when making future plans (Griffen 2006).

3.3.2 Steps of cost benefit analysis

The following steps for CBA come, with modification, from Snell (1997):

1. **Define the decisions to be guided.** The project being analyzed must be precisely defined. It is generally helpful to define its purpose and then the with-project and without-project situations.
2. **Define the group of people whose point of view is to be applied.**
3. **Define the criteria and parameters of the analysis**. Such as:
   - Project life, or period of analysis
   - Numéraire
   - Discount rate
   - Categories of costs and benefits
   - Adjustments (shadow pricing, omission of transfer payments, etc.)
4. **Calculate the incremental economic benefits**. All types of benefits attributable solely to the project must be valued, for each year of its life. This is unnecessary in the case of LCA.
5. **Calculate the incremental economic costs.** List all the costs attributable solely to the project, by year. Project costs are generally categorized as:
   - Initial (capital) costs
   - Recurrent (annual) costs
   - Replacement costs
6. **Formulate the net benefit stream**. Sum the costs and benefits year by year for the analysis period. The net benefit is benefit less cost for each year. For LCA, there is no net benefit stream, but all costs should be summed for each year.
7. **Perform the economic analysis**. Discount the net benefit stream and calculate the appropriate indicators. For LCA, discount the annual costs, sum them and give the total discounted cost for each alternative.
8. **Carry out sensitivity tests**. Check the response of the indicators or results to different values that were assumed in the previous steps.
9. **Check for costs or benefits not included in the CBA**.
10. **Report analysis.**
    - Define the project
    - State the purpose of the analysis
    - Make clear the assumptions and criteria
    - Provide enough detail for the analysis to be checked
    - Show results, base case and sensitivity tests
    - Comment on analysis and results, but avoid pre-judging the decision

These steps are further elaborated upon in the following sections of this chapter and in the framework (Chapter 5).

3.3.3 The costs and benefits

Determining the costs and benefits that should be counted in a CBA is the most difficult task of the analysis. The following guidelines are general rules:

Define the with- and without-action situations and alternatives. All project alternative should be defined carefully, especially the without-action cases. Without-action could mean the continued deterioration of a present system, or the maintenance and repair of the system to preserve its current conditions. In the case of deterioration, the costs will be approximately zero but the benefits will decline with time. In the case of maintaining the status quo, there will be costs in order to keep the benefits approximately equal to current conditions.

In Section 5.1 it is argued that for most control improvement projects there is no viable without-action alternative.

List all costs and benefits for each situation. In determining which costs and benefits are relevant, boundaries should be drawn based on the decision the CBA is aimed to inform and whom the analysis is being done for. There are some costs, however, that in most cases can be categorically left out of an economic CBA. These are:

- Transfer payments or transactions within the group under consideration, for example between government agencies or departments
- Sunk costs
- Contingencies
- Depreciation
- Loans, repayments and interest, except replacement costs

In all cases, care must be taken not to double-count costs and benefits. In the case of LCA, it can be helpful to list the benefits, even though they will not be valued. This can be used to confirm that the benefits of all alternatives are similar enough to make LCA a valid method. The benefits may also be relevant to a wider project evaluation (See Figure 6 for the context of economic assessments within a full project analysis).

Value the costs and benefits listed. The unit of measurement, or numéraire, used to value costs and benefits should always be defined explicitly. Domestic pricing is the most common unit. In economic CBA, financial prices for marketable goods may be adjusted by shadow price factors (SPF). Shadow pricing corrects market distortions, in order to approximate the prices at which a perfect market would arrive. It is helpful to categorize costs and benefits that may have the same SPF. In the case of non-marketable goods and services, the special techniques discussed in Section 3.1 are used to arrive at values for the analysis.

Values should always be given at constant prices. If a real increase is expected, escalation can be included.

For LCA in control improvement projects, costs should be of the marketable type and benefits are not valued.

Discounting costs and benefits. When costs and benefits occur at different times, discounting can make present values (PV) of future values (FV) at a time difference of n, for a discount rate of r, according to:

$$\frac{PV}{FV} = \frac{1}{(1+r)^n}$$

The discount rate can be determined by the social time preference rate, the opportunity cost of capital or the capital rationing device. These methods are based on different views of the discount rate, and therefore give different values. The social time preference rate is generally the lowest (2% to 6% for example), which reflects a relatively high value on resources over development. The opportunity cost of capital rate is related to the real interest rate of borrowing money and is typically the highest, commonly around 10% to 12%. The capital rationing rate can be high or low, as it tries to capture the rate at which resources should be used without over- or under-development. Discount rates for projects related to environmental resources, such as water, are typically low, reflecting the long-term importance of related decisions and actions (Snell 1997). Which discount rate to use is subjective and depends on the values of those the analysis is performed for, as well as the type of project. In many cases, an agency or institution has suggested or mandated discount rates for specific types of projects, such as those involving water resources (Merrett 1997).

The length of the analysis period is another important consideration, as it influences the outcome of the CBA. Ideally, the analysis is based on the useful life of a project. In practice, however, this is not always simple to determine. In many cases, especially with infrastructure, a project may be maintained or improved to serve a long time. In these cases, it often makes little improvement on results to continue an analysis past 30 or 40 years – unless there are significant costs associated with decommissioning the project. In projects with predictable lump sum replacement costs, a CBA should end just before an expected payment (Snell 1997).

3.3.4 The indicators

The result of a CBA is an indicator, or indicators, of the relative merit of the project under consideration. Indicators, calculated following valuation and discounting, provide different information to the user of the CBA, as described below:

- **Net present value (NPV)** – The NPV is the total discounted benefits less the total discounted costs for the period of the analysis. An NPV greater than zero, therefore, indicates that the benefits are greater than the costs.
- **Benefit-cost ratio (B/C)** – The B/C is the ratio of the total discounted benefits over the total discounted costs for the period of the analysis. A B/C greater than one indicates a project with greater benefits than costs.
- **Net benefit-investment ratio (N/K)** – The N/K is the ratio of the present value of the gross benefits less all costs except investment costs, divided by investment costs.

- **Internal rate of return (IRR) –** The IRR is the discount rate at which the total discounted cost is equal to the total discounted benefit. For the IRR, NPV is zero and B/C is unity.

Which indicator(s) is most useful should be guided by the question to be answered with the analysis. As general rules: NPV is the most reliable for yes/no type decisions. The IRR, with a pre-decided test discount rate or threshold level is commonly used, but it is easy to manipulate. For optimization between technically mutually exclusive alternatives, maximizing NPV is appropriate (Snell 1997). For ranking mutually independent projects competing for limited resources, the B/C or N/K ratios can be helpful. Care should be taken with ratios that the values are not manipulated by the interpretation of costs and benefits (Griffen 2006).

For LCA, the total discounted economic cost of each project alternative is compared, instead of calculating indicators (Snell 1997).

3.3.5 Sensitivity analyses

CBA involves uncertainty, both in the precision of values used and in the value judgments themselves. Instead of spending large amounts of time and resources perfecting estimates, it can be useful to check the sensitivity of the results to various inputs (Kalman and Lund 2000). Some useful parameters to check with sensitivity tests are the costs, the benefits, the SPF values, forecasted and estimated values and the timing of costs and benefits. Useful tests can be decreasing the predicted benefits, for example, by 20%; shifting the benefit start to later than predicted; changing the frequency or number of recurrent cost events; and determining the value of parameters at which the indicator would switch to the opposite conclusion. These sensitivity analyses can show how vulnerable the CBA results are to inputs and assumptions and can help determine which values or estimates are most important to the results and warrant effort to improve (Snell 1997).

4 A review of control improvement projects in urban drainage systems

The difficulties of making economic evaluations of control improvement projects in urban drainage systems are clear. Despite the obvious challenges, assessments must still be made, in order to inform investment and design decisions. Looking at how projects are being evaluated in practice can help identify trends or information useful in creating a relevant framework. To this end, a literature review of control improvement projects was made. The following sections of this chapter summarize the findings of the review. In Section 4.1 the approach of the review is explained. In Section 4.2 the projects are summarized. Section 4.3 lists the findings from the review. In Section 4.4 limitations of the review are noted. In Section 4.5 the implications of the findings for the framework are discussed.

4.1 Approach of project review

In an effort to standardize the project information as much as possible, the project review focused on finding examples of modelled or implemented systems with enough information to determine (at least most of) the following:

- The size of the drainage system and/or population served
- Motivation for the project
- Type of existing system, infrastructure
- Type of alternatives considered and/or implemented
- Whether results are simulated or measured
- What types of data series or rain events results are based on
- How control performance was measured
- How benefits were measured
- The performance result values
- The project costs and what is included or not
- The project benefit values and what was included or not
- How the project was evaluated
- The implementation time
- Any conclusions or findings from the project

Eleven projects of varying size and type were identified in Europe, North America and Japan. Interviews and email correspondence were conducted with several of the project managers and paper authors to fill information gaps or enhance understanding. These communications provided interesting insight into operation and management details of the projects. Brief summaries of each case are provided below, with conclusions on the technical and evaluation aspects of the project.

4.2 Project review

4.2.1 Kessel-Lo, Belgium

Project description

As the sole wastewater utility operating in the Belgian region of Flanders, Aquafin oversees 230 WWTPs, 3000 CSOs and 1100 pumping stations in systems of roughly 90% combined sewers. Due to the Water Framework Directive's surface water quality legislation and the impact of CSOs on receiving water bodies, Aquafin, like other European wastewater utilities, was driven to contribute to the Good Ecological Status of the watercourses influenced by their infrastructure. Motivated to find cost efficient methods for reducing CSO emissions throughout their system, Aquafin, investigated control improvement, using the town of Kessel-Lo as a case study. Kessel-Lo (population 25,000; area 22km^2) was chosen because it showed high control potential in the preliminary analysis and is representative of catchments in the area, which are typically flat and semi-urbanized, with populations of 20 to 50 thousand. The study used local rainfall measurements from 2007 to model overflow volumes of four alternative projects. The four alternatives were:

1. Disconnection by separate sewer
2. Increased storage through additional retention basins
3. Adjustment of throttle pipes
4. A central automatic reactive (CAR) control system

Each alternative was compared to the current case of local, static control.

Kessel-Lo has eight CSO structures, which discharge to the Dijle River. Wastewater is treated at the Leuven WWTP, where Kessel-Lo contributes 30% of the plant's dry weather flows. As the WWTP will soon be renovated and emptying its storm tanks is a complex process, no changes were made to the control of the treatment works or the intake pumps. Since diverse spill behaviour was occurring under the existing conditions, Equal Filling Degree control algorithms were used to optimize in-line storage of the sewer. The control algorithm was applied to different combinations of sluice gates and pump stations in six scenarios to explore the possibilities of improved control. One of the control improvement scenarios was selected for detail design.

Key tasks

First, measurements were made using three rainfall gauges and eight flow meters distributed throughout the system to create a one-year rainfall series. An existing detailed model for Kessel-Lo was updated and elaborated to simulate the different project alternatives. Conceptual models were setup to define promising control strategies and test their performance. Cost estimations were made for each project alternative. The costs were used, along with water quality considerations, to determine the preferred project alternative. The selected control improvement option is now in detail design.

Useful values

In estimating the costs for the four alternatives, typical values from literature and local experience were used. These are:

- For separate sewer: 750€/m laid pipe.
- For storage reservoirs: 775€/m^3 installed.
- For control system: 30,000€ to equip an office with SCADA and algorithm (control centre), 35,000€ per control outpost[4]
- Basic man-hours were assumed constant for all alternatives.

Results

Alternative	CSO volume reduced (%)	Costs (M€)	Factor of control cost
Disconnection *25,50,75%, centre*	44-93	23-68	100x
Increased storage *7100m*	70	5.7	15x
Throttle adjustment	23	0.13	1X
CAR Control *Six scenarios*	20-65	0.1-0.3	1X

The six control scenarios showed that overflow volumes could be significantly reduced with as few as two control locations, while equipping all controllable locations resulted in an additional profit of only 4% - at 130% of the cost. The (very) low cost of control improvement is due to the fact that most of the needed infrastructure and detailed models are already in place.

In addition to the high cost of disconnection, another disadvantage of this option was discussed qualitatively. The authors were concerned that the high reduction in CSO volume was misleading, since potentially polluted storm water would still be discharged directly to the receiving body.

Technical conclusions

- Control potential may be high where diversity in hydraulic structures and in-system storage exist. These characteristics are typical of flat catchments with diffuse urban development.
- Costs will be dependent on local conditions, but control alternatives seem to offer promising cost efficiency by reducing needed storage.
- For system managers there are significant practical advantages from control, namely, its flexible, adaptive nature (adjustment of the control algorithm for new conditions) and its 'emission light' approach to pollution prevention (through strategic spilling).
- Personnel involvement from feasibility through operation is important for project success.

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[4] Assumes: 5,000€ for actuator (sluice), 10,000€ hydraulic engine group, 15,000€ additional monitoring devices with connections, 5,000€ power and communication transmission infrastructure for location

Evaluation conclusions

- Only rough estimates of cost and performance were used to compare multiple project alternatives. More detailed assessments were not needed, since the very large differences in results indicated control to be the best alternative by far.
- When preliminary cost estimates were improved with annual equivalent values, depreciation and operational costs, the results hardly changed and only confirmed RTC as the most cost-efficient option.
- Although operational benefits from flexibility and adaptability were not evaluated formally, they were discussed qualitatively as added benefits of control alternatives.
- Benefits were not addressed, only the difference in costs of alternatives. This is in keeping with the objective to find cost effective ways of reducing surface water pollution from CSOs to meet regulatory requirements.
- The potential for increased pollution with the disconnection alternative (since storm water is not treated before it is discharged) was evaluated qualitatively and informally in the decision making process.
- Although disconnection and storage alternatives outperformed the control option, control was still preferred, since it met the performance objectives at a lower cost. This is in keeping with the emphasis on finding a cost-effective solution to reduce pollution, over maximizing system performance.
- The efforts to evaluate the feasibility of the control alternative were higher than those for the other options, which were assessed with calculations and minor model adjustments. The control options required monitoring and extra modelling to identify the different control alternatives well enough to compare them to disconnection, storage or throttle adjustments.
- The upfront investigation costs were viewed as a strategic investment for Aquafin, since they have multiple systems to improve.

(Dirckx, Thoeye, et al. 2011) (Dirckx, Schütze, et al. 2011) (Dirckx, Schütze, et al. 2011)

4.2.2 Messel, Germany

Project description

Sequencing batch reactor (SBR) WWTPs are found in small townships throughout Germany. Following standard design guidelines for these plants, however, often leads to over-dimensioned systems equipped with numerous measurement instruments. This is a promising combination for control projects. A research study was initiated in Messel, in order to investigate the potential benefits of integrated automatic predictive (IAP) control in urban drainage systems with SBR WWTPs. In addition to CSO abatement, the study needed to check the performance of the WWTP under the increased hydraulic loads of the improved control conditions.

The Messel system is typical for those served by SBR WWTPs, it consists of a small catchment (1.3km^2, population 3,750) with one CSO overflow and two storage reservoirs (350m^3 and 1,100m^3) with overflow structures, as well as the treatment plant and receiving surface water body. The existing WWTP had a state-of-the-art computer aided control device connected to numerous sensors in the sewer and WWTP. Data from the measuring devices was not being used, before the control project was initiated. Since SBR plants run in cycles, the control strategy involves pre-emptively switching the WWTP between dry- and wet-weather cycle modes, based on measured water level in the sewer and rainfall data in the catchment. The controller is able to adapt the cycle duration dynamically, based on the current situation. By continuously monitoring the sludge level and suspended solids in the treatment process, the cycle durations could be optimized to increase the flow rate through the plant without compromising the treatment. Control strategies were developed to reduce hydraulic peaks in the effluent of the plant and to optimize the inline storage of the sewer, based on the free capacity in the retention basin. IAP control scenarios were first simulated for various extended rainfall series and single-events, followed by full-scale implementation, starting in 2004.

Key tasks

A detailed model of the sewer system and SBR WWTP were set up, as well as a pollution load water quality model. The sewer model was calibrated with data from flow and water level meters and one rain gauge. The WWTP model was calibrated with data from an 11-day monitoring campaign. The water quality, sewer and WWTP models were integrated with a bi-directional linking interface. Cost estimations were made of the different control scenarios, followed by full-scale testing and operation.

Results

IAP facilitates considerable optimization of the SBR WWTP. The performance results include these optimizations:

- Cost savings of at least 20,000 US$/year, when IAP is compared to storage alternatives. This is based on investment, operation and replacement costs for a 50-year project life[5].
- 20% mean annual reduction in CSO volume
- 26% mean annual reduction in number of CSOs
- 26% mean annual reduction in COD emissions from CSOs
- 12% mean annual reduction in total COD emissions (WWTP and CSOs)
- The maximum flow rate could be increased, for short periods, from 230 to 460m^3/hour due to control improvements in the WWTP.
- The treatment efficiency of the plant was comparable or better using the improved control system.
- Initial system test results were consistent with the simulation results.
- Realization of the IAP project occurred without any problems and has run smoothly since implementation.
- Full scale testing was running within three years of the project's initiation.

[5] The replacement costs have been significantly lower than expected when the estimations were made, making these savings very conservative (Wiese, 2013).

Technical conclusions

- The proactive and predictive nature of IAP has operational, economic and environmental benefits for systems with SBR WWTPs.
- The ability to use different optimization criteria depending on actual operating conditions is useful for SBR WWTPs.
- With IAP control, SBR plants can effectively treat combined sewage at higher than design flow rates, due to the built-in excess capacity.
- Most SBR plants are equipped with measurement devices that facilitate adaptation to meet changing operational conditions quite easily.
- SBR plants are often designed with a lot of potential for optimisation.
- Academic partners made technical contributions. It is not known how the project was funded.

Evaluation conclusions

- This case evaluated the costs of different control alternatives to determine the best investment for performance return. The control level was not altered, however, only the number of control sites and their locations. No actual costs were given for the control or storage alternatives.
- Benefits were represented by the cost savings of control, when compared to a storage option.
- The performance results appear to be mostly attributable to control improvement.
- The feasibility and design of the control improvement system required monitoring and modelling before there was a good understanding of whether the system would be successful. The pilot project was made, in part, to evaluate this so that investment in similar future projects would be less risky.
- Operational adaptability and flexibility, as well as greater information on internal system processes and increased motivation to review data and performance were noted as appreciable benefits from control improvement. These benefits were only discussed qualitatively.
- No surface water quality measurements were made to value benefits.

(Wiese, Simon and Schmitt 2005) (Wiese 2013)

4.2.3 Quebec, Canada

Project description

In Canada, the Ministry of Environment sets discharge limits linked to downstream water usage, which translate to an allowable number of overflows per year. At the Quebec Urban Community (QUC), the frequency of CSOs on the St. Lawrence and St. Charles Rivers had to be reduced to two and four times per year, respectively. The QUC (550km^2, population 230,000) is divided into Easterly and Westerly catchments, which both have WWTPs that discharge to riverside recreation areas during storm events. An important environmental objective for the QUC was to protect these areas for summer recreation use. Ambitious compliance schedules combined with budgetary constraints, however, made traditional infrastructure improvements unattractive options for meeting the QUC's objectives. In turn, the QUC investigated a large-scale integrated automatic predictive (IAP) control system. Preliminary analyses suggested that better use of the existing infrastructure could deliver significant cost savings in capital improvements. To validate these predictions, an IAP control system was initiated first as a pilot in the Westerly catchment (360km^2, population of 150,000), in 1999. Full implementation for the QUC followed, in 2009. The control strategy integrates the urban watersheds, sewer, WWTPs and hydraulic capacity of the diffuser, which is influenced by the St. Lawrence River tide.

In the pilot phase of the project, the control system was used to optimize 15,000m^3 of storage in two existing tunnels and to maximize flow to the Westerly WWTP. Project components included four new monitoring locations, 13 rain gauges, two regulators and the five control gates for the in-tunnel storage. No additional storage facilities were built. Activities included construction and modification of monitoring and control stations, development of the communication system and the design and set-up of the control system. Existing models were calibrated using precipitation series and measurements of rainfall, sewer flows and water levels, gate openings and capacities of the pump stations and Westerly WWTP. The controller sets operating points for the gates and pumps based on present and future rainfall, flow rates in the sewer, pump capacities, WWTP capacity and the tide in the St. Lawrence River (which influences the WWTP capacity). The pilot was run for three years, before the project expansion began, in 2003.

For the full project, which was implemented in two phases, components included 14 new retention basins (totalling 122,000m^3), 18 control sites, 18 regulators, 15 measurement sites and two pump stations in both the Easterly and Westerly catchments. In addition to the significant construction activities, the existing models and IAP control system were expanded to the full project.

Results

For pilot phase:

- 76% reduction in mean CSO volume and 38% reduction in mean CSO frequency were measured for rainfall events from 1999 – 2001. These results are compared with static control simulations for the same period. The very large reductions in CSO emissions are, in part, attributable to the significant and previously underutilized in-system storage of the two tunnels.
- The project cost $4.366 million ($1.7 million in capital expenses, $2.666 million net present value for 25 years for operation and maintenance).
- Cost savings of more than 75%, when compared to the minimum estimate ($20 million) for building new storage facilities.
- The project took three years from initiation to operation.

For full system:

- 46% reduction in mean CSO volume and 45% reduction in mean CSO frequency were measured over all locations for 32 events in 1998. These results are use static control simulations for the same period for the comparison. Since significantly more storage was added to the system, it is not known how much of the CSO reduction can be ascribed to control.

- $145 million project costs, including engineering and discounting. Note the $4.366 million pilot study were sunk costs, at this point (the total project costs, therefore, were $150 million). The notably higher cost of implementing the full system is due to the fact that capital improvement costs are included, while no major capital improvements were made in the pilot phase of the project.
- 37% cost savings from IAP control, when compared to the static storage alternative ($240million) and 17% when compared to a local reactive control option ($180million).
- Storage savings of 45% when compared to the 250,000m^3 static storage alternative and 28% when compared to the 190,000m^3 local reactive control option.

<u>Implementation and operational experience</u>:

- No changes to personnel were necessary and 50-hours per operator was sufficient for training.
- No problems occurred with personnel or equipment from implementing the new technology.
- Changes to operation and maintenance have been integrated into existing activities and budgets.
- Weekly cleaning is required for sensors.
- The meteorological forecasting model must be calibrated and validated every three months.
- For quality control, processing and archiving of the database must be done monthly.
- Hydraulic models must be calibrated yearly and performance reports compiled after all rainfall events.

Technical conclusions

- Systems with the following characteristics are likely good candidates for advanced control projects: significant rainfall heterogeneity, multiple overflow structures, distributed storage facilities, multiple or satellite WWTPs and many control devices.
- IAP control systems can be practical, effective and cost-efficient solutions for CSO reduction.
- Operator and stakeholder input is important from the early stages of the project for smooth realization.

Evaluation conclusions

- The cost estimations included the capital improvement investments, as well as the control aspects and initial assessments of the project, making it unclear what control cost.
- The performance results combined the gains from infrastructure expansion, control improvement and initial optimization activities for the project, making it unclear what control contributed.
- The holistic reporting of costs and performance results is in keeping with the objective of the project to minimize the costs of meeting the regulatory goals.

- The benefits were represented by the cost savings from the control project, when compared to the costs of a storage alternative.
- Significant upfront costs were required to evaluate the feasibility of a control improvement project. The pilot project was used to limit the risk of investment.
- The difference between the pilot and full projects in terms of control potential and the inclusion of new infrastructure (for full project) highlight the bias in reported costs and performance results.
- Operational flexibility is an important benefit of control projects, which is realized through the ability to redefine control objectives and constraints and to improve performance through on-going operational experience.
- No water quality measurements were made.

(Colas, Pleau, et al. 2004) (Pleau, et al. 2005) (M. Pleau 2013) (Colas 2013)

4.2.4 Paris-Ile-de-France, France

Project description

A central supervisory predictive (CSP) control project was initiated in Paris-Ile-de-France, in 1999. The goal was to develop a plan that could meet stringent water quality objectives in the Seine and Marne rivers, when a 10-year wet-weather event occurs during a summer low flow regime. In order to meet the environmental objectives, significant system-wide expansions had been planned for the catchment of 19,000km^2 and eight million people. These included a combination of best management practices, increased in-line retention, new off-line retention (fifteen basins and four tunnels), one satellite high-rate treatment facility, five new wastewater treatment plants, wet weather high-rate treatment at the WWTPs and inter-basin water transfers. These capital improvement projects were simulated in the existing system model. When the CSP control system was added to the model, it showed that by controlling 50 (of 264) of the most important overflow sites, the project objectives could be met for a lower overall investment. It is unclear which, or how much, of the originally planned capital improvements were ultimately implemented with the control project. Hence, it is not known what structures control was applied to, or how the algorithm was set-up.

Results

- CSO volume was reduced by 25% for both the ten-year design and actual events, compared to the simulated system with static capital improvements only.
- The total cost for the project, including capital improvements, was $3.1 billion; a 25% savings compared to the estimated $4.2 billion cost of the project without CSP control.
- A portion of the system tested by the US Environmental Protection Agency, showed 65% more suspended solids were captured when the CSP control system was used, compared to a local reactive control alternative.

Technical conclusions

- A strategic use of advanced control systems can lead to significant performance improvements by targeting only a few locations.
- Adding advanced control to capital improvement projects can lead to greater performance for less cost.
- Advanced control systems can be successfully implemented and operated in large, complex catchments.
- When evaluating performance of control improvements in supervisory systems, the operator cannot be distinguished from the rest of the system.
- The reduction rates of pollution loads were notably higher than the rates for CSO volume.

Evaluation conclusions

- The costs for this project were reported holistically for the control and capital infrastructure improvements. It was unclear what was included in the costs.
- Performance measures were also reported holistically for the total project and there was no intention of measuring water quality directly.
- The holistic values for cost and performance are in keeping with the objective to meet the mandated performance level.
- The benefits of control were represented as the cost savings compared to achieving equivalent results without control. This is consistent with the objective of meeting the performance goal with the lowest investment.

(Colas, Pleau, et al. 2004) (Stinson 2005) (M. Pleau 2013)

4.2.5 Wilmington, USA

Project description

Motivated by US Environmental Protection Agency's CSO policy, Wilmington (25km^2 catchment, population 72,000) investigated control improvements to meet their long-term plan of 85% reduction in CSO volume. A 2003 study used an existing calibrated hydraulic model to simulate control scenarios, using three years of continuous rainfall data. The selected alternative involved applying coordinated automatic reactive (CAR) control to four new control sites (of 40 existing CSO structures) and the outlet of a storage basin. Accompanying capital improvements included a pump station upgrade, siphon cleaning, a new flow-regulating site and construction of a relief sewer. No details on the control algorithm were available. It is unknown if the project was implemented.

Results

- Including the improved control components in the project increased the CSO capture rate by 9% (for a project total around 85%) for the three-year rainfall series and by 32% for the annual average.
- The control alternative also reduced the total estimated cost of the project from \$160 million to \$40 million, by reducing the necessary storage.

Technical conclusions

- Control can provide significant savings on capital improvement projects; this is especially appreciable in small communities facing large expenditures due to mandated performance levels.

- The existence of a calibrated model for the present system makes assessing control alternatives a rapid and relatively simple process.

Evaluation conclusions

- This project compared the total project costs of a storage alternative to a control option with the same performance level. It was not clear what was included in the cost estimates.
- This project reported the performance results attributable just to control in the context of the total project gains.
- The upfront investigations required modelling and the set-up of the control algorithm to identify potential control projects. The storage alternative was based on simple calculations.
- Benefits were not addressed, only cost savings from including control. This is consistent with the goal to minimize costs of meeting the required performance level.
- No water quality measurements were made, as they are not required by the regulations.

(Colas, Pleau, et al. 2004) (M. Pleau 2013)

4.2.6 Louisville, USA

Project description

Public use of the Louisville sewer district's receiving waters was prohibited due to 17 million cubic meters of annual CSOs. The city (97km^2, 325,000 people and 114 CSO locations) investigated control improvement in an effort to avoid US Environmental Protection Agency fines, while maximizing financial and physical resources. A preliminary assessment of the sewer system's in-line storage and simulations of control scenarios indicated that a central automatic reactive (CAR) control strategy could achieve significant reductions in annual CSO volume, minimize flood risk and optimize the WWTP operations. The project, implemented in 2001, combined the CAR control system with unspecified capital improvements. No details were available on the control set-up.

Results

- The annual average volume of CSOs was reduced by 52% for the combined control and infrastructure improvements.
- The cost of the control components is estimated to be $30 million and to have reduced the total project cost from $260 to $150 million.
- The control project took three years from initial studies to implementation.

Evaluation conclusions

- This project gave a value for the cost of the control part of the project, in the context of the total project cost. It was not specified, however, what was included in either estimate.
- The performance achievements were reported holistically for the control and infrastructure parts of the project, so the return on the control investment could not be determined.

- No water quality measurements were made, as they are not required by the regulations that motivated the project.
- No benefits, apart from cost savings of the with-control alternative, were reported. This is consistent with the goal to minimize costs of meeting the required performance level.

(Colas, Pleau, et al. 2004)

4.2.7 Unknown catchment, Japan

Project description

Increasing pollution from CSOs in Japan's surface waters motivated a national initiative to research and popularize innovative technologies for preventing discharges. Advanced control systems were one of the 25 technologies. Formerly, control improvement projects had not been applied in Japan, due to three key challenges:

1. The localized high intensity rainfall that occurs in Japan is better suited to storage solutions than control.
2. For Japan, no evaluations had been made of the relation between the pollution load and the volume of CSO.
3. For lack of reference projects, the costs of implementing control projects in Japan were unknown.

To address these issues, a research project was made to investigate the potential for advanced control systems in Japan. In 2005, a typical catchment of 20km^2 and 530,000 people was used for simulations of central automatic predictive (CAP) control of in-pipe storage gates and a storage reservoir of 20,000m^3. The storage gates are closed during dry weather, passing sewage through a recessed aperture in the gate. Based on predicted rainfall and measured system status, the control algorithm tries first to maximize flow to the WWTP, then to optimize storage throughout the sewer, before discharging to the retention basin. The in-pipe gates are opened based on multiple input data, such as in-pipe water level, rainfall and the status of connecting pipes and overflow locations. Results were measured in kilograms of BOD reduced per year, using 85 rainfall events measured over one year.

Results

	Control	Storage
BOD reduced (kg/year)	40,000	92,000
BOD reduction rate (%)	20	
Construction costs ($/year)	180,000	1,740,000
Total annual costs ($/year)	380,000	1,770,000
Specific cost of reduction ($/1000kg)	9,500	19,000

Compared to a water level based set-point for opening the gates, adding the control algorithm reduced BOD emissions by an additional 7%.

The in-pipe gates and control algorithm successfully prevented CSOs and flooding for all rain events in the year of testing;

Technical conclusions

- For systems with large sewer pipes, like those common in Japan, in-pipe gates combined with CAP control is an economical and effective means of reducing pollution from CSOs in surface waters.
- Academic partners and public funding supported this project.

Evaluation conclusions

- Cost estimates for construction and annual expenditures were given for this case. Additionally, the specific costs for a CAP control project were estimated to be roughly half the costs for storage alternatives. This type of reporting is consistent with the objective of making control improvement projects options for consideration in Japan, by reducing uncertainty and investment risk. What was included in the cost estimates, however, was not specified.
- Water quality benefits were represented by the reduction of BOD. It is not clear if this was measured, or estimated using CSO volume. It is also not clear if there are any gains from infrastructure improvements included in the performance results.
- No economic benefits were discussed for this project.

(Meguro, et al. 2007).

4.2.8 Tokyo, Japan

Project description

In 2001, due to regulatory and public demand for improved surface water quality, Tokyo initiated a long-term improvement plan for their sewer. One component of the strategy was Quick Action projects for reducing CSO emissions from the city's 82% combined sewers. Quick Action projects had to minimize CSO's as quickly and affordably as possible, within Tokyo's limited available space. Further, the solutions should be adaptable to the upcoming long-term sewer improvements. As part of the Quick Action scheme, the city implemented central automatic predictive (CAP) control systems at two of its primary pump stations, Shinozaki and Umeda.

The Shinozaki project integrates the primary Shinozaki pump station and three upstream secondary pump stations for the 21km^2 catchment. The aim of this project was to reduce pollution loads of the combined sewer to the (acceptable) levels achieved by the city's separated sewers. The control system estimates inflow to the pump station by using measured and forecasted precipitation data, the water level in the upstream trunk line, the starting time of the upstream pumps and the pump-characteristic curves. According to the estimated inflow, the control system aims to avoid CSOs by maximizing upstream in-line storage and optimizing pumping. In order to accommodate the high intensity rainstorms that occur in Tokyo, the pump controller operates at two-minute intervals, based on ten-minute predictions. In reality, there is a delay in the pump start, which has been problematic in extreme precipitation events.

Results for this project compared the overflow volumes and pollution loads for the existing local automatic reactive control and the CAP system, using rainfall events during testing in August 2002. Further simulation was made for an extreme rainfall event in October 2003.

The Umeda system integrates nine storm water pumps and the Umeda pump station, in the catchment of 16km^2. In addition to reducing CSO emissions, the Umeda project was also designed for flood control. The system estimates the inflow to each pump station by using measured and forecasted precipitation data, the water level in the upstream canal, the starting time of all the system pumps and the pump-characteristic curves. According to the estimated inflow, the control system aims to avoid CSOs by maximizing water level (storage) in the upstream canals – without inundating the grit chamber – and minimize flooding by optimizing storm water pumps. In order to accommodate the high intensity rainstorms that occur in Tokyo, the pump controller operates at one-minute intervals, based on ten-minute predictions. The Kosuge WWTP has reserve capacity for treating the increased flows due to CSO and flood prevention; no additional spill was measured for the rain events during testing.

This project, implemented in 2004, used a full year of rainfall events from the testing period (34 events in 2006) to compare the CAP system with simulations of the former local automatic reactive control. This project was fully operational within three years.

Results

	Shinozaki	Umeda
• CSO volume reduced (%)	30	19
• CSO BOD reduced (%)	40	27
• CSO COD reduced (%)		28
• CSO SS reduced (%)		24
• Project implementation time (years)	3	3

The only cost information provided for the Tokyo control improvement project was "approximately $3 million". It is not clear if this includes both Shinozaki and Umeda, or possibly additional projects. No details could be clarified.

Technical conclusions

- Both projects reported that the challenges of controlling CSOs during extreme rainfall events, common in Tokyo, were best met with the CAP control systems.
- For catchments with high intensity precipitation events, the frequency, accuracy and spatial resolution of rainfall prediction is critical to the effectiveness of a CAP control system.
- When CSOs do occur, due to high intensity rainfall events, the pollution load reduction is greater than the overflow volume reduction.
- During moderate rainfall, flooding was preventable with the CAP control system.
- For the Umeda project, CAP control led to reduced pumping through optimization of the system.

- For the Umeda project, both CSO and flood control objectives could be met using the same CAP control system.
- CAP control systems can be rolled out quite quickly.
- CAP control was an effective solution in a relatively flat catchment with a simple sewer network.
- Operator involvement and input were important factors in the successful design, implementation and operation of the systems.

Evaluation conclusions

- No evaluations were reported for the system and costs were not provided.
- Performance was measured for several water quality factors, as well as CSO volume, which could potentially be used to determine benefits. However, no surface water quality measurements were reported.
- It is not clear if there were any optimization or infrastructure components to the projects.

(Kuno and Suzuki 2006) (Maeda, Mizushima and Ito 2005)

4.2.9 Vienna, Austria

Project description

In an effort to meet water protection regulations, a central automatic predictive (CAP) control system was integrated into a larger capital improvement project that aimed to:

1. Minimize Vienna's CSO emissions
2. Moderate the loads received at the WWTP
3. Improve the operational management of the sewer

The project serves a catchment of 260km^2 and a population of 1.8 million. The infrastructure expansion components of the project involve building large storage sewers beside the Donau, Donaukanal, Wienfluss and Liesing, in order to minimize discharges that occur during rainfall events. The CAP control system includes an online network of 25 rain gauges, 40 flow measurement devices and 20 water level meters throughout the sewer. Forecasted and measured rainfall values are used to predict catchment runoff and sewer flows. An optimization model controls the system's regulators, surcharge, flows, overflow volumes and the water levels in the system channels. A self-learning system was included to improve the rule basis.

The rule-base was set up so that, at the beginning of an event, the pumping to the wastewater treatment plant is maximized and all runoff is stored in the retention pipes, as long as capacity is available. If a combined sewer overflow cannot be avoided, priority is given to the discharge into the river Donau. Discharge priority is given to the upstream overflows, to avoid mixing runoff from the Wienerwald area with that from the city centre.

Simulated results are based on multiple events, including heavy and extensive rainfall series. The project was completed in 2005.

Results

- Mean reduction in CSO volume was 33% (107,000m^3) for constant areal rainfall and 13% (43,000m^3) for spatially and temporally distributed rainfall. The reason for the difference is attributed to the limited available events with sufficient areal rainfall information.
- For an extensive rain event, with most of the system already operating at capacity, a 2.5% reduction in CSO volume and 6.2% reduction in COD were achieved.
- 3.5 years were needed for project realization.
- No cost information could be determined for this project.

Technical conclusions

- There are benefits for CSO and pollution mitigation to be gained from the CAP control system.
- Performance improvement is expected with experience in operation.
- The project setup and installation time should not be underestimated for such a large-scale project.
- Control offers greater gains in pollution abatement than represented by CSO volume

Evaluation conclusions

- No costs or savings were provided for this project. This may be due to the fact that control was used for reasons other than minimizing costs.
- This project shows the performance gains from control, when the system is operating at capacity.
- Water quality results were represented by the reduction of COD. It appears this was estimated based on CSO volume. It is not clear if there are any gains from infrastructure improvements included in the performance results.
- Academic partners supported this project's development and realization.
- No economic benefits were given for this project.

(Fuchs and Beeneken 2005)

4.2.10 South Bend, USA

Project description

In 2008, the city of South Bend, Indiana (population 100,000, 50km^2 catchment) was required to reduce CSO volume by 30% and dry weather overflows to one per year (from 29), or face $800,000 in annual fines to the US Environmental Protection Agency. Specifically, the city needed to reduce emissions along the Saint Joseph River, which bisects the city, includes a popular paddling course and discharges into nearby Lake Michigan. The city included an integrated automatic predictive (IAP) control system, as part of larger infrastructure improvements. The control system aimed to:

1. Decrease the number and volume of overflows by optimizing existing storage
2. Eliminate dry weather overflows through blockage detection
3. Calibrate existing system models

4. Develop a sewer characterization
5. Rationalize maintenance activities.

The existing sewer system's major features were 36 overflow structures to the Saint Joseph River, an 11km-long interceptor parallel to the river and the WWTP. A throttle pipe transfers flows from the main trunk line to the interceptor. Existing system models were already in use.

For the control improvement project, 127 water level and flow meters were installed throughout the sewer at CSOs, interceptors, pump stations and in trunk lines. An automated throttle was added parallel to the existing pipe, to divert more flow to the interceptor, when capacity is available. Additionally, the project reduced the 36 direct discharge structures to nine structures with retention basins and IAP control. These nine locations, which service 26% of the combined sewer area, were determined to achieve 85% of the total potential benefit of automating every regulator.

Based on rainfall predictions and the current system status, the control strategy maximizes flows to the WWTP and storage in the main interceptor (via the new throttle pipeline). If a CSO is unavoidable, the algorithm prioritizes discharges downstream of the paddling area and city center. The control algorithm and its integration with the existing models and WWTP control system were developed by a doctoral candidate with independent funding for developing the technology. The system was brought online in 2011 and has been in full operation since 2012.

Key tasks

The first step was to install monitoring stations, concentrated along the river. From the measurement campaign, a system characterization was developed and existing models were calibrated. Initial optimizations were made for the system. Control modelling identified overflow structures with best control potential. The control algorithm was set up and connected to the WWTP control system. An implementation team was formed to handle stakeholder participation. The control aspect of the sewer improvement project was implemented in three phases, over one year, to test the system and ensure smooth transition from manual to automated operations.

Results

- 85% of emission reduction achieved through strategic control at nine (of 36) regulators.
- 23% reduction in total annual CSO volume, including infrastructure expansions.
- 54% mean annual CSO volume reduced at control sites.
- Dry weather overflows reduced from 29 per year to once per year, in year of monitoring program only 10 dry weather overflows occurred.
- Total project costs reduced from $600 million to $500 million, by including IAP control.
- Cost of control evaluation and monitoring equipment was $2million, cost of control valves and installation was $2.2 million.

- Results of initial investigations showed that simple operations and maintenance tasks could return significant improvements in performance, before control was included.
- Costs for control algorithm, model upgrades and testing were covered by project partners and are not available.
- Significant operation and maintenance benefits were achieved, estimated worth of $1.7 million per year, from:
  - Elimination of 230m^3/s of infiltration and illicit connections
  - Identification of system "hotspots" and proactive maintenance
  - Flood warning
  - Improved monitoring system
  - Rationalized maintenance activities
- Project was online within three years. An additional year was taken for testing before full automation was used.

Technical conclusions
- Future expansions of control system will be faster and more efficient
- Stakeholder buy-in is essential to the project's success
- Significant benefits were realized in the operation and maintenance of sewer system

Evaluation conclusions
- This project combined initial system optimizations, capital expansion and control improvement aspects in reporting performance and costs. Estimations of the hardware and construction for the control improvement were provided, but these do not include any modelling or development of the control algorithm. Further, the extensive testing and rollout process of the project were not included.
- This project estimated benefits by determining the costs saved by including control from lower capital investment, rationalized operation and maintenance and avoided fines. This calculation of benefits was motivated by the need to "sell" the control project to a stakeholder group. No environmental or water quality benefits were included.
- The learning costs were not quantified for this project, but they were acknowledged to be "significant".
- The upfront investigation costs for evaluating the feasibility of a control alternative were shared by technical and financial partners.
- Better understanding of the system and increased operational flexibility were evaluated qualitatively. An attempt to quantify these benefits was made by estimating the savings from operation and maintenance.

(Henthorn 2013)

4.2.11 Hoeksche Waard, NL

Project description
In the province of Zuid Holland, the Netherlands, a water board and five municipalities in its district joined with the Technical University of Delft and

Deltares to implement a central automatic reactive (CAR) control system. The project was motivated by a subsidy for promoting innovation in the water chain and improving cooperation between actors in the Dutch water sector[6]. Funds for implementing the Water Framework Directive had been earmarked for the subsidy program.

The project was initiated in the Hoeksche Waard polder (population 85,500, catchment 300km^2), which consists of agricultural land and the municipalities of Binnenmaas, Cromstrijen, Korendijk, Oud-Beijerland and Strijen. The primary objectives of the project were:

- To improve cooperation between the municipalities and with the water board
- To reduce operation and maintenance costs through greater efficiency
- To improve surface water quality through reduced emissions and strategic spilling
- To increase knowledge of the existing system in operation

Data was collected for all municipalities and five WWTPs, however, control pilots were only implemented in the three villages of Klaaswaal (municipality of Cromstrijen), Strijen and Piershil (municipality of Korendijk). The sewers, WWTPs and surface waters for these villages are isolated from each other and different control strategies were used in each case.

For Klaaswaal, the control approach was to reduce surface water pollution by first optimizing existing in-system storage to minimize spills and then to prioritize unavoidable spills away from a sensitive area in the village centre. Overflows were preferred at the periphery of the village, where a separate sewer was installed and the water quality is less sensitive to emissions. Optimization of the WWTP operations was not included in the control strategy of this pilot, since Klaaswaal's wastewater is treated in a plant shared by another village. The Klaaswaal project was brought on-line in 2011.

For Strijen, the control strategy was to reduce spills by optimizing the existing in-system storage and by increasing influent to the WWTP, when measured sludge levels and turbidity in the settler indicate the treatment processes can handle higher hydraulic loads. The Strijen project was brought on-line in 2011.

For Piershil, the approach was to coordinate two pump stations into the WWTP in order to improve treatment processes through more equalized inflows and to gain energy savings through more efficient pumping. The Piershil project was not brought on-line, due to technical problems unrelated to the control project.

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[6] In the Netherlands, responsibility for water is roughly divided between companies, which provide domestic and industrial water supply services; municipalities, which operate sewers within their district; and water boards, which manage surface water levels and quality, wastewater treatment and flood control (van Nooijen, Kolechkina and van Heeringen, et al. 2011)

Before the control project was initiated, several capital improvement projects had been implemented. These consisted of disconnecting 7 hectares and building 23 retention basins for 4250m^3 of new storage. This project cost €9 million and reduced COD by 19,135kg/year. This is roughly 60% of the 33,000kg COD/year of reductions that had been expected of the projects.

Key tasks

The project consisted of:

1. A monitoring campaign, which measured water levels throughout the systems and inflows to the five WWTPs.
2. The development of an information system that collected the measurements from the monitoring campaign in a central database. The information system effectively combined data from the WWTPs (managed by the water board) and the sewers (managed by the municipalities).
3. The implementation of control pilot projects in the villages. This task mainly involved the development of the control software and adjustments of the information system to facilitate bi-directional communication between the control centre and the pumping stations in the sewer systems
4. Updating the system models and making analyses of the sewer operation.

Results

- The total project costs were €2.5 million – divided between the subsidy, the water board and the municipalities. Annual renewal costs were estimated to be €215,000.
- The project costs are broken down by task, with estimations for the costs of repeating each task in a new project:

	Actual costs	Costs to repeat
Upfront organization for project	€209,000	€169,000
Initial optimizations from information system	€152,000	€126,000
Development of monitoring plans	€169,000	€150,000
Cost to build monitoring infrastructure	€778,000	€397,000
Implementation of monitoring campaign	€248,000	€150,000
Analyses	€159,000	€141,000
Actions – control and optimization	€678,000	€141,000
Integrate results into municipalities/water board	€41,000	€25,000
Project closeout	€65,000	€16,000
Total	**€2,499,00**	**€1,314,000**

These results are based on a €35/hour average wage, as required by the subsidy. However, €85/hour is more typical for the project area and using this value, the cost to repeat the project is €1,816,250.

- The measurement campaign showed that the models were not consistent with the physical system and that simple adjustments could achieve performance gains equal to almost half of the total kg of COD reduced by the project. It was estimated that 10,641kg COD/year could be captured through system optimizations estimated to cost €100,000. Some of these, so called “Quick Wins”, were realized as part of the project.

- Simulations of the control improvement projects achieved a combined capture rate of 3,547kg COD/year, for the €2.5 million investment.
- While the values for performance achievements from optimization and control are rough estimations of potential results, they indicate that 10% of overall emissions reductions would come from control improvement, while optimization would contribute 50%.
- The rough potential cost per kg COD per year of emission control for the three project components would be: capital improvements - €470/kg COD-year, optimization - € 10/kg COD-year, control project - €110/kg COD-year.
- The measurement campaign uncovered excess flows in the system from infiltration and illicit connections of 17,800m^3/day – roughly double the expected flow. The extra cost for pumping and purifying these flows was estimated to be almost €8 million per year.
- The measurement campaign showed that the existing system had been performing worse than believed. Emissions of kg COD per year were 48% greater than estimated from the models.
- Environmental and water quality benefits from the implemented project could not be determined because measurements are not taken/documented frequently or accurately enough to determine reduction in overflow volumes, frequency or duration. Water quality metrics are not being measured.
- 30% of the cost of the project was estimated to be reusable for future projects.
- Implementation took three years.

Technical conclusions

- Although the calculations are rough, optimization appears to provide the best return on investment, for this project.
- Maintaining measurements after implementation is important to accurately determine project success.
- For this case, the areas with the biggest learning costs are in the building and implementation of the monitoring campaign and in the implementation of the control system. This is due to the extensive effort that was required to make the control systems of the individual communities connect with the central data collector and to receive control signals. Additionally, the central control software had to be developed to be able to control small sewer systems on a high frequency basis.
- Operator involvement and inter-agency communication was reported to be key for the project, especially the interaction between multiple agencies.

Evaluation conclusions

- In addition to savings on infrastructure investment, this project attempted to value benefits of better information and communication, which were represented by operations and maintenance savings. Environmental and water quality benefits were not valued since the measurements to quantify the impacts were not made.

- During the ex-post evaluation of this project, it was estimated that greater performance gains for the investment were possible.
- Many of the values used for the benefits were based on assumed (as opposed to measured) impacts or results.
- Many of the benefits accounted for should not have been included, as they were not technically economic benefits of control improvement. These errors could be due to the authors' lack of economic background, or to show the "success" of the project, which had received subsidy funding.
- Financial and technical partners from academia, the private and public sectors supported this project.
- The upfront investments to investigate control alternatives were covered by the grant.

(van Velzen 2013) (Mol 2013) (van Nooijen 2013) (van der Eem and Dijkstra 2012) (Mol, van Dongen and van Velzen 2012) (van Heeringen 2013)

4.3 Findings of the project review

Due to the newness of control improvement projects in urban drainage systems, there are few documented examples in literature. This poses several key problems for reviewing the evaluation processes:

1. Most papers are dedicated to technical aspects of implementing control projects, not on why they were selected or how they were evaluated.
2. There is little overlap in projects to provide confirmation of values or findings.
3. There is little consistency in the reporting of project performance, costs or general information. This makes it difficult to compare and analyse different projects.

Despite these challenges, some findings from the review are listed below.

- In eight of the eleven cases reviewed, legislation, such as the EU's Water Framework Directive and the US Environmental Protection Agency's CSO Control Policy, is the chief driver for control improvement projects and the main determinant of how performance is measured. The remaining three cases were motivated indirectly by regulation, since they were research projects aimed at facilitating the use of control options to meet changing operational and regulatory needs.
- Control improvement is commonly implemented as part of a wider project. This is true of seven of the cases reviewed, and possibly others that did not specify. For most projects this means there are three components: (1) optimization of the existing system, (2) control improvement and (3) infrastructure expansion. Each component has associated costs and performance results, but in practice, these are usually viewed holistically and reported together. This makes it difficult to determine the cost and performance gains achieved by control improvement.
- Reported results are based on different types of rainfall events and durations. While results should be given for long-term series, the values are often for

only a few rainfall events or design storms. These may be representative or selected to show a project's best performance, though this is never made clear. Further, results may be reported as mean annual values, or for specific events or periods of time.

- Reported results are based on different portions of a system. Sometimes reported results are the average performance for a whole system, while other times only the performance of selected overflow structures is used. This may be due to a lack of system-wide measurements, such as the Hoeksche Waard project. In other cases, like Quebec, no explanation for the selective reporting is given. In still other cases, it is altogether unclear if the results represent the full system or not.
- It is difficult to isolate the explicit costs of control improvement for several reasons:

    a) The starting and ending conditions (in terms of control, infrastructure and level of optimization) of each project are different and unclear. This makes the costs difficult to compare without detailed information, which is not provided.
    b) Reported costs commonly combine the investments for control improvements with those for a wider project (infrastructure expansion) or system modifications (optimization). This is true of seven of the nine cases that provided cost information.
    c) It is commonly unclear what capital costs are included, whether operation, maintenance or replacements are accounted for, or if discounting was used.

- In practice, benefits of control improvement projects are not quantified unless necessary. The avoided costs of pricier alternatives are almost always used to represent the benefits of a control improvement project. The Hoeksche Waard and South Bend cases are the exception. These projects were motivated to quantify benefits to meet stakeholder expectations. Neither project tried to value environmental or water quality benefits, however; they focused instead on operational and capital cost savings.
- There are currently no standards for evaluating control improvement projects; this leads to three ubiquitous problems with the reported evaluations:

    a) The specific returns (in performance) on investment are unknown. This is because marginal improvements in control are not identified. From interviews it seems there is no incentive to optimize the costs and benefits within a project, once a budget is made to reach a specific result.
    b) The reported benefits of control projects are often over estimated. This is because project results are measured and reported holistically, without distinguishing the achievements of control from capital improvements or initial optimization. Also, results may be selected to represent the best performance scenarios.
    c) The reported costs of control projects may be misleading. In most cases, systems already have some model or equipment necessary for

the control improvement project. These sunk costs were often not made clear or quantified. This may lead to under-representation of control costs for situations without models or control infrastructure.

- The new and innovative nature of improved control systems has led to many projects receiving special technical and/or financial support. It has also instigated partnerships between academia and the public and private sectors. This was reported for five of the eleven projects, but likely played a role in more. In these cases, innovation and technology development may be emphasized over economic efficiency. Extra cost from inefficiency is in addition to inherent learning costs, which are rolled into the reported values, due to the newness of these types of projects. By contrast, partnerships can also lead to under-reported costs, when outside funding or unpaid labour do not show up in project expenditures. To illustrate these problems:
    a) The Hoeksche Waard project, estimated that repeating the project in a similar system would cost around 70% of what was spent on the original project, because of learning costs that were encouraged by the subsidy (Van der Eem and Dijkstra 2012).
    b) The South Bend project did not pay anything for their control algorithm or its integration into the system models, because these were developed by a doctoral candidate with independent grants (Henthorn 2013). These costs were not included in the project values.
- The most reportedly valued advantages of control projects were cost savings, better understanding of the sewer system and operational flexibility and adaptability. Nine of the project tried to quantify the costs savings from reduced infrastructure investment. The South Bend and Hoeksche Waard projects tried to quantify the benefits from improved information. Operational flexibility and adaptability were not quantified by any projects, but were mentioned qualitatively in at least five of the cases reviewed.
- Control improvement projects require more upfront costs to assess their feasibility than traditional infrastructure alternatives. Control options require modelling and measurement campaigns, to define potential projects. By contrast, infrastructure solutions can be assessed for feasibility using basic preliminary calculations. This makes a difference in the timing and perceived risk of investments for control and infrastructure projects. The upfront costs of the feasibility investigations needed in order to include control improvement alternatives can be off-putting to decision-makers. In Kessel-Lo, Quebec, Wilmington and South Bend efforts were made to moderate the risk of upfront investment. In Messel and Japan, it was an objective of these research projects to limit uncertainty for future projects. In cases, such as Hoeksche Waard, a project partner shared the upfront costs.
- While most projects appeared to optimize their existing system before implementing control improvements, only the Hoeksche Waard project tried to quantify the investment and performance attributable to optimization alone. Anecdotal evidence from several projects and the (rough) ex-post estimations for Hoeksche Waard, suggest that optimization may be the highest performance return on investment (M. Pleau 2013) (Henthorn 2013)

(Mol 2013) (Wiese 2013) (van der Eem and Dijkstra 2012). This implies that there are benefits, in terms of performance and operations, from the feasibility investigations for the control alternative. These gains usually came from rectifying a difference between actual and believed system conditions, such as increased flows from infiltration and illicit connections.

In addition to the findings regarding the evaluation of control improvement projects, some interesting technical conclusions can be drawn from the project review. Since these can also be used to inform the framework, they are included below:

- Control improvement projects have been implemented in systems of various sizes, types and conditions with consistent performance benefits and cost savings, compared to static CSO prevention measures, such as storage.
- Performance of control improvement projects is most commonly measured by the reduction of average annual CSO volume. This is true of nine of the eleven projects. Water quality values and reduction in CSO frequency are used to a lesser extent. These were used for six and three of the eleven projects, respectively.
- Where water quality and overflow volume were measured (projects Paris, Tokyo and Vienna), the rates of reduction in pollution load were greater than the corresponding rates of reduction in CSO volume.
- The project time frame, from initial studies to implementation, is typically about three years. This is true of the six projects that commented on this.
- Cost savings ascribed to control improvement varied from 25 to 95% of project costs. This wide range is due to the different starting points of projects, in terms of existing control infrastructure, and the alternatives used for comparison. Storage – the most commonly compared alternative – typically cost two- to five-times control options with similar performance results. Storage costs were estimated around 750 €/m^3, in Europe, and 1000 \$/m^3, in North America.
- CSO volume reduction attributed to control improvement projects is mostly between 20 and 30%, though the range is 2.5 to 75%. For many projects, it seems that the reported results for control include performance gains from optimization of the existing system and even infrastructure expansion. For projects that reported the performance gains of control in an already optimized system (projects Messel, Wilmington, Vienna and Japan), the values are at the low end of the range (2.5-9% and possibly up to 20%). Additionally, comparing reduction rates may be misleading, since performance results are based on different scenarios and rainfall series.
- CSO frequency reduction was reported between 15 to 35%.
- Although many systems have some existing measurement equipment, the data are under-, or not, utilized without the incentive of the control project. This was reported to be the case in South Bend, Tokyo, Messel and Hoeksche Waard, among others.
- In some cases the control systems serve performance objectives in addition to CSO prevention. In most of these projects, reducing emissions is the primary objective, but not always. In Tokyo's Umeda project, for instance,

flood avoidance was equally as important as CSO prevention. Likewise, in Hoeksche Waard, improving cooperation and communication between agencies was a primary objective.

- Early, continued and active operator involvement in a project is key to its successful design, implementation and operation. This factor was noted for at least five projects. Despite academic warnings of operator resistance to control improvement projects, cases that reported on this issue uniformly noted the receptive attitude and quick adjustment of operators. As few as 50 hours of training per operator were reportedly successful for implementation.
- Where noted, projects were able to implement the control project with the existing operation and maintenance personnel and activity level. In most cases (Hoeksche Waard, South Bend and Quebec, among others) this meant reassignment of tasks and more proactive and comprehensive maintenance programs.
- The DWA guideline, especially its preliminary assessment for control potential (PASST), was used successfully in the setup and implementation of projects, such as Kessel-Lo and Quebec, and reportedly many more in Germany.
- The presence of existing control structures and measurement equipment seems to have the biggest impact on project cost and rapidity of project implementation.

4.4 Limitations of the project review

Before the project review's implications for the framework are discussed, it is important to recognize some limitations. Most notably, the number of projects reviewed is too small to determine any true trends. Furthermore, the large variation in project sizes, types and conditions creates very little overlap in observations. Significant inconsistencies in the evaluations and reporting of project results, costs and general information also make it difficult to compare the projects. Additionally, the tendency to report successful projects, or the best results of a project, creates uncertainty in how representative reported values are.

A final consideration of the published projects is the interests of the authors. Some authors are consultants who support control solutions and provide related services. In other cases, authors work for institutions with the express aim of promoting control solutions. This is not to discredit the results, but to bear in mind the potential for bias.

4.5 Implications of the project review for the framework

Despite the limitations of the project review, there are some implications that can be drawn for the framework.

1. Regulation as the chief driver of control improvement means that:
    a. The performance level (or benefits) of all alternatives for a given project are the same, since it is set by the regulation.
    b. Some action must be taken, "do-nothing" is not a viable option.
    c. Optimizing the system is not as important as meeting the regulatory requirements as cheaply as possible. This means that minimizing cost is a key criteria for alternative selection and that there is no incentive for measuring benefits to water quality and the environment if they are not required.
2. Since projects differ in so many ways (scale, existing infrastructure, catchments, etc.) and reporting of results and costs is currently inconsistent, it is unlikely that rule-of-thumb values will emerge as reliable estimates for project performance or costs. It is therefore necessary to prepare at least some form of evaluation for all potential projects.
3. Standardizing the evaluation and reporting of control improvement projects is important to ensure accurate assessments and to facilitate better understanding for potential future control projects.
4. To make explicit the investment and performance gains from improved control:
    a. The control aspect of projects must be distinguished from the infrastructure expansion or initial optimization components.
    b. The bias in reported costs and results, due to different starting points and control potential should be minimized.
5. The upfront costs needed to assess the feasibility of control alternatives are problematic because:
    a. The investments are required before it is clear if control is a promising option.
    b. There is more investment needed to assess the feasibility of control projects than infrastructure solutions.
    c. The difference in timing of investments, makes control projects difficult to compare to infrastructure alternatives in economic evaluations, since control options have higher sunk costs from the feasibility phase and lower costs for detail design and implementation.
6. Rationalizing the upfront costs for assessing the feasibility of control alternatives is important to incorporate in the evaluation, to ensure that control options can be compared to infrastructure alternatives and decision-makers are not put off by investments they perceive to be uncertain or risky.

5 A framework for making economic evaluations of control improvement projects in urban drainage systems

Using the combined findings of the literature and project reviews, several conclusions were drawn for the development of the framework. These conclusions are described below.

1. Least cost analysis is the best approach for evaluating (most) control improvement projects.

LCA is the preferred method for evaluating control improvement projects because:

1. LCA is a special case of CBA. In Chapter 3 it was argued that there is no known method better for making economic project evaluations than CBA.
2. LCA does not require economic valuation of benefits. In Chapter 3 it was determined that important benefits of control improvement projects are related to water quality and environmental health, for which there is no practical or reliable technique for making economic valuations.
3. Most control improvement projects are well suited to evaluation by LCA. In Chapter 4 it was determined that most cases are motivated by regulation, which means they share four key features:
   a. Something must be done; “do nothing” is not an option.
   b. The regulations set performance standards that all viable project alternatives must meet; from the perspective of the decision-makers this makes the benefits of every alternative effectively equal.
   c. In most projects, minimizing the costs to meet the regulatory standards is an important criterion for alternative selection.
   d. Since measurement of performance (either in CSOs or water quality) is not required by most regulations, there is no incentive to measure the metrics from which benefits can be valued.

2. The framework should create better understanding of the investments and performance gains attributable to improved control.

This conclusion is based on the Chapter 4 findings that:

1. In most cases, control improvement is part of a wider project that includes three components: optimization of the existing system, control improvement and infrastructure expansion.
2. The costs and performance gains for these components are measured and reported holistically, making the contribution of control unclear.
3. The different starting points and control potential of projects creates bias in the reported costs and results.

3. The framework should rationalize the upfront costs associated with the feasibility assessments of control improvement projects.

This conclusion is based on the Chapter 4 findings that evaluating the feasibility of control improvement projects requires greater upfront investment than traditional infrastructure solutions. This is relevant, because:

1. The investments to assess the feasibility of control alternatives are needed before it is clear if control is a viable or preferred option. Feasibility for infrastructure projects can be determined with less investment and are more certain to be viable options. The perceived risks of the upfront costs for control can be off-putting to decision-makers.
2. The upfront investments to assess the feasibility of control alternatives are sunk costs by the time an economic evaluation is made of project alternatives. This difference in the timing of investments for control and infrastructure alternatives is not captured in the economic evaluation.
3. There may be valuable project benefits from the feasibility investigations of control, regardless of whether control improvement is ultimately selected as the preferred alternative.

The framework for making economic evaluations of control improvement projects was created to inform decision makers by addressing these conclusions in a way that is both pragmatic and based in best economic practices. In the following sections of this chapter, the framework is presented and explained. In Section 5.1 the framework is introduced. In Section 5.2 the framework is put in context of the greater project evaluation process. Section 5.3 provides details on the first step of the framework. Section 5.4 discusses the feasibility investigations for control improvement alternatives. Section 5.5 details the second step of the framework. Finally, in Section 5.6, some general remarks are made for using and adapting the framework.

5.1 Introduction to the framework

The framework has two noteworthy features, based on the conclusions discussed above.

1. The framework uses a two-step evaluation.

In the first step, a preliminary assessment is made to decide whether to include control improvement as a project alternative. The purpose of the first step is to help decision makers rationalize the upfront investment to investigate control by:

- Determining if there is sufficient control potential.
- Quantifying the marginal costs of including control alternatives.
- Identifying potential benefits that may be gained from the feasibility investigations, regardless of whether control is a selection alternative.
- Identifying any institutional problems with implementing a control solution, before the investment is made.

In the second step, a LCA of project alternatives is made to select the preferred solution. The purpose of the second step is to decide on a project to take to detail design.

2. The framework takes a categorized and marginal approach to evaluating control alternatives.

Three categories are identified within each control improvement project. These categories are used to measure and report project costs and performance gains. The categories are:

- System optimization, which refers to the costs and results associated with bringing the existing system to its best state.
- Control improvement, which refers to the costs and results associated with the control elements of the project.
- Infrastructure expansion, which refers to the costs and results associated with new infrastructure aspects of the project.

The purpose of the categories is to make explicit the investments and performance results attributable to control.

Benchmark levels of control are used to measure and report the marginal performance gains achieved for incremental improvements in control. The benchmark levels are [7]:

1. Local manual static or reactive (LM)
2. Local automatic reactive (LAR)
3. Central supervisory reactive (CSR)
4. Central automatic reactive (CAR)
5. Central automatic predictive (CAP)
6. Integrated automatic predictive (IAP)

The purpose of the marginal approach is to reduce the bias in the reported costs and performance results from different starting points. Additionally, the marginal approach can help to identify points of diminishing return on investment in control.

The information from the categorized and marginal approach is particularly helpful for increasing understanding of control improvement projects and for cases where future expansion or additional control projects are likely.

The framework is schematized in Figure 5. Step 1 is detailed in Section 5.3 and Step 2 in Section 5.5.

[7] See Chapter 2 for descriptions and definitions of these control levels.

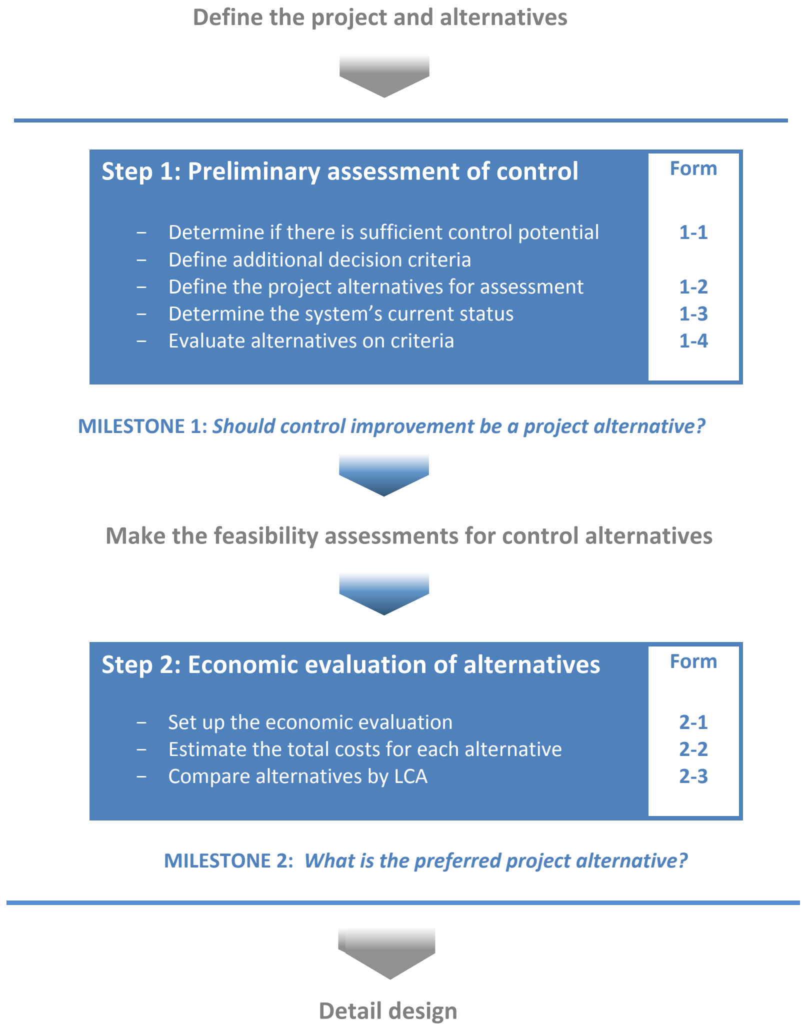

Figure 5 The framework for making economic evaluations of control improvement projects in urban drainage systems. Blue elements indicate the framework, grey elements show aspects of context.

In order to maintain the readability of the framework, the steps are described below, in general terms. A series of forms, however, is included in Appendix A to supplement the framework. The purpose of the forms is to provide additional detail on the steps and to concentrate the information needed for each task in an organized way.

5.2 Context of the framework

The economic evaluation presented in this framework is part of a larger problem analysis. Figure 6 schematizes the context of the framework within the larger process. Blue elements represent the framework, grey elements represent the greater problem analysis.

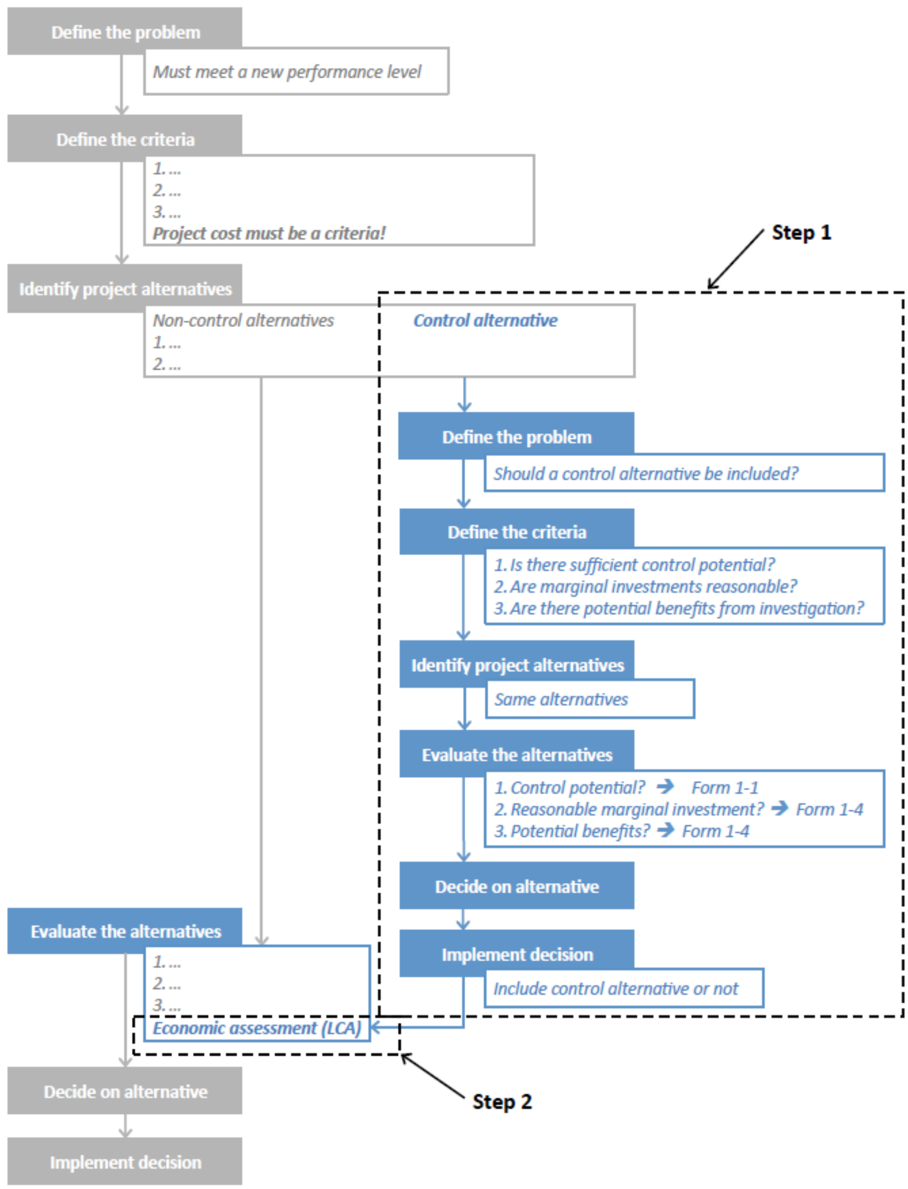

Figure 6 Framework (blue) in the context of a problem analysis process (grey)

5.3 Step 1: Preliminary assessment of control

The purpose of this step is to determine whether or not to include a control option in the project alternatives. To this end, the control potential will be tested, additional decision criteria will be established, the current system status will be determined and the project alternatives will be evaluated on the criteria.

5.3.1 Step 1.1 Determine control potential

The first task is to determine if there is any potential for control in the existing system. In order to minimize the upfront effort and costs of this evaluation, the DWA created the PASST (Planning Aid for Sewer System Real-Time Control) scorecard, which offers a quick pre-assessment of control potential, based on easily available system information. This tool has been used successfully in practice (Stinson 2005) (Dirckx, Schütze, et al. 2011); however, there are alternatives, such as SYNOPSIS, developed by Zacharof, et al. (2004).

Form 1-1 in Appendix A provides the PASST scorecard for completing Step 1.1. The acceptable minimum level of control potential must be decided by case.

5.3.2 Step 1.2 Define the decision criteria

Sufficient control potential will always be a criterion for including a control alternative. If there are additional criteria for making this decision, they should be defined, so they can be evaluated. Potential criteria are:

- If marginal investments for including the control alternative are reasonable. What is "reasonable" must be defined by case.
- If there are sufficient potential benefits from the investigation phase to limit the risks of upfront investments. What is "sufficient" must be defined by case.
- If there are technical or financial partners available.

5.3.3 Step 1.3 Define the project alternatives

Each project alternative should be described as completely as possible, distinguishing its optimization, control and infrastructure aspects.

For using the framework, the current and proposed control levels of each alternative should reference the following benchmarks:

1. Local manual static or reactive (LM)
2. Local automatic reactive (LAR)
3. Central supervisory reactive (CSR)
4. Central automatic reactive (CAR)
5. Central automatic predictive (CAP)
6. Integrated automatic predictive (IAP)

These control levels assume an optimized system. This will often not be the case for the existing operations, in which case some initial effort and investment may be needed to reach the optimized condition. This optimization should be included in the project description. One way to distinguish optimization from the other project components is to make it one of the alternatives to be evaluated. This will make identifying the marginal differences between optimization and control improvements easier.

Form 1-2 in Appendix A can be used to define each alternative.

5.3.4 Step 1.4 Determine the system status

Determining the existing system status will give an idea of what is needed to evaluate the feasibility of each project alternative.

Technical aspects

Technical information is necessary for assessing the feasibility of control improvement projects. The first task is to determine what presently exists; the second is to determine what is needed to evaluate each alternative. From this information the marginal investments for investigations and can be estimated. This must be done with regards to:

- Technical system information
- Data needed for various analyses
- The models needed for simulations

The needs for the optimization, control and infrastructure aspects of each alternative should be identified separately.

Institutional aspects
For assessing the feasibility of control alternatives, there may be intuitional aspects to consider, depending on the decision criteria. Some potential issues for control improvement projects are:

- Special efforts to secure permits
- Organizational changes
- Personnel trainings, meetings or changes
- Operational changes

Identifying potential institutional challenges or benefits may influence the decision of whether to include a control improvement alternative.

Form 1-3 in Appendix A can be used as a guide to help determine the system status and the needs for evaluating the feasibility of each alternative.

5.3.5 Step 1.5 Evaluate the alternatives on decision criteria

Control potential was established in Step1.1. If additional decision criteria were defined in Step 1.2, the alternatives should also be evaluated on them.

Using the proposed criteria in Step 1.2, the final tasks of Step 1 are:

1. To estimate the marginal costs of making the feasibility assessment of a control improvement project.
2. To identify the potential benefits of making the feasibility assessment of a control improvement project, including identifying partners.

The purpose of these tasks is to inform the decision of whether to make the upfront investments necessary to include control alternatives. The level of detail and accuracy needed for the estimations must be determined on a case-by-case basis.

Determine the feasibility investigation costs
Based on the status of the existing system and what is needed to analyse each alternative (Form 1-3), the marginal investments for investigations can be estimated. At this stage, the costs considered are only those needed for investigating each alternative, not for implementing them. Hence, operation and

maintenance costs are not necessary. Similarly, costs need not be discounted, as investigation will likely take place within one to two years.

The costs for investigating optimization, control and capital improvement aspects of each alternative should be estimated and reported separately.

Identify potential benefits of the feasibility investigations

Identifying benefits that may result from investigating control improvement, regardless of whether it is ultimately selected as the preferred alternative can help justify the upfront costs. Potential benefits to consider are:

- Investigations can uncover excess sewer and WWTP flows from infiltration and illicit connections. Reducing such flows can have significant cost savings from decreased pumping and treatment.
- Investigations can improve operational efficiency of the sewer and WWTP, rationalize maintenance and identify problem spots in the system.
- The information and knowledge gained from investigations can reduce the project costs for all alternatives through better-informed design.

These benefits are not all easy to quantify. However, in many cases the operational staff and managers will have an idea that there is unaccounted for flow, that operations are not optimized, or that system information is not complete and current. For the preliminary assessment phase, a good starting point is to hold meetings between management and the operations staff for the sewer and WWTP. Such meetings can be a quick way of identifying differences between what operators observe in the field and what managers assume or expect. Such differences show potential areas that can benefit from investigation.

Finally, though it is not a strict benefit of investigating control improvement projects, it is worthwhile to identify any opportunities for grants, special funding or partnerships that may moderate or share some of the financial load or risk of investigating and/or implementing a control improvement project.

Any additional project criteria should be assessed and included in the consideration of incorporating a control alternative.

Form 1-4 in Appendix A can be used as a guide to help estimate the marginal investments for investigating project alternatives.

The decision of whether to include control improvement alternatives must be made on a case-by-case basis. If the findings of Step 1 suggest that a control improvement project is worth pursuing, the necessary feasibility investigations must be made before continuing to Step 2. If not, review alternative solutions.

5.4 Investigate the feasibility of control improvement alternatives

In Step 1, the basic tasks needed to assess the feasibility of control alternatives were identified in Form 1-3, so that the cost of making the investigations could be estimated. While the feasibility assessments are not part of the framework, they are necessary before Step 2 can be completed.

It is beyond the scope of this thesis to detail how feasibility investigations should be carried out. The DWA (2005) offers guidelines for this process. However, for the purposes of implementing Step 2 of the framework, the outcome of the feasibility investigations should make it possible for control alternatives to be well enough defined to estimate their potential performance and costs. This is needed so that control solutions can be compared to other project alternatives.

Feasibility tasks, such as measurement campaigns, data processing, model preparation, simulations and analyses must be planned and carried out. In cases where models and sufficient data already exist, this process may be quite rapid. In other cases, however, the time required for these assessments should not be underestimated. If measurement equipment is not already in place and data series must be collected to determine the baseline conditions, this can take at least one year (Wiese, Simon and Schmitt 2005) (M. Pleau 2013) (Kuno and Suzuki 2006). Foregoing the initial measurement phase can result in a final project that does not perform as expected, or one that is difficult to determine the success of (Mol, van Dongen and van Velzen 2012).

During the feasibility investigations, the investments and results attributable to optimization, control and infrastructure improvement aspects of each alternative should be kept separate. Additionally, the level of control or its scope should be increased incrementally, recording the marginal difference in cost and performance for each step.

5.5 Step 2: Make economic evaluation of project alternatives

The second step of the framework is to test the economic efficiency of the project alternatives using a LCA. With some modification, the tasks for this assessment are based on those described for CBA, in Chapter 3.

For the purposes of this framework, the benefits of all alternatives are considered to be equal and only the costs need to be estimated. Secondary or additional benefits that arise from the different alternatives may be dealt with in project evaluations based on other project selection criteria. These evaluations are outside the scope of this framework. See Figure 5 for the context of Step 2.

5.5.1 Step 2.1 Set up the economic evaluation

Define the analysis

The first task is to clearly define the objective and type of analysis. In most cases case, the objective will be to compare multiple alternative projects. The objective may also define the level of effort and expertise required for the analysis, helping to ensure the correct allotment of budget, personnel and scheduling is provided.

Define the point-of-view and audience

Different parties experience different costs (and benefits) of a project. Defining the entity the analysis is prepared for creates a virtual boundary that helps to clarify costs that should or should not be included.

Define the parameters of the analysis

The following parameters should be specified for the analysis:

- Discount rate
- Numéraire
- Project life and duration of analysis
- Adjustments (shadow price categories and factors, omission of transfer payments, etc.)
- Method of presenting of results
- Format or method of expressing intangible or unquantifiable items

In most cases, the discount rate, numéraire, duration of analysis and adjustments will be set by an administrative or regulatory body. Domestic pricing is usually the numéraire and adjustments are often not included. Merrett (1997), Snell (1997) and Griffen (2006) can offer guidance on determining values for analysis parameters. The method for presenting results, according to this framework, will most often be the total discounted economic cost of each alternative.

If desired, additional project factors, intangibles and unquantifiable items can be listed with the cost for each alternative so they can be considered together. This can be developed into a table, depending on the project and decision makers.

Form 2-2 in Appendix A can be used as a guide to help set up the project analysis.

5.5.2 Step 2.2 Estimate the total project costs for each alternative

Determine the incremental project costs

For each alternative, estimate the initial, recurrent and replacement costs needed for the detail design, implementation and future operation and maintenance of the project. List these costs incrementally, as expenditures per year. Make explicit the values for optimization, control and capital improvement components. The costs spent on evaluating the feasibility of control alternatives should not be included, as they have been spent at this point and are sunk costs.

In order to implement different alternatives, there may be differences in the required institutional or organizational activities. The associated costs should be included for each alternative. This can be achieved, in most cases, by quantifying activities in personnel hours and additional equipment or facilities costs required for:

- Special permitting or regulatory efforts needed
- Inter- and intra-organizational changes needed
- The personnel trainings, meetings or changes needed
- Operational changes needed

Costs should be based on best estimates, accompanied by references or explanation. Extra allowances to ensure against under-estimation or price contingencies should not be included. An estimate to cover minor cost items that are not yet detailed can be included as part of a best estimate. Any unquantifiable cost should be listed as such. If shadow pricing is used, SPF values should be listed in a separate column, with a final column listing economic values (SPF times the financial prices). This provides transparency and an easy way to remove or change an adjustment. The rationale behind SPF values should be provided.

Form 2-2 and its supplement in Appendix A can be used as a guide to help identify costs by alternative.

Identify marginal project benefits

A LCA approach does not require the valuation of benefits, since, in theory, they should be the same for all alternatives. While the primary benefits may be comparable for each alternative, there will likely be secondary benefits that are not. Primary benefits refer to those results that meet the primary project objectives and criteria, such as reduction rates of CSOs. Secondary benefits are either ‘bonus’ outcomes or those that meet secondary project objectives and criteria. It can be helpful to list the benefits, even though they will not be valued. This can be used to confirm that the benefits of all alternatives are similar enough to make LCA a valid method. The benefits may also be relevant to a wider project evaluation (See Figure 6 for the context of economic assessments within a full project analysis).

Although the performance gains should be the same for all alternatives, the portions attributable to optimization, control and infrastructure should be made explicit. When secondary benefits are listed, they should also be attributed to optimization, control and capital improvement aspects of the project.

In an effort to facilitate the consideration of potential benefits, a list of benefit categories is provided in Appendix A, with the corresponding appropriate valuation techniques.

5.5.3 Step 2.3 Make the economic evaluation by LCA

Perform the economic analysis

Discount the annualized economic costs and sum them to find the total economic project cost for each alternative. The discount rate, numéraire and pricing used should be noted with the analysis.

The total discounted economic cost for the optimization, control and capital improvement aspects of the project should be distinguished.

Form 2-3 in Appendix A offers a template for a LCA spread sheet.

Carry out sensitivity tests

It may be useful to carry out sensitivity tests on various inputs, especially those recognized as uncertain. If these tests identify an input or parameter as especially influential to the results additional effort may be required to improve the estimate.

Report analysis results

The results of the LCA will be the total discounted project cost of each alternative. The costs and performance results attributable to the optimization, control and infrastructure aspects of the alternatives should be reported explicitly, to show the relative return on investment. If benefits or intangibles are accounted for in any way, they should be noted with the cost information for each alternative.

The importance of the presentation of results should not be underestimated. In many cases, this presentation is the only part of the analysis decision-makers will see. The results should be clear and concise, but must also include important implications, assumptions, exceptions and limitations. In many cases, it will be helpful to use some form of table to summarize and combine the results of the analyses for the different alternatives.

The report should:

- Define the project alternatives
- State the purpose of the analysis
- Make clear the assumptions and criteria
- Make clear the starting conditions and sunk costs
- Identify the optimization, control and capital costs and performance gains
- Provide enough detail for the analysis to be checked
- Show results and sensitivity tests
- Identify benefits, unquantifiable and intangible items, if relevant
- Comment on the analysis and results, without pre-judging the decision

Once a preferred alternative is selected, the next step is detail design. The DWA (2005) offers guidelines for designing and implementing control improvement projects.

5.6 Considerations for using the framework

There are a few considerations for using the framework that warrant mention.

Distinguishing the costs and performance results for the optimization, control and infrastructure components of control alternatives enables understanding of the returns – in terms of performance – for the respective investment. In practice, however, it is faster and easier to holistically measure and report the costs and results for each alternative. This “lumped” style of project assessment was observed in the projects reviewed in Chapter 4. Although the framework promotes a categorized approach, it can easily be modified for the lumped values. In this case, the total project cost and total performance gains are used in place of those for optimization, control and infrastructure.

In case a full CBA is preferred, Chapter 3 provides information and suggested literature on how benefits can be valued and the analysis made. While the framework is tailored to LCA, it can be easily modified to include a benefit stream.

The project objectives and criteria should be defined before the economic evaluation starts (See Figure 6 for the context of the framework). To ensure these are consistent with the needs of the framework, however, the design criteria should clearly and quantitatively define:

1. The design events, data series and scenarios for analysing project alternatives
2. The performance metrics, values and means of measuring them

In many cases the design criteria will be pre-defined by administrative bodies or regulations. These criteria often try to standardize performance, instead of reflecting the best management for each case. In general, long-term rainfall series should be used for simulations and water quality metrics are the best measure of performance for pollution prevention (Dirckx, Thoeye, et al. 2011). The DWA (2005) offers detailed recommendations for establishing design criteria.

6 Conclusions and Recommendations

In this chapter conclusions are drawn for the research questions posed in Chapter 1. Based on the findings of this thesis, recommendations are given for evaluating control improvement projects in urban drainage systems and for future research. The conclusions are presented in Section 6.1, the recommendations in Section 6.2.

6.1 Conclusions

A framework has been developed for making economic evaluations of control improvement projects in urban drainage systems. The framework uses a modified cost benefit analysis approach to combine best economic practices with pragmatic limitations on benefit valuation. The framework aims to standardize evaluations to ensure that projects are assessed correctly and produce useful information for further understanding. Foremost, the framework is a practical way of providing relevant information to advise decision-makers on investments in control improvement projects.

6.1.1 Conclusions on evaluation method

A literature review was made for project evaluation methods, economic valuation techniques for water resources and practical applications of control improvement projects in urban drainage systems. It was determined that LCA – a special case of CBA, in which benefits are not valued because they are the same for every alternative – is the best method for making economic evaluations of control improvement projects. This conclusion is based on the key findings that:

1. Presently, there is no better way to make economic assessments of water resources projects than CBA (of which LCA is a special case).
2. There is no practical and reliable way of valuing, in economic terms, the water quality and pollution abatement benefits from control improvement projects.
3. In practice, control improvement is used in projects motivated by the need to meet regulatory standards, which makes the performance goals (benefits) of all alternatives effectively equal.

Expressing the costs and benefits of control improvement as functions of overflow volume is not practical. There are too many inconsistencies in the way costs are reported to establish reliable rules-of-thumb. Since benefits are not measured and there is no practical way to value them, there is also no advantage in writing benefits as a function of overflow volume.

6.1.2 Conclusions on evaluations in practice

A literature review was made of documented control improvement projects in Europe, North America and Japan. Eleven projects with sufficient available information were studied to gain insight into how projects are being evaluated and implemented. Additional interviews and email correspondence with authors and project managers were used to augment the published information. The findings of the project review show that there are currently three traits common in evaluations of control improvement projects:

1. Control improvement projects are evaluated by comparing their costs to the costs of infrastructure alternatives with similar performance results; economic benefits from pollution prevention are never estimated.
2. Most control improvement is part of a wider project that involves aspects of optimization, control and infrastructure expansion. The costs and performance results for projects are reported holistically, without making explicit the contribution of control.
3. Different projects have different starting points and control potential, but these are not made clear in the evaluations.

The latter two points make evaluation results inconsistent, ambiguous and misleading. The current way of evaluating control improvement projects are attributed to two key factors:

1. A lack of standard for making economic assessment, which leads to common errors in the approach to evaluations and the reporting of results.
2. Regulation as the main driver of control improvement, which promotes a holistic approach to projects, based on the need to reduce CSOs to meet a set requirement. Project managers are not motivated to measure benefits or determine the explicit contributions of control.

6.1.3 Conclusions on the framework

The framework was designed to standardize evaluations and rationalize the upfront costs of control improvement projects within the practical limitations of benefit valuation and project managers' incentive to make correct assessments. A modified CBA approach was used to achieve these goals. The modifications are:

1. The special case of LCA is used, since benefit valuation is impractical and is not necessary due to regulation being the driver of most control improvement projects.
2. The framework uses a two-step assessment in order to rationalize the upfront costs of investigating the feasibility of control improvement projects.
3. The framework uses a categorized and marginal approach to make explicit the performance gains and investment in control improvement.

The framework presented in this thesis offers a pragmatic standard for making economic evaluations of control improvement projects in urban drainage systems, in order to inform decision-makers on investment.

6.2 Recommendations

Based on the framework presented in this thesis, the following suggestions are made for correctly evaluating a control improvement project:

1. Establish robust baseline conditions through monitoring and modelling.
2. Optimize the existing system and determine the improvements in performance and the associated costs.
3. Use system models to simulate incremental improvements in control and infrastructure. For each step, determine the marginal gains in performance and estimate the associated investment costs.
4. If a control improvement project is implemented, continue monitoring the performance results accurately and frequently enough to determine the realized gains.
5. Perform ex-post assessments of the project to make explicit the costs and benefits attributable to control improvements.

6.2.1 Future research

- Case studies should be made to distinguish the costs and performance results for optimization, control and capital improvement aspects of projects, in order to identify trends in the relative value of control. The framework can be used for this research.
- Studies on the marginal costs and performance gains for incremental improvements in control could help identify points of diminishing returns on investment. The framework can be used for these studies.
- Ecological studies should be made on the water quality and ecosystem impacts from CSOs. A better understanding of the influence of CSO occurrence, frequency and volume could be used to estimate economic values for overflows and to inform the performance metrics used in surface water regulations.
- Economic studies on the value of surface water pollution from overflows would provide interesting insight into the true benefits of improved control systems.

Appendix A

A Framework for evaluating control improvement projects in urban drainage systems

Form 1-1: Assess preliminary control potential (PASST scorecard)

	Criterion	Evaluation (score values in brackets)		
A. Catchment				
A.1	Catchment area (flow length in the main collector)	long > 5km (2)	medium (1)	short < 1km (0)
A.2	Differences between current and planned development area	large (2)	small (1)	none (0)
B. Wastewater production				
B.1	Areas with increased pollution of surface runoff	several (2)	1-2 (1)	none (0)
B.2	Variability in time and space of wastewater production (e.g. producers of heavily polluted wastewater, connections from separate systems)	high (2)	medium (1)	none (0)
C. Sewer system				
C.1	Number of existing control devices (e.g. pumps, sluices, weirs)	several (4)	1-2 (2)	none (0)
C.2	Slope of trunk sewers	flat <0.2% (4)	medium (2)	steep >0.5% (0)
C.3	Capable loops in sewer system	several (4)	1-2 (2)	none (0)
C.4	Number of existing storage tanks and pipes ($50m^3$)	>4 (4)	1-4 (2)	0 (0)
C.5	Number of discharge devices	>6 (4)	2-6 (2)	<2 (0)
C.6	Total storage volume (tanks and pipes)	$>5000m^3$ (4)	$2000\text{-}5000m^3$ (2)	$<2000m^3$ (0)
C.7	Specific storage volume (total storage volume related to impervious area)	$>40m^3/ha$ (4)	$20\text{-}40m^3/ha$ (2)	$<20m^3/ha$ (0)
C.8	Number of collectors to WWTP	>2 (3)	2 (1)	1 (0)
D. Operational system behaviour				
D.1	Local flood areas	several (2)	1-2 (1)	none (0)
D.2	Number of non-uniformly used tanks	>1 (4)	1 (2)	none (0)
D.3	Non-uniform discharge behaviour	significant (4)	medium (2)	insignificant (0)
E. Receiving water				
E.1	Local differences in hydraulic capacity	strong (4)	medium (2)	none (0)
E.2	Local differences of load capacity (e.g. swimming, aquaculture, protected areas)	significant (4)	medium (2)	insignificant (0)
E.3	Sensitivity of receiving waters	very sensitive (2)		less sensitive (0)
F. Wastewater treatment plant (WWTP)				
F.1	Admissible combined wastewater inflow	$>1.0f_{s,QM}\cdot Q_{s,aM}+Q_{F,aM}$ (3)	$>f_{s,QM}\cdot Q_{s,aM}+Q_{F,aM}$ (1)	$<f_{s,QM}\cdot Q_{s,aM}+Q_{F,aM}$ (0)
F.2	Sensitivity of WWTP to hydraulic or pollutant peaks	very sensitive (2)		less sensitive (0)

Scores: 0-24 Probably not suitable for improved control

25-35 Probably suitable for improved control

>35 Very suitable for improved control

A Framework for evaluating control improvement projects in urban drainage systems
Form 1-2: Define project alternatives (page 1 of 1)

This form should help define the project alternatives that are proposed for evaluation.

Project alternatives	Alternative description	Control level
Existing system	*Optimization:* *Control:* *Capital:*	
Base case[1] (Base)	Optimization: Control: Capital:	
Alternative 1 (A1)	Optimization: Control: Capital:	
Alternative 2 (A2)	Optimization: Control: Capital:	
Alternative 3 (A3)	Optimization: Control: Capital:	
Alternative 4 (A4)	Optimization: Control: Capital:	
Alternative 5 (A5)	Optimization: Control: Capital:	

[1] The base case may be the optimization-only place holder used for comparing control improvement alternatives

A Framework for evaluating control improvement projects in urban drainage systems

Form 1-3: Determine the system status (page 1 of 2)

This form should help identify the activities and tasks needed to make a feasibility analysis of project alternatives. By identifying what technical information and data are available or needed for each alternative, a clearer idea can be formed of what investment is required before including a control alternative.

Refer to the Control Matrix for guidance on what is required by different control levels

Differentiate between optimization, control and capital improvement aspects of the project unless the lumped approach is being used.

Technical system information and data	Have	Needed: Base	A1	A2	A3	A4	A5	*Comments, notes*
Sewer water levels	☐	☐	☐	☐	☐	☐	☐	
Surface water levels	☐	☐	☐	☐	☐	☐	☐	
CSO water quality	☐	☐	☐	☐	☐	☐	☐	
Surface water quality	☐	☐	☐	☐	☐	☐	☐	
Precipitation series/events	☐	☐	☐	☐	☐	☐	☐	
System storage, locations	☐	☐	☐	☐	☐	☐	☐	
Sewer flows and capacities	☐	☐	☐	☐	☐	☐	☐	
Surface water flows and capacities	☐	☐	☐	☐	☐	☐	☐	
WWTP flows and capacities	☐	☐	☐	☐	☐	☐	☐	
Pump capacities	☐	☐	☐	☐	☐	☐	☐	
Sewer dimensions	☐	☐	☐	☐	☐	☐	☐	
CSO events, volumes, durations[1]	☐	☐	☐	☐	☐	☐	☐	
System model	☐	☐	☐	☐	☐	☐	☐	

Institutional aspects	Have	Needed: Base	A1	A2	A3	A4	A5	*Comments, notes*
Special permits, licences:	☐	☐	☐	☐	☐	☐	☐	
Special proofs or analyses:	☐	☐	☐	☐	☐	☐	☐	
Monitoring plan for compliance:	☐	☐	☐	☐	☐	☐	☐	
Changes to risks of failure:	☐	☐	☐	☐	☐	☐	☐	
Qualified personnel:	☐	☐	☐	☐	☐	☐	☐	
Adjustments between agencies:	☐	☐	☐	☐	☐	☐	☐	
Adjustments within agencies:	☐	☐	☐	☐	☐	☐	☐	
Incorporate control into O&M plan:	☐	☐	☐	☐	☐	☐	☐	
Emergency or failure procedures:	☐	☐	☐	☐	☐	☐	☐	
Health and safety modifications:	☐	☐	☐	☐	☐	☐	☐	
Data management system:	☐	☐	☐	☐	☐	☐	☐	
Personnel involvement in control:	☐	☐	☐	☐	☐	☐	☐	

[1] Consider whether these exist/are needed by location and time, or average values

A Framework for evaluating control improvement projects in urban drainage systems

Form 1-3: Determine the system status (page 2 of 2)

Activities

What measurement campaigns and durations are needed, by alternative, for optimization, control and capital improvement?	
What preliminary modelling is needed, by alternative, for optimization, control and capital improvement?	
What personnel meetings are needed, by alternative, for optimization, control and capital improvement?	
Will special efforts be needed to secure permits, by alternative, for optimization, control and capital improvement?	
Will organizational or operational changes be needed, by alternative, for optimization, control and capital improvement?	

A Framework for evaluating control improvement projects in urban drainage systems
Form 1-4: Estimate marginal investment for investigating alternatives (page 1 of 1)

This form should help identify the costs for _investigating_ each alternative, not implementing them. No O&M or annualized costs are needed.

The activities and tasks on Form 1-3 can help to identify the labour and materials costs for each alternative.

Differentiate between optimization, control and capital improvement costs unless using the lumped approach.

Preliminary labour costs for investigating alternatives

Hours for:	Measurement campaigns	Data collection	Modelling	Personnel meetings	Institutional assessments	**Total hours**	**Labour costs**
Base							
A1							
A2							
A3							
A4							
A5							

Preliminary material costs for investigating alternatives

Costs for:	Measurement equipment	Data collection	Modelling hard and software	Other	**Material costs**
Base					
A1					
A2					
A3					
A4					
A5					

Identify potential benefits of investigation

Are there likely excess flows from infiltration and/or illicit connections?	
Could operations and maintenance be improved with more information?	
Could the overall project benefit from more information?	
Are there potential sources for funding or grants?	
Are there potential partners in academia, private or public sector?	
Are there permitting or regulatory flexibility for control?	

Estimate marginal investment for investigating alternatives

	Total costs	Potential benefits
Base		
A1		
A2		
A3		
A4		
A5		

A Framework for evaluating control improvement projects in urban drainage systems

Form 2-1: Set-up for economic analysis (page 1 of 1)

Analysis objective

	Ex-anti Investment	Ex-anti Optimization	Ex-post Evaluation
Compare alternative solutions, projects	☐		
Determine optimum control level, combination		☐	
Determine investment necessary	☐		
Determine optimal project timing[1]		☐	
Review project for upgrade, rehabilitation, decommission[1]	☐		
Gain insight for new project[1]			☐
Evaluate project success, failure[1]			☐
Other[1]	☐	☐	☐

Analysis Point-of-View

Group whom analysis serves: ____________________

Analysis type

Economic LCA ☐

Other: ____________________

Capital costs only ☐ Project life costs ☐

Analysis parameters

Discount rate: ____________________

Numéraire: ____________________

Shadow price factor/adjustment categories: ____________________

Shadow price factors/adjustments: ____________________

Expected project life: ____________________

Start year of analysis: ____________________

Final year of analysis: ____________________

Presentation of results:

Method for showing intangible, unquantifiable items: ____________________

Method for including suitability and effectiveness: ____________________

Presentation of analysis

Audience: ____________________

Method of presentation: ____________________

A Framework for evaluating control improvement projects in urban drainage systems

Form 2-2: Determining the marginal costs for project alternatives (page 1 of 1)

This form should help identify the costs associated with *implementing* each alternative.

The control matrix and the costs listed on the Form 2-2 supplement can help to identify the labour and materials costs for control alternatives.

Differentiate between optimization, control and capital improvement costs unless using the lumped approach.

Estimate labour costs by alternative

Hours for:	Planning/ Design	Implementation	Operation/ Maintenance	Organization/ Management	**Total hours**	**Labour costs**
Base						
A1						
A2						
A3						
A4						
A5						

Estimate material costs by alternative

Cost for:	Planning/ Design	Implementation	Operation/ Maintenance	Organization/ Management	**Total Material cost**
Base					
A1					
A2					
A3					
A4					
A5					

Estimate the total costs by alternative and project component

Total costs	Optimization	Control	Capital
Base			
A1			
A2			
A3			
A4			
A5			

A Framework for evaluating control improvement projects in urban drainage systems

Form 2-3: Perform economic least-cost analysis (page 1 of 1)

This form can be used as a guide for preparing the cost estimates for each alternative. Costs should be attributed to the optimization, control or capital improvement components of ea alternative, unless the lumped approach is used. The total discounted economic cost of each alternative is then compared to the others.

A list of potential costs is provided in the Form 2-2 Supplement

Costs for alternative [name]

[currency] *at* ***[year]*** *prices, Domestic numeraire*

	Financial Prices							**SPF**	**Economic Prices = SPF x Financial Prices**						
Initial	Year 1	Year 2	Year 3	Year 4	Year 5	....	Year N		Year 1	Year 2	Year 3	Year 4	Year 5	....	Year N
Initial Cost 1															
Initial Cost 2															
Initial Cost 3															
Initial Cost 4															
Recurrent															
Recurrent Cost 1															
Recurrent Cost 2															
Recurrent Cost 3															
Recurrent Cost 4															
Replacement															
Replacement Cost 1															
Replacement Cost 2															
Replacement Cost 3															
Replacement Cost 4															

Total economic costs								
Total discounted economic costs at [discount rate]% per year								

TOTAL DISCOUNTED ECONOMIC COST FOR ALTERNATIVE:

A Framework for evaluating control improvement projects in urban drainage systems
Form 2-2 Supplement: Potential cost for control improvement projects (page 1 of 1)

Costs	Initial	Recurrent	Replacement
Upfront - *Probably sunk costs by the time LCA is in progress, consider*			
Preliminary project evaluation - tasks completed before Step 2	*x*		
Planning and design			
Coordination of authorities, stakeholders, planners, engineers, operators	x		
Data verification and preparation	x		
Detail system design and operation plan	x		
Final model and control strategies	x		
Risk and failure analysis	x		
Implementation			
Measurement equipment (quality, discharge, level, etc)	x		x
Actuators (valves, weirs, pumps, gates, etc)	x		x
Controllers (feedback regulators, local, SCADA, etc)	x		x
Structural components (reservoirs, sewer, discharge facilities, etc)	x		x
Electrical system (switchboards, motors, transformers, fuses, housing etc)	x		x
Computers and computer equipment	x		x
Software	x		x
Communication infrastructure (remote data transmission system)	x		x
Spare parts (for monitors, actuators, controllers)	x		
Power supply	x		
Central operation building/refurbishment	x		x
Land acquisition	x		
Labor	x		
Materials	x		
Calibrate and validate models and control in system	x		
Personnel changes, training, qualifications	x		
Permitting and licensing	x		
Merging, separating, reorganizing administrative bodies	x		
Production of new O&M, procedure and training material	x		
Creation of data collection and storage procedure, system	x		
Operation and Maintenance			
Operation and maintenance labor		x	
Operation and maintence material		x	
Rent, facilities		x	
Ex-post assessments			x
System tests, adjustments, performance assessments		x	
Logging, archiving data and decisions		x	
Model and control calibration, validation, upgrades		x	x

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Potential benefits and valuation techniques

Benefits	PF	MP	NFI	RCM	COI	TCM	HPM	CVM	CM	AEM
Non-CSO related										
Energy savings - efficient WWTP operation		x								
Maintenance efficiency - rationalization		x								
Reduced storage needs - lower capital investment		x								
Information storage		x								
Improved WWTP process		x								
CSO related										
Direct-use										
Increased or improved recreation uses						x	x	x	x	
Increased or improved fishing, wildlife harvesting		x								
Improved or increased transporation, navigation		x								
Increased or improved tourism						x	x	x	x	
Increased or improved domestic water supply	x	x	x	x						
Increased or improved industrial water supply	x	x	x	x						
Improved, increased irrigation water supply	x	x	x	x						
Increased, improved energy resource		x								
Indirect use										
Improved flood and storm protection		x		x						
Improved pollution abatement				x	x					x
Improved nutrient retention				x						x
External ecosystem support	x			x						
Soil erosion and control	x			x						
Shoreline/bank stabilization				x						x
Reduction in global warming				x						
Micro-climate stabilization	x									
Non-use										
Option								x	x	
Bequest								x	x	
Existance								x	x	

Acronyms refer to Production Function (PF), Market Prices (MP), Net Factor Income (NFI), Replacement Cost (RCM), Cost of Illness (COI), Travel Cost Method (TCM), Hedonic Pricing Method (HPM), Contingent Valuation Method (CVM), and Choice Modelling Method (CM), Avoided Expenditure Method (AEM).

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Control matrix

In this table the relevant control levels are listed, with general indications of the needs for each, with relation to the others. Systems should be considered individually, thus this table is only a guide. The case of LMS can serve as the 'non-control solution' case for comparison. Each control level is based on the optimized case, therefore some effort may be necessary to reach this. The control levels use definitions of EPA (2006)

Legend:

- (blank) not applicable, no action/item
- 0 base level action/item
- \+ marginal increase in action/item

		Level of Control					
		LOCAL		REMOTE			
		Local manual* (LM)	Local automatic reactive (LAR)	Central supervisory reactive (CSR)	Central automatic reactive (CAR)	Central automatic predictive (CAP)	Integrated automatic predictive (IAP)
Planning and design							
Technical information & data needs	Sewer water levels	0	+	+ +	+ +	+ +	+ +
	Surface water levels	0	+	+	+	+	+ +
	CSO water quality[1]						+
	Surface water quality[1]						+
	Precipitation series/events[1]					+	+
	System storage, locations	0	0	+	+	+ +	+ +
	Sewer flows and capacities	0	+	+	+	+	+
	Surface water flows and capacities						+
	WWTP flows and capacities						+
	Pump capacities	0	+	+	+	+	+
	Sewer dimensions	0	+	+ +	+ +	+ +	+ +
	CSO events, volumes, durations	0	+	+	+	+ +	+ +
Activities	Planning, design	0	0	+	+	+ +	+ + +
	Measurement campaigns[2]	0	0	+	+	+ +	+ + +
	Personnel meetings	0	0	+	+	+	+ + +
	Preliminary modeling		+	+ +	+ +	+ + +	+ + +
Project implementation and operation							
Equipment & infrastructure	Water level, flow instruments		0	+ +	+ +	+ +	+ + +
	Precipitation instruments					+	+
	Water quality instruments[1]						+
	Power		+	+	+	+	+
	Redundant power, communication			+	+	+	+
	Central control center			+	+	+	+
	Hard infrastructure components[3]	+ + +	+ +	+	+	+	0
Control components	Programmable logic controllers		+	+	+	+	+
	SCADA/communication			+	+	+	+
	Central SCADA server			+	+	+	+
	Active operator input, monitoring	0	+	+ + +	+ +	+ +	+ +
	Central control server			+	+	+	+
	Central control algorithm			+	+	+	+
	Precipitation forecast model					+	+
	Rainfall-runoff model					+	+
	Online hydrodynamic model			+	+	+	+
	WWTP model[4]						+
	Surface water quality model[5]						+
Activities	Modeling, validation, calibration			+	+ +	+ +	+ + +
	System testing, adjustments	0	0	+	+ +	+ +	+ + +
	Emergency/failure plans	0	0	+	+	+ +	+ +
	Data recording, processing	0	0	+	+	+ +	+ + +
	Documentation of control decisions	0	0	+	+ +	+ +	+ + +
	General system O&M	+ +	+	+ +	+	+	0

* Can be local manual static and reactive control

[1] Often, water quality and precipitation measurements will be necessary for all project alternatives in order to meet regulatory or permitting requirements. This only shows which control alternatives specifically require it.

[2] This is a very general indicator, since the measurement campaigns necessary will depend on what information/data is already available and what is needed, as determined in the previous section.

[3] In most cases, control and hard infrastructure improvements will both be made. The ratio of control to hard infrastructure will vary, making the indications in the table general indications of the idea that with greater control less hard infrastructure is

[4] A WWTP model may not be necessary if the WWTP is integrated into the central control algorithm simply by the optimizing the inflow to the plant and/or accounting for changes to quality of the treated effluent that will be discharged to surface water

[5] A water quality may be integrated into the central control algorithm by accounting for changes to quality of the WWTP effluent discharged to surface water, as well as the CSO volumes, durations, quality and locations

Bibliography

Agudelo, J.I. *The Economic Valuation of Water - Principles and Methods.* Delft: UNESCO IHE, 2001.

Akesbi, Azzedine. “Policy Reform and Natural Resource Management - Valuation Methods.” Rabbat, Morocco: Centre de Orientation et de Planification de l'Education, 2006.

Bateman, I.J., M.A. Cole, S. Georgiou, and D.J. Hadley. “Comparing contingent valuation and contingent ranking: A case study considering the benefits of urban river water quality improvements.” *Journal of Environmental Management*, 2006: 221-231.

Birol, E., P. Koundouri, and Y. Kountouris. “Using Economic Valuation Techniques to Inform Water Resources Management in the Southern European, Mediterranean and Delveloping Countries.” In *Coping with Water Deficiency*, by Koundouri, 135-155. Springer, 2008.

Breinholt, A., P.A. Santacoloma, P.S. Mikkelsen, H. Madsen, M. Grum, and M.K. Nielsen. “Evaluation Framework for Control of Integrated Urban Drainage Systems.” *11th International Conference on Urban Drainage.* Edinburgh, Scotland, 2008.

Butler, D., and J. Davies. *Urban Drainage.* Third Edition. London: Spoon Press, 2011.

Cities, Blue Green. *Blue Green Cities.* 2013. www.bluegreencities.ac.uk (accessed 2013).

Colas, H. “Personal communication.” August 2013.

Colas, H., M. Pleau, J. Lamarre, G. Pelletier, and P. Lavallee. “Practical Perspective on Real-Time Control.” *Water Quality Resources Journal, Canada*, 2004: 466-478.

de Haan, A, and P. de Heer. *Solving Complex Problems: Decision-making support in highly complex situations.* The Hague, 2012.

Deltares. “Delft-FEWS Showcase.” *deltares.nl.* 2011. http://oss.deltares.nl/web/delft-fews/showcase-details?p_p_id=56_INSTANCE_xuN0&p_p_mode=view&templateId=SHOWCASE&_56_INSTANCE_xuN0_articleId=149338 (accessed June 2013).

Dharmaratna, D., and L. Gangadharan. *Project 7: Economic Valuation of Cities as Water Supply Catchments.* Center for Water Sensitive Cities, 2011.

Diamond, P.A., and J.A. Hausman. “Contingent Valuation: is some number better than no number?” *Journal of Economic Perspectives*, 1994: 45-64.

Dirckx, G., Ch. Thoeye, G. De Gueldre, and B. Van De Steene. “CSO management from an operator's perspective: a step-wise action plan.” *Water Science & Technology*, 2011: 1040-1052.

Dirckx, G., M. Schütze, S. Kroll, Ch. Thoeye, G. De Gueldre, and B. Van De Steene. “Cost-efficiency of RTC for CSO impact mitigation.” *Urban Water Journal*, 2011: 367-377.

—. “RTC versus static solutions to mitigate CSO's impact.” *12th International Conference on Urban Drainage.* Porto Alegre, Brazil, 2011.

Duchesne, S., A. Mailhot, and J. Villeneuve. "Global Predictive Real-Time Control of Sewers Allowing." *JOURNAL OF ENVIRONMENTAL ENGINEERING*, 2004: 526-534.

Duchesne, S., A. Mailhot, and J-P. Villenueve. "Global Predictive Real-Time Control Of Sewers Allowing Surcharged Flows." *Journal of Environmental Engineering*, 2004: 526-534.

DWA. *Advisory Leaflet DWA-M 180E Framework for Planning of Real Time Control of Sewer Networks.* Rules and Standards, German Association for Water, Wastewater and Waste, Hennef: DWA, 2005.

Engelhard, C., S. De Toffol, and W. Rauch. "Suitability of CSO performance indicators for compliance with ambient water quality standards." *Urban Water Journal* (Taylor & Francis) 5, no. 1 (June 2008): 43-49.

EPA, US. *Real Time Control of Urban Drainage Networks.* Washington DC: United States Environmental Protection Agency, 2006.

Fuchs, L., and T. Beeneken. "Development and Implementation of a Real-Time Control Strategy for the Sewer System of the City of Vienna." *Water Science & Technology* , 2005: 187-194.

Griffen, R. *Water Resources Economics: the analysis of scarcity, policies and projects.* Boston: MIT Press, 2006.

Henthorn, P. "Personal communication." *South Bend, Indiana Distributed Real-time Control Project.* 7 October 2013.

IAWPRC Task Group on Real Time Control. *Real-Time Control of Urban Drainage Systems. The State-of-the-art.* Edited by W. Schilling. Michigan: International Association on Water Pollution Research and Control IAWPRC, 1989.

Kallis, G., and D. Butler. "The EU Water Framework Directive: measures and implications." *Water Policy*, 2001: 125-142.

Kalman, O., and J. Lund. "Benefit–Cost Analysis of Stormwater Quality Improvements." *Environmental Management*, 2000: 615-628.

Kuno, K., and T. Suzuki. *Availability of CSO Control and Flood Control of Real-Time Control System in Urban Pumping Station.* Bureau of Sewearge Tokyo Metropolitan Government, 2006.

Ludwig, D. "Limitations of Economic Valuation of Ecosystems." *Ecosystems*, 2000: 30-35.

Maeda, M., H. Mizushima, and K. Ito. "Development of the real-time control (RTC) system for Tokyo sewage system." *Water Science & Technology*, 2005: 213-220.

Meguro, T., K. Tamura, M. Matsuura, and S. Tonari. "Study and assessment on real time control for the reduction of CSOs." *NOVATECH.* 2007. 801-808.

Merrett, S. *Introduction to the Economics of Water Resources: an international perspective.* London: UCL Press Limited, 1997.

Mol, B. "Personal communication." *ISA Hoeksche Waard Project.* July 2013.

Mol, B., P. van Dongen, and E. van Velzen. "Kosten-baten analyse ISA Hoesche Waard." Waterschap Hollandse Delta, 2012.

MSD, St. Louis. *Metropolitan St. Louis Sewer District.* 2009. http://www.stlmsd.com/home (accessed 2013).

Pleau, M. "Personal communication." August - September 2013.

Pleau, M., Colas, H., P. Lavalle´, G. Pelletier, and R. Boninb. "Global optimal real-time control of the Quebec urban drainage system ." *Environmental Modelling and Software* (Elsevier) 20 (2005): 401-413.

Rauch, W., and P. Harremoes. "Genetic Algorithms in Real Time Control Applied to Minimize Transient Pollution from Urban Wastewater Systems." *Water Resources*, 1999: 1265-1277.

Ruijgrok, E.C.M. *Valuation of Nature in Coastal Zones.* Utrecht, 1999.

Savenje, H.H.G. "Why water is not an ordinary economic good, or why the girl." *Physics and Chemistry of the Earth*, 2002.

Schütze, M., A Campisano, H Colasc, W Schilling, and P. Vanrolleghem. "Real time control of urban wastewater systems—where do we stand today?" *Journal of Hydrology* (Elsevier) 299 (2004): 335-348.

Schütze, M., A. Campisano, H. Colas, P. Vanrolleghem, and W. Schilling. "Real-Time Control of Urban Water Systems." *International Conference on Pumps, Electromechanical Devices and Systems Applied to Urban.* Valencia, Spain, 2003.

Schütze, M., and U. Haas. "Real time control of a drainage system, applying the new German RTC guidelines." *NOVATECH.* 2010.

Schütze, M., V. Erbe, U. Haas, M. Scheer, and M. Weyand. "Sewer system real-time control supported by the M180 guideline document." *Urban Water Journal* 5, no. 1 (March 2008): 67-76.

Snell, M. *Cost-Benefit Analysis for engineering and planners.* London: Thomas Telford Publications, 1997.

Stinson, M.K. *Benefits of Sewerage System Real-Time Control.* US EPA, 2005.

Turner, K., S. Georgiou, R. Clark, and R. Brouwer. *Economic valuation of water resources in agriculture.* FAO Water Report, Rome: Food and Agriculture Organization of the United Nations, 2004.

van der Eem, J.P., and T. Dijkstra. *Hoeksche Waard Regionaal Feitenonderzoek Eindrapportage.* Eindrapport, Gemeente Binnenmaas, 2012.

Van der Eem, J.P., and T. Dijkstra. *Hoeksche Waard Regionaal Feitenonderzoek Eindrapportage.* Waterschap Hollandse Delta, 2012.

van Heeringen, K-J. "Personal communication." *Deltares.* Delft, Aug-Sep 2013.

van Nooijen, R.R.P. "Personal communication." *Technical University Delft.* 2013.

van Nooijen, R.R.P., A.G. Kolechkina, K-J. van Heeringen, and E. van Velzen. "Implementation of central control for multiple sewer systems." *12th International Conference on Urban Drainage.* Porto Alegre, 2011.

van Nooijen, R.R.P., A.G. Kolechkina, P.E.R.M. van Leeuwen, and E. van Velzen. "Agile Design of Sewer System Control." *18th IFAC World Congress.* Milano: International Federation of Automatic Control, 2011. 14176-14182.

van Velzen, E. "Personal communication." *Waterschap Hollandse Delta .* Feb-Nov 2013.

Vanrolleghem, P.A., L. Benedetti, and J. Meirlaen. "Modelling and real-time control of the integrated." *Environmental Modelling and Software*, 2005: 427-442.

Viessman, W. *Water Supply and Pollution Control.* Pearson Prentice Hall, 2005.

Wei, Chih-Chiangi, and Nien-Sheng Hsu. "Optimal tree-based release rules for real-time flood control operations on a multi-purpose multi-reservoir system." *Journal of Hydrology* (Elsevier) 365 (2009): 213-224.

Wiese, J. "Personal communication." June 2013.

Wiese, J., J. Simon, and T.G. Schmitt. "Integrated real-time control for a sequencing batch reactor plant and a combined sewer system." *Water & Science Technology*, 2005: 179-186.

Winnipeg. "Wastewater Collection System Operation for Winnipeg." 2008. http://www.winnipeg.ca/waterandwaste/sewage (accessed 2013).

Zacharof, A.I., D. Butler, M. Schutze, and M.B. Beck. "Screening for real-time control potential of urban." *Journal of Hydrology*, 2004: 349-362.

Zacharof, A.I., D. Butler, M. Schutze, and M.B. Beck. "Screening for real-time control potential of urban wastewater systems." *Journal of Hydrology*, 2004: 349-362.

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