Optimal design of storm sewer networks: Past, Present and Future

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ABSTRACT
Optimal design of storm sewer networks aims to minimize construction costs whilst ensuring good system performance under specified design criteria. It has proved to be a complex NP (Non-deterministic Polynomial time) optimization problem, encompassing multimodal, discontinuous (or mixed discrete-continuous), non-convex features. This problem has been heavily studied since its concept was proposed in the late 1960s. However, there has been limited success in real-world practice due to the intrinsic complexity of the problem. This paper is aimed at providing a systematic and up-to-date review of achievements in this field and discussing problems and key issues today in the context of future research needs in sewer optimization.

KEYWORDS
Separate System; Storm Sewer; Network Design; Optimization

INTRODUCTION
Storm sewers play an important role in wet weather management. Without efficient drainage, storm water may cause urban flooding with severe consequential problems, such as public inconvenience, economic and environmental damage, infectious disease, and even threat to public safety. Therefore, it is vital to maintain reliable performance of storm sewer systems. However, in the face of tight budgets and more stringent regulation, sewer engineers are confronted with a significant challenge and urged to pursue cost-effective strategies for design, operation and management of storm sewers. This study focuses on the first of these issues: the design of storm sewer networks.

In conventional sewer design, the underlining principle is that all sewer conduits should be designed to deliver a free-surface flow, thus an un-pressurized or just full condition could be ensured. The relationship between pipe size and its capacity is approximated based on the hydraulic resistance equations, typically the Manning equation and Colebrook-White equation. Given a design flow (velocity or discharge) and pipe roughness, these equations can be used to determine the size of a sewer. To simplify calculations, a steady flow approximation is mostly used. In designing a network, each pipe is considered as a separate entity and in a sequence from upstream to downstream. Without any concept of optimization, the design is simply based on the idea of keeping pipe slopes as flat as possible, giving a unique but over-expensive solution.
Optimal storm sewer design aims to minimize the network construction cost whilst ensuring a good system performance. Depending on the problem formulation, the problem can be considered as a single-objective or multiple-objective optimization problem whilst satisfying a set of constraints. Its general formulation can be defined as follows:

\[
\vec{f}(\vec{x}) = \min \left[ f_1(\vec{x}), f_2(\vec{x}), \ldots, f_n(\vec{x}) \right]^	op \\
\text{Subject to} \quad g_i(\vec{x}) \geq 0 \quad \text{for} \quad i = 1, 2, \ldots, k \\
\quad h_j(\vec{x}) = 0 \quad \text{for} \quad j = 1, 2, \ldots, l
\]

Where: \( \vec{x} = [x_1, x_2, \ldots, x_n] \) decision variable vector, \( T \) problem dimension
\( g(\vec{x}) \) inequality constraints
\( h(\vec{x}) \) equality constraints

Often a multiple objective problem can be transformed into a single objective problem by setting up a linear combination of the objectives with different assigned weighting factors, or keeping one key objective and transforming others into design constraints. Complete enumeration of all possible solutions can truthfully find the globally optimal solution for the problem. However, due to the problem complexity in nature, an exhaustive search using complete enumeration is usually computationally unaffordable and inapplicable for continuous variables. Optimization techniques turn out to be essential in addressing the problem effectively and locating optimal solutions efficiently. During the design, the optimization technique is usually integrated with a sewer network hydraulic simulator, which evaluates the hydraulic performance of each potential solution. Compared to the traditional design method, optimal sewer design demonstrates several distinct advantages:

a. It renders a potentially valuable and practical solution for rigorously incorporating local economic considerations into the hydraulic design process (Dajani, et al. 1972).

b. It targets obtaining the cheapest design solution whilst providing more reliable serviceability. In this way, it can reduce the use of oversized pipes, which may lead to reduced flow velocities and increase the risk of sediment deposition and subsequent blockage in pipes (DoE/NWC, 1981).

c. It enables sewer engineers to investigate a great number of scenarios and deliver more design alternatives, implementing potential tradeoffs among various design objectives.

d. It significantly eases the whole design procedure by automatic computer-based design and releases designers from tedious manual calculations associated with the design.

e. It can work closely with sophisticated simulation models, providing the possibility of detailed investigation of the dynamic drainage process, and leading to optimization solutions that are more hydraulically correct and reliable.

**HISTORICAL REVIEW OF SEWER OPTIMIZATION**

The topic of optimal sewer design has been heavily studied. Its concept was first proposed in the mid 1960s (Deininger, 1966; Holland, 1966) when advances in the computer power shined light on engineering research. Comprehensive cost-effective designs incorporating early simulation models and optimization technologies became computationally tractable and flourished in 1970s and 1980s. Various early optimization techniques were developed, including Linear Programming (LP) (Deininger, 1966; Dajani and Hasit, 1974), Non-linear Programming (NLP) (Holland, 1966; Price, 1978), and Dynamic Programming (DP) (Mays and Yen, 1975; Walters and Templeman, 1979).
LP is a special form of mathematical programming. It can easily handle a large number of decision variables and implement the optimization in an efficient, reliable and deterministic manner. Nevertheless, the approach poses several strict requirements for its implementation: (i) its implementation basically requires all objective functions and constraints to be linear. However, highly dynamic hydraulic conditions are hardly possible to have a linear relationship with decision variables, such as pipe diameters and slopes; (ii) LP requires individual segments of the problem to operate as well independently as together. This inevitably requires each pipe to be designed separately, and implies that every pipe flow is independent of flows in adjacent pipes, which, even for a tree-like network, is only true under a steady state condition (Walters, 1992); (iii) All decision variables are treated as continuous variables. Its solutions often encompass continuous diameters, which have to be adjusted by rounding each continuous diameter up to its nearest commercial size.

NLP techniques can generally deal with non-linear objective functions and constraints, but entail much increased computational difficulty due to the discontinuous and non-differentiable objective function. Moreover, most of them could not deal with discrete diameters (Price, 1978; Gidley, 1986). Because of various difficulties encountered with their application, mathematical programming techniques, like LP and NLP, had limited success and soon fell out of favour with researchers when more advanced optimization techniques emerged.

DP and its modified version Discrete Differential Dynamic Programming (DDDP) (Mays and Wenzel, 1975) were popularly applied techniques, and DDDP is still well-liked in some current studies. DP became popular and favoured mainly because many sewer design requirements can be met by its key features:

a. DP needs the optimization problem to be represented in a sequential form and be divided into stages, this corresponding well to the design of tree-like drainage networks. Argaman, et al. (1973) proposed “Drainage Lines”, which pass through all manholes being the same number of pipes away from the system outfall, to divide a sewer network into multiple levels. The Drainage lines were later renamed as “Isonodal Lines” by Mays and Wenzel (1976).

b. At each stage, the implementation of DP is based on sets of states and decisions. An input state is transformed by a decision into an output state, incurring a cost (stage return). For each output state, the cumulatively optimal decision can be identified over the decision variables, and consequently incur an optimal cost up to this stage. The process of making stage decisions continues until all stages have been traversed, usually from upstream nodes to the system outfall, at which point, the overall optimal set of decisions can be traced back through the system.

c. DP is flexible with regard to the form of the objective function. It can deal with non-differentiable and discontinuous functions. Moreover design constraints generally do not pose a problem for its implementation (Gidley, 1986).

d. Dynamic programming tackles the decision in a discrete manner at each stage. It directly produces solutions with discrete diameters. Hence it is free of the problem experienced by mathematical programming that the final solution may not be optimal after the post-processing to round up continuous pipe sizes.

Since finer discretization of the state variables, such as manhole depth, induces greater computation, Mays and Yen (1975) developed Discrete Differential Dynamic Programming (DDDP) to address this problem. DDDP defined the discrete depth in a more useful way by
introducing a trial trajectory lying in the centre of the depth corridor. In an iterative process, 
the solution of the previous iteration is employed as the new trial trajectory, and the discrete 
depths at each manhole are re-defined correspondingly. This process is implemented until its 
solution and the trial trajectory coincide. Experiments indicated that DDDP can generally 
achieve better optimization performance and efficiency than the standard DP approach. 
Although DP has been widely applied and shows distinct improvement over mathematical 
programming, it also has its own drawbacks:

a. Both “Drainage Lines” and “Isonodal Lines” are numbered from the “root” of the 
sewer network, usually system outfalls. When multiple outfalls are present in the 
system, it will entail difficulties in separating the system and identifying sequential 
stages using these lines.

b. DP designs each sewer individually in conjunction with simplified hydraulic 
evaluations, typically using the resistance equation for steady flows. However these 
simplifications may introduce significant inaccuracy in estimating pipe flows, 
especially for those far downstream. Consequently, the solution obtained can be 
infeasible or sub-optimal.

c. With a multilevel structure, DP needs to consider the optimization as a sequential 
decision problem. However, the optimization proceeding from sewer to sewer in 
sequence is only valid when all pipes carry supercritical flows (Yen, 2001). For 
surcharging and backwater situations, which are common for storm sewer flows, 
downstream conditions can propagate upstream and affect flow conditions upstream. It 
implies that the system has to be considered as a whole in design. Therefore, for any 
flooding oriented design, DP would inevitably deal with the problem in a 
fundamentally invalid fashion.

d. Most DP models only use a single state variable, either invert or crown elevation. 
Consequently, the only influence that the preceding stages exert on the current stage is 
the entering invert (or crown) elevation (Gidley, 1986). This means that the diameter 
progression constraint cannot be enforced, which may lead to an infeasible solution 
overcame this problem by having a two-component state containing the pipe depth and 
size of the previous stage. However, this modification significantly increases the 
problem complexity and induces largely increased computation cost when the network 
is large.

e. Since only one decision is made at each stage, there is only a single objective value to 
be passed through the solution “tree”, generated throughout the optimization. For this 
reason, DP generally has difficulty to handle multiple-objective design problems. 
Furthermore, DP lacks an ability to deal with high dimensional problems. Typically 
when involving the network layout into design, it is intractable to formulate the 
problem into a multilevel structure.

For the above-mentioned reasons, LP, NLP and DP appear inappropriate for delivering 
sophisticated and comprehensive sewer design solutions. In the early practice using these 
techniques, the design problem was mostly handled as a pipe sizing and slope design problem 
for sewer networks with a fixed plan layout. Comparatively little research has been involved 
with designing network layout, namely number and location of manholes, because it 
significantly increases the complexity of the optimization task (Walters, 1992). In the late 
1980s, some design tools also came into view, varying from spreadsheet model (Brown and 
Koussis, 1987; Miles and Heaney, 1988) to more user-friendly computer programs (Yen, et 
al. 1984; Chau, 1992). Although computer models produced more accurate and favoured
solutions, restrained by technologies of the time in related disciplines, design practices generally entailed many modelling simplifications and limitations. Typically, maintaining system continuity and satisfying different design constraints pose considerable practical difficulties in design. Furthermore, solutions cannot be guaranteed to be the true optimum because some methods evaluate very few options and will stop the optimization once a feasible solution is found (Heaney, et al. 2002).

Over the last decade or so, due to increased consideration of water quality, sustainability and integrated management, the scope of sewer system design has been greatly expanded to involve a wider spectrum, e.g. environment, ecology, sustainability, control and maintenance. Benefiting from developments in Artificial Intelligence (AI) and Operation Research (OR), various innovative optimization techniques, especially metaheuristic algorithms, have emerged and been broadly applied to engineering optimization problems. Since Cembrowicz and Krauter (1987) made an attempt to use Evolutionary Computation (EC) for sewer optimization, Evolutionary Computation approaches, particularly genetic algorithms (GAs), have been the most popular and successful optimization techniques for this task (Cembrowicz and Krauter, 1987; Walters and Lohbeck, 1993; Heaney, et al. 1999; Afshar, et al. 2005).

Compared to the early optimization techniques, GAs encompass many important advantages:

a. They are independent of design objectives, and hence it is not necessary to manipulate objective functions. GAs can generally handle any kind of system without the need for special simplifications on system representation. The situations of backwater, surcharge flow, energy losses at junctions and system flooding can all be taken into account using standard simulation software. In this way, a precise and complete evaluation of system hydraulic performance becomes possible.

b. Since the sewer network is simulated and evaluated as a whole, flow continuity can be automatically maintained. Moreover, the intrinsic storage capacity of the system, provided by conduits and manholes, can be utilized for a design considering flooding. It has been found that with surcharging, the capacity of a system before surface flooding occurs can be increased beyond the design capacity, perhaps even doubled (Butler and Davies, 2000).

c. Mutual effects exist between sewers. A small change in a remote part of the sewer network may have significant affects downstream. In reverse, downstream hydraulic situations can propagate backwards especially under flooding or surcharging situations. Therefore the design should consider the system performance globally. This can be easily realized by GAs, but seldom possible for most conventional optimization methods.

d. GAs normally work in a quasi-exhaustive search manner. Hence there is a better chance that true optimal or near-optimal solutions may be found.

e. GAs can easily handle optimization problems with multiple objectives, which are usually intractable for conventional methods. Multi-objective optimization is necessary for sewer design due to the nature of design criteria, typically hydraulic performance and capital cost.

Despite of all above merits and numerous successes in real-world applications, GA is still not a perfect method which leaves nothing to be desired. The deficiencies of GAs are mainly from the following aspects:

a. As a stochastic algorithm initialized with randomly generated populations, a GA initialized with different random seeds may produce different solutions to the same
problem. This can easily induce confusion to sewer engineers and the public who generally lack a sound knowledge of stochastic modelling.

b. Compared to enumeration method, GAs are proved to be very efficient and robust in finding near optimal solutions. However, as in the natural evolution process, they require a large population of solutions over a large number of generations to achieve a sound level of good solutions. As a result, GAs always entail a high computational cost, which may be prohibitively time-consuming and consequently impractical.

c. GAs attempt to conduct the investigation on the collective performance of a design scenario rather than on any individual decision variable. Hence no heuristic tuning can be made for individuals, even for those seriously violating optimization objectives.

d. Several parameters related to configuration and execution of the algorithm, such as crossover probability, mutation rates and population size, have to be established during the optimization. Since no general rule is available to determine these parameters, a large number of trial-and-error pre-runs are required to find appropriate parameter values.

Other advanced approaches such as Ant Algorithms and Simulated Annealing emulate different natural mechanisms, but generally encompass similar features to those of GAs for sewer design. Some applications found that the optimization efficiency and effectiveness of these two methods would be greatly reduced when handling large networks (Afshar, 2006; Diogo and Graveto, 2006). Tabu Search (Liang, et al. 2004; Farmani, et al. 2006) and Cellular Automata (Guo, 2005; Guo, et al. 2007b) approaches are classified as localized searching algorithms, which are often superior in optimization efficiency, but have a strong tendency to be trapped in local minima. As a result, they generally lack the ability to ensure that the global optimum can be eventually obtained.

Hybrid methods, which combine the best features of more than one algorithm, have become increasingly attractive in research and application. Farmani, et al. (2006) and Guo, et al. (2007a) employed local search techniques to seed a multi-objective GA (NSGAII) in the design of sewer networks. All these hybrid approaches have demonstrated enhanced optimization performance, but with much reduced computation cost.

Although a large number of applications have been implemented by using various advanced techniques in the last two decades, research attention has mainly been paid to exploring new emerging optimization techniques to boost optimization performance. Only a few attempts have incorporated new developments in research of urban drainage theory and modelling. Although sophisticated simulation models, e.g. InfoWorks (Wallinford Software, 2001) and SWMM (Rossman, 2006), became common tools for wet weather flow management, highly simplified hydrological and hydraulic calculations are still generally adopted in sewer optimization practice. The problems concerned also appeared to be too trivial, such as designing a small network with a limited number of decision variables and a single objective. Based on the authors’ knowledge, optimal storm sewer design does not appear to have had a significant impact on design practice. There is a clear gap between the research and the real-world practice. The majority of sewer design applications are still based on traditional and scientifically inferior methods (Gidley, 1986; Bowen, et al. 1989). Experts in this field estimate that this situation may still persist over a prolonged period, and optimal design of sewer networks is likely to be a long-term objective due to the following possible reasons:

a. The key driving force for design optimization is to achieve cost savings. However, compared to conventional methods, many studies only reported marginal or modest
cost savings, mostly within the range of 5%-15%. Some researchers claimed that cost savings could be as high as 30% and even more significant when larger systems and a full scale of design were considered (Gupta, et al. 1983; Li and Matthew, 1990), but no systematic proofs have been provided so far. Moreover, some researchers only tackled problems for which an experienced and cost-conscious designer could relatively easily locate a nearly optimal design using traditional methods (Gidley, 1986). Thus its advantage in terms of cost saving has not been sufficiently attractive for sewer designers to abandon traditional approaches, which generally meet current needs.

b. Costing models employed in sewer optimization were often highly simplified, generalized or unrealistic, hence the costs produced by these models can notably differ from the actual tender costs. As a result, the solution obtained by design optimization may deliver unreliable cost information, and even not be optimal in reality. This will undoubtedly lead to a reduction in its creditability and clients’ confidence in its applications.

c. Storm water drainage is a common but important public service. Its failures, such as urban flooding, will always attract high public concern, and probably have a more noteworthy consequence from the social aspect than the monetary aspect. Therefore, for a political reason, regulators and asset owners incline to have a more politically-correct, conservative and cautiously-designed drainage system instead of simply pursuing the cheapest solution.

d. As an ongoing study, none of the optimization techniques applied for optimal sewer design is unfawled. The researchers themselves have not always made a strong case in favour of optimization (Gidley, 1986). One distinct problem is that many of these techniques entail an excessively high computation cost. A tradeoff is always necessary between affordable computational cost and acceptable solution optimality, especially for big or complex design problems. Many optimization techniques also have difficulty in manipulating design constraints, which normally do not pose an obstacle to conventional design methods. Moreover, in most cases, only near-optimal solutions can be guaranteed instead of obtaining true optimal or globally optimal designs.

e. High uncertainties generally exist in system loads, hydrological and hydraulic processes, and modelling. The virtues of precisely cost-effective designs, obtained by optimization under certain design criteria, are highly compromised by these uncertainties, especially for designs without consideration of reliability and risks.

f. With experience accumulated over years, sewer engineers may find the traditional design methods more intuitive, perceptive or convenient. With a more theoretical sense, the design procedure is fully heuristic and deterministic. It is also relatively easy to introduce modifications and special treatment on system segments where site specific factors are atypical, such as special soil or groundwater zones, and conflicts with other underground facilities. However sewer optimization often requires a re-run of the whole optimization procedure after any change in the original design.

g. Both sewer designers and owners normally lack a decent knowledge of optimization techniques, the majority of which have emerged in the last decade. Therefore, they may not have a straightforward sense of optimization, especially for the situation where different results are produced by stochastic techniques after different implementations. Indeed, it may be wise for them to be sceptical until more confidence has been built up upon practices (James and Robinson 1981). There is usually a significant time lag before new technologies gain wide acceptance (Burian, et al. 1999; Ashley, et al. 2006).
h. A number of computer based design tools have been developed, either for research purposes (Miles and Heaney, 1988; Chau, 1992) or as commercial packages, such as WinDes (Butler and Davies, 2000) and StormCAD (Hatchett, et al. 2002). These tools greatly relieve engineers from the tedious calculations, and enable the design process to be more interactive and intuitive via dynamic graphical displays and animations. However, they either follow the same principles as conventional design methods, or entail many modelling simplifications and limitations. Sophisticated design tools have not been readily available. Consequently, this may also lead to the slow and limited acceptance of optimal sewer design by sewer engineers.

Although the above technical weaknesses and practical difficulties have been experienced in design practice, they should not be considered as reasons to conduct a negative campaign against the journey taken in optimal sewer design. On the contrary, current problems are often drivers or triggers for further advances in research. In fact, great motivation and ambition to attain a more reliable, efficient, effective and easily-handled design technique or tool always exist to push forward this study.

**FUTURE DEVELOPMENT**

Based on the above discussion, complete and sophisticated sewer optimization appears to be unachievable at the current stage. The study of optimal sewer design is surely a long term exercise. However, diverse innovations continually rising in all associated fields certainly open new horizons to move forward this study. In this section, a number of prospects for future development in sewer optimization are discussed.

a. Improve the design efficiency: The high computational cost remains as the major obstacle in real-world applications of sewer optimization. Developing faster optimizers, particularly hybrid optimization approaches, appears to be the most promising path to achieve high optimization efficiency.

b. Implement integrated design: Beyond the complete network design over pipe size, slope and network layout, the scope of sewer design concerns has been extensively expanded beyond those of cost and flood protection, by involving environment, ecology, energy, sustainability, maintenance, control and management interests. However, this study is currently at its very early stage and certainly requires considerable further research.

c. Handle multiple design objectives: So far, sewer optimization has considered only one objective, construction cost, or, at most, two objectives: construction cost and flooding. Since wet weather flow management currently covers many disciplines, sewer optimization may further involve other interests, e.g. environment, energy and maintenance. Handling the problem as a multi-objective optimization appears to be necessary and has several distinct advantages: i) There is no need to introduce unrealistic weights in order to combine objectives; ii) It skips the problem of evaluating different objectives in the same monetary sense, some of which are often very difficult to be quantified; iii) it offers more design alternatives to decision makers.

d. Involve feasible design constraints: Past applications normally only considered constraints which can be tackled by optimization techniques. However, without the proper consideration of design constraints, solutions can be infeasible. So it is essential to involve all necessary constraints. Due to the varying importance of different constraints, constraint preference based design is desirable.
e. Enhance design quality: A precise and superior design is always pursued in order to ensure credibility of solutions. Concerns in pursuit of this target include more reliable data, more sophisticated models, long-term simulation and true globally optimal solutions.

f. Consider uncertainties and risks: Uncertainties in urban drainage process, data and modelling generally exist and are usually unavoidable. So these uncertainties should be systematically considered, and the performance reliability of designed systems needs to be assessed. Optimal risk-based design, integrating economics, uncertainty and risk concerns into an optimization framework, is the ultimate model for design that engineers need to strive for in the future (Mays, 2001).

g. Benchmark design problems: Benchmarking, by defining a set of representative design problems in terms of network characteristics, design criteria, cost model, design objectives, design constraints, simulation method and tool, will be greatly helpful to promote collaborative, competitive or comparative studies to overcome “paradigm blindness”, to open up new emerging methods and tools, and to identify the most effective design approaches.

h. Investigate impacts of cost models: Different cost models could have different degrees of smoothness, and consequently induce varying difficulty for the optimization problem. However, so far, only a few works have addressed this problem, which clearly deserves more investigations, such as sensitivity analysis over the format of cost functions and their parameters.

REFERENCES


