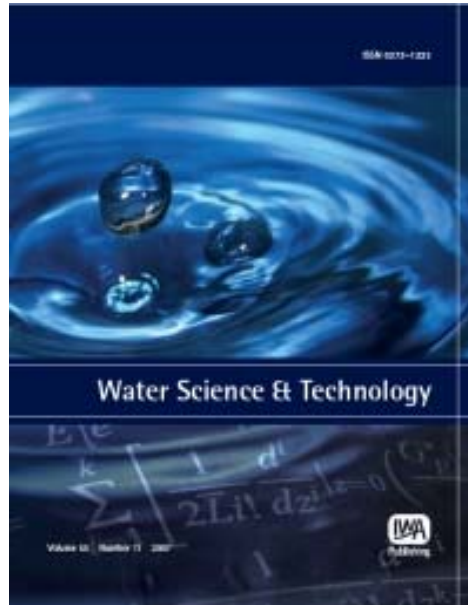


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# A multi-objective optimisation model for sewer rehabilitation considering critical risk of failure

Ben Ward and Dragan A. Savić

## ABSTRACT

A unique methodology for the optimal specification of sewer rehabilitation investment is presented in this paper. By accounting for the critical risk of asset failure, this methodology builds on previously successful work which explored the application of multi-objective optimisation tools to assist engineers with the specification of optimal rehabilitation strategies. The conventional sewerage rehabilitation specification process relies on the expertise of professional engineers to manually evaluate CCTV inspection information when determining the nature and extent of the rehabilitation solution. This process is not only tedious and subjective but it has no quantifiable means of identifying optimal solutions or possible combinations of optimal solutions in the delivery of catchment wide rehabilitation programmes. Therefore, the purely manual process of sewer rehabilitation design leaves a number of unanswered questions, such as: (1) Does the solution offer the greatest structural benefit to the network? (2) Is the solution the most cost-effective solution available? (3) Does the solution most greatly reduce the risk of critical asset failure? The application of a multi-objective genetic algorithm optimisation model, coupled with an enhanced critical risk methodology, has successfully answered these questions when applied to a case study data set provided by South West Water (UK).

**Key words** | asset management, critical risk, optimisation, planning, sewer, sewer rehabilitation

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## INTRODUCTION

Most sewerage networks are compiled of ageing assets that are becoming increasingly more susceptible to failure. Abraham & Gillani (1999) categorise sewer system failure into three distinct modes: hydraulic, environmental and structural. Structural failure can have varying degrees of severity, ranging from minor sewer fabric defects, such as cracking, to complete loss of structural integrity where a full or partial collapse may be observed. The failure rate, or collapse rate, within a network is one of the major indicators that a sewerage system is deteriorating. In the most recent Asset Management Plan (AMP) submissions, nearly all of the UK's 10 water and sewerage utility companies have demonstrated a commitment to improve their sewerage asset failure rate (Ofwat 2009). This is normally achieved through increased investment towards sewerage asset maintenance. To ensure that this increased level of investment returns the highest possible benefit, it will be crucial for comprehensive sewerage rehabilitation

strategies to be developed and implemented over the next few years.

Only recently have authors begun to report on the application of Hydroinformatic tools to the problem of optimal sewerage asset management (Adey *et al.* 2003; Elachachi & Breyse 2007). In comparison, methodologies addressing the optimal management of water distribution systems have been widely reported for numerous years, (Shamir & Howard 1979; Woodburn *et al.* 1987; Kim & Mays 1994; Halhal *et al.* 1997; Malandain *et al.* 1998). If we purely consider the amount of published literature in the two fields, it would appear that the management of sewerage assets is less suited to the application of such Hydroinformatic tools. However, it will be shown here that the sewerage industry is in fact well suited to take advantage of such Hydroinformatic tools. Notably, how the specification of optimal rehabilitation strategies can be improved through the increased use of structural condition grading information to inform decision-making

processes. In this respect, sewers have a distinct advantage over their clean water asset counterparts, in that their condition can be ascertained relatively efficiently (Kathula *et al.* 1999; Feeney *et al.* 2009), which in turn can be utilised for the implementation of prioritised maintenance and rehabilitation strategies (Newton & Vanier 2006).

## METHODS

The multi-objective optimisation model presented in this paper utilises the standard sewer condition classification grading information obtained from CCTV inspections which are undertaken in-line with the current WRc (2004) Method of Sewer Condition Classification (MSCC4), to identify optimal rehabilitation solutions in terms of three conflicting objectives:

1. maximise structural condition improvement;
2. reduce construction cost; and
3. minimise critical asset risk of failure.

A data management process and optimisation environment has been specifically developed to solve these three conflicting objectives that are associated with the optimal specification of sewer rehabilitation solutions, shown in Figure 1. The optimisation environment is based upon a genetic algorithm (GA) approach, which is now a mature technology often used in water and wastewater planning and management (Nicklow *et al.* 2010). GAs stem from the field of evolutionary computation and they are widely used within multi-disciplinary industries to generate solutions to search and optimisation problems by mimicking behaviours found in biological evolution, namely, survival of the fittest, cross-over and mutation.

*Data pre-processing.* The CCTV data are managed and coded using a commercial software package InfoNet developed by Innovyze (2010). InfoNet is used as a data pre-processing tool because of its geospatial data storage functionality and its ability to calculate structural and service condition grade information from raw CCTV data. Post data loading and condition coding, the CCTV database is interrogated to remove structurally sound assets from being passed forward for consideration by the optimisation model. The optimisation model is driven by the extracted survey data which is directly processed within the optimisation environment, to permit the application of a multi-objective optimisation algorithm.

*Optimisation environment.* The optimisation environment uses a macro-driven programme to collate and

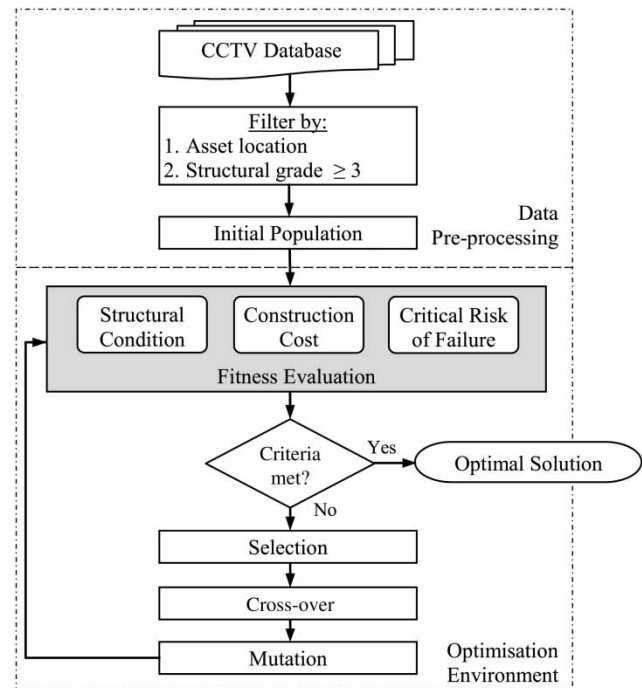


Figure 1 | Data processing and optimisation environment.

present the raw CCTV into a format which allows the assignment of rehabilitation solutions to each segment of asset. The macro undertakes this process by creating a 'chainage' (distance) value at increments along the assets. In this example, the term 'chainage' is used to describe an imaginary line that is used to measure distance along a sewer. In sewer survey measurements, the chainage starts at 0 m in the starting manhole and observations are reported at 0.1 m increments until the end manhole is reached or the survey is terminated, e.g. a collapse or blockage is observed. Within the optimisation environment, the repair chainage is defined to 1.0 m accuracies which have been termed segments. Whilst it is recognised that rehabilitation solutions can be delivered to accuracies of 0.1 m, which are equal to the resolution obtained from the condition inspection equipment, it was deemed more practical to define the accuracy of the model in accordance with the minimum isolated repair length, i.e. 1 m. Therefore, within each 1 m segment the accumulative structural score is calculated and displayed. The objective function formula, embedded in the optimisation spreadsheet template, then updates itself to encompass the cell ranges for each individual sewer length. Thus permitting the evaluation of the objective function(s) at asset level, i.e. the score improvement, construction costs and risk of failure can be considered per individual sewer length. In accordance with this level of

accuracy, the condition of each 1 m segment of sewer is represented as the sum value of the defect scores within that metre. Similarly, for practical purposes, a minimum repair length of 1 m is adopted.

**Optimisation tool.** This model uses a well established GA optimisation tool developed by the University of Exeter, GANetXL, (Bicik *et al.* 2006; Savić *et al.* 2011). The optimisation model evaluates numerous rehabilitation solutions within the optimisation environment using a multi-objective GA. Upon establishing the optimisation environment, the GA assigns an initial random population of solutions, as a string of 1s and 0s, against each segment of the sewer. These 1s and 0s become the decision variables in the problem which represent the rehabilitation action: either rehabilitate (1) or do nothing (0). After an initial random population of decision variables are assigned, the GA evaluates the fitness of each solution based on the objective function(s) scores which are calculated dependent upon the decision variable values. If the fitness of the solution meets the stopping criteria for the algorithm then the optimal solution is said to be found. A maximum number of generations were used as the stopping criterion for the optimiser. A maximum value of 10,000 generations was decided upon based on experimental results. However, if the solution falls short of the criteria then the following GA operators are performed: selection, cross-over, mutation (Murphy *et al.* 1993) and the new solutions are re-evaluated. An important aspect in the optimisation process is how the algorithm uses the objective function(s) to prescribe the optimality of a particular solution, such that solutions can be ranked against one another. The main advantage of this approach is the ability of a GA to find a set of Pareto-optimal (trade off) solutions in a single run of the algorithm.

## Model development

Between 1980 and early 2000, UK water and sewerage companies largely employed asset management policies that involved the implementation of selective rehabilitation. Selective rehabilitation meant that non-critical sewers (Category C) would only receive maintenance on a reactive basis (Fenner *et al.* 2000). As we observe a behavioural shift in the industry towards more proactive maintenance, utility companies are becoming increasingly more and more concerned with the identification of critical assets, due to the high associated costs to the business when failure of said assets occur. Modern deterioration models that task themselves with the identification of defective assets are not typically founded on the use of asset criticality as a primary

means for investigation (Berardi *et al.* 2009 and Black *et al.* 2005). Instead, other factors that might contribute to the observation of different deterioration rates amongst sewerage assets are often used, i.e. material, age and ground conditions (Davies *et al.* 2001). Indeed, the use of criticality is often considered as an additional decision support element, used for evaluating the consequence element of the risk of failure. Whilst the identification of defective assets should not be prioritised towards critical sewers, it would be fundamentally flawed if a rehabilitation strategy were developed which considered the consequence of failure of critical and non-critical assets as equal. Thus, a balance must be struck to ensure that assets of equal likelihood of failure are rehabilitated in order of priority, i.e. where a bias towards the rehabilitation of critical sewers is given. This can be achieved using criticality as a surrogate measure to define the consequence of failure. It is important, however, that non-critical assets displaying characteristics of high failure probability are not neglected, hence the use of a bias function such as a criticality weighting is used instead of a blanket ruling for the repair of critical assets first.

## Objective functions

### Structural condition improvement objective function

The MSCC4 coding system developed by the WRc (2004), assigns a structural condition score to all structural defects that are observed along the asset's length during a condition inspection. The score value given to each observation is directly proportional to the severity of the defect observed. The optimisation tool utilises this scoring system to evaluate the structural condition of the asset prior to and post different intervention scenarios.

### Rehabilitation cost objective function

The cost objective is one of the most important elements in this model. It successfully allows the comparison of numerous different rehabilitation solutions against one another, in order to determine which solutions are more financially favourable than others. For example, the model can be tailored to distinguish between different contractor costs, where one contractor's rates may favour contiguous lining as opposed to another contractor whose rates favour patch repairs. If these costs are accurately captured in the model, the outputs will promote solutions according to each of the contractor's individual preferences. Similarly, the client may over rule the objective function to promote their

preference. To facilitate the accurate modelling of rehabilitation costs the total cost of any rehabilitation strategy is a function of the raw unit rate cost(s), client specific on-cost(s) and the contractor mobilisation cost(s) associated with the repair or combination of repairs.

### Critical risk of failure objective function

Risk is an important element to consider in any sewer rehabilitation strategy. Kaplan & Garrick (1981) acknowledge that risk considers the likelihood of something occurring and the consequence of such an occurrence. This paper adopts a ‘critical risk’ philosophy which attempts to model risk by understanding and evaluating the likelihood of a sewer failing and the consequence of that failure. The optimisation model uses the peak structural score observed for each asset, under the MSCC4 coding system, as a surrogate measure for the likelihood of failure. The methodology used to evaluate a sewers’ criticality uses five consequence grades which are defined by a system that broadly follows the criticality grading guidance set out in the Sewer Risk Manual (SRM), (WRc 2004). Following this guidance, a sewerage asset is termed ‘critical’ if the collapse or repair of the asset is either disruptive, expensive and/or if the asset is deemed to be of strategic importance. The UK Water Industry uses three criticality categories to distinguish between the different impacts of asset failure: Category ‘A’ refers to sewers where the cost of rehabilitation post asset failure would typically be in excess of double the planned renewal costs; Category ‘B’ identifies assets where the cost of failure is less than ‘A’, but where the associated disruptions caused by collapse would make failure of these assets less desirable; and Category ‘C’ applies to assets that are deemed non-critical from the above criteria. It is typical for Category ‘A’ assets to possess any of the following characteristics: large diameter, greater than 3 m deep, beneath traffic sensitive streets, in bad ground, present troublesome access conditions and/or lie in close proximity to other infrastructure assets. The consequence based criticality approach used in this paper applies a further level of granularity to the existing approach by allowing for the original sewer criticality codes, ‘A’ and ‘B’, to be escalated by appending an ‘x’. This is applied where the consequence of failure is deemed to be of significant importance, for example where asset failure would almost undoubtedly cause disruption to surrounding critical infrastructure, i.e. railways or major roads. The consequence criteria, which are applied via the use of Geographical Information System (GIS) analysis tools, are listed in Table 1.

**Table 1** | Example consequence criticality definitions

Code	Description of sewer category
Ax	Under railway Under motorway/Protected street Under traffic sensitive street Would disrupt hospital traffic Would disrupt fire station access
A	WRc (2004) SRM sewer criticality classification
Bx	Would pollute Class 1 or 2 main river In hospital complex Under traffic sensitive street
B	WRc (2004) SRM sewer criticality classification
C	Non-critical

## RESULTS

A unique methodology for the optimal specification of sewer rehabilitation investment is presented in this paper. By accounting for the critical risk of asset failure during the specification of rehabilitation solutions, this methodology builds on the recent work of Ugarelli & Di Federico (2010) and Ward & Savić (2011) which has reported notable benefits in the use of optimisation tools to assist engineers in the specification of optimal rehabilitation strategies. To ascertain the effectiveness of this approach, a catchment case study is considered. The CCTV data used in the study originate from a recent sewer rehabilitation project implemented by South West Water, UK. The objective of the project was to use a deterioration model to efficiently target CCTV survey investigations within catchments leading to the identification and rehabilitation of defective sewers. The case study catchment has a total sewerage network of 37.4 km, of which ca. 8% (2.9 km) was surveyed using South West Water’s targeted deterioration model. The effectiveness of the deterioration model being able to successfully identify sewers in a defective condition is evident in the structural condition grade summary, Figure 2, which shows a high percentage of structural condition grade 4 and 5 sewers from these targeted investigations.

An initial filtering process was conducted outside of the optimisation environment to remove all structural sound assets from consideration by the model. Approximately 60% (1.727 km) of the raw CCTV data were passed forward into the optimisation modelling environment. The key characteristics of the 1.727 m of data which includes sewer age, diameter, material and criticality classification, are presented in Figure 3. Read & Vickridge (1997) estimate that 78% of all sewers in England and Wales are constructed

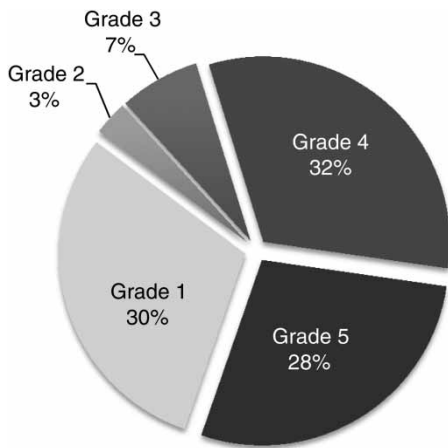


Figure 2 | Structural condition profile summary.

from Vitrified Clay. Therefore, given the relatively small nature of the catchment, it is not surprising that the majority of the surveyed assets in this study are less than 225 mm diameter Vitrified Clay sewers. The high volume of sewers populating the oldest age band, i.e. pre-1896, is also typical of a data set obtained from a targeted deterioration model. The model aims to identify assets that are most likely to be in a poor condition; therefore, it is of no surprise that pre-1896 assets are prevalent in this data set. Most importantly, the data have sewers spanning all of the enhanced criticality classification codes from Ax to C.

Upon establishing the raw data within the optimisation environment, a macro driven process is performed to incorporate the three objective functions within the model environment. This process permits the live evaluation of

different rehabilitation solutions as the GA iteratively searches the solution spaces for optimal rehabilitation strategies. For any given rehabilitation solution, the following aspects, which constitute the main objective functions, are evaluated: pre- and post-intervention structural condition scores ( $S^0$  and  $S^1$ ), raw rehabilitation cost and mobilisation cost ( $C_{raw}$  and  $C_{mob}$ ), post-rehabilitation peak structural condition score ( $S_{peak}$ ) and the asset criticality weighting ( $C_{weight}$ ). A tabulated example of an evaluated output from a rehabilitation strategy for 10 assets is produced in Table 2.

In this example the rehabilitation strategy scores the following for each of the objective functions:

1. Structural condition improvement ( $\Delta S$ ) = 6,777
2. Rehabilitation construction cost ( $C$ ) = £74,934
3. Critical risk of failure ( $R$ ) = 1,450

The values of the objective function items 1 and 3, condition improvement and critical risk of failure, are meaningless numbers except where a Pareto optimal trade-off curve is presented to the user. Halhal *et al.* (1997) explained that each point on the Pareto optimal curve is not dominated by any other point, i.e. in going from one point to another it is not possible to improve on one criterion without making at least one of the other criteria worse. The GANetXL optimisation model used in this analysis (Savić *et al.* 2011) evaluates each of the objective functions separately. In contrast, a single-objective optimisation problem is solved by finding a single optimal solution. Therefore, when a multi-objective problem is solved successfully, wide arrays of solutions are presented as Pareto optimal trade-off curves. In this instance, these solutions show the trade-off between the three

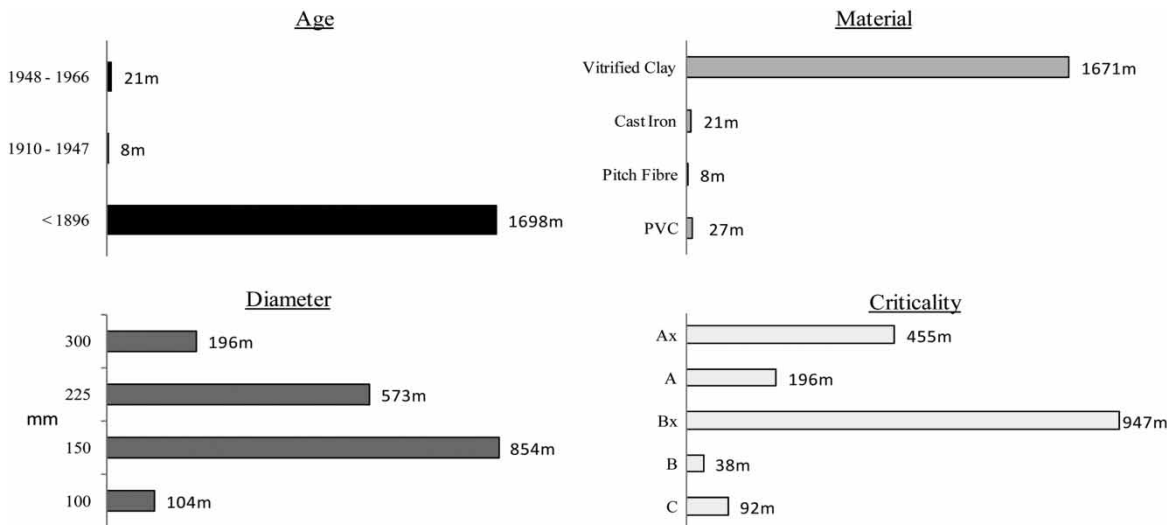
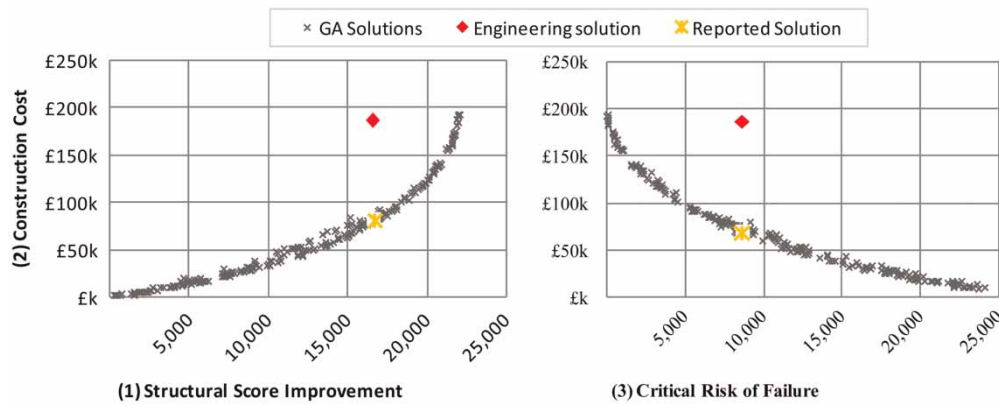


Figure 3 | Sewer characteristics.

**Table 2** | Sewer rehabilitation strategy analysis

Asset data			Structural condition			Construction cost			Critical risk		
ID	Diameter (mm)	Criticality code	$S^0$	$S^1$	$\Delta S$	$C_{raw}$	$C_{mob}$	$C$	$S_{peak}$	$C_{weight}$	$R$
1	100	A	80	80	0	£0	£0	£0	80	4	320
2	225	C	770	0	770	£6,863	£500	£7,363	0	1	0
3	225	Bx	3,845	0	3,845	£35,497	£500	£35,997	0	3	0
4	225	A	165	165	0	£0	£0	£0	165	4	660
5	150	B	314	0	314	£3,600	£500	£4,100	0	2	0
6	300	Ax	290	0	290	£3,930	£500	£4,430	0	5	0
7	225	Ax	220	40	180	£1,183	£500	£1,683	30	5	150
8	300	A	80	80	0	£0	£0	£0	80	4	320
9	150	C	241	0	241	£3,668	£500	£4,168	0	1	0
10	150	A	1,137	0	1,137	£16,694	£500	£17,194	0	4	0
<b>Objective function outputs</b>			-	-	6,777	-	-	£74,934	-	-	1,450

**Figure 4** | Engineering and optimisation solution comparison.

objective functions being considered. Thereby, a range of Pareto optimal solutions is presented to the user to aid in their selection of the most suitable rehabilitation strategy. It is most common for decision makers to evaluate solutions in terms of cost. Therefore, the two non-monetary based objective functions that are evaluated in this case study are presented graphically along the  $x$ -axis against a common financial baseline along the  $y$ -axis of Figure 4. Figure 4 provides a direct comparison between conventional engineering solutions that have been produced for the catchment and those solutions identified by the optimisation tool.

It can be seen that a conventional approach to sewer rehabilitation produced a solution to the problem at an estimated construction value of £186,541. In terms of Objective Function (1) Structural condition improvement, this solution was evaluated at 16,650. However, an equivalent

solution in terms of structural condition improvement, is identified by the optimisation model at a cost of only £82,319, hereby acknowledging a potential saving in excess of £100,000 between the conventional engineering solution and that of the optimisation model. Similarly, an even greater saving of £116,000 can be achieved for the delivery of an equally beneficial solution in terms of Objective Function (3) Critical risk of failure, when it is compared using a financial baseline of Objective Function (2) Construction cost. Figure 4 illustrates that the GA optimisation tool is capable of producing a wide array of non-dominated solutions for the user to select, ranging from an investment value of £200,000 to £0, which represent the options for fixing all or none of the observed structural defects, respectively. Alternatively, the user can use these trade-off solution curves to fix an acceptable level of critical risk within each

catchment by delivering the combination of rehabilitation solutions that reduce the critical risk of failure to below this pre-defined level. This advance level of solution expenditure vision and improved understanding of rehabilitation solution benefit, provides both planners and engineers alike with a unique platform for engineering creativity and advanced financial planning capabilities.

## CONCLUSIONS

Sewerage systems are an essential element of the urban water infrastructure system. The rehabilitation and maintenance work associated with these assets form a large part of a utility company's annual expenditure. Therefore, as these infrastructure systems age, the pressure to effectively manage and rehabilitate these systems is also increasing. The result is a demand in the need for engineers to develop rehabilitation strategies that meet multiple conflicting objectives: maximisation of the overall structural condition improvement of the network (Objective Function 1), minimisation of construction costs (Objective Function 2), and minimisation of the risk of critical asset failure (Objective Function 3). Conventionally, it has only been possible to develop sewer rehabilitation strategies on an asset-by-asset basis which calls on engineering best practice guidance to determine when a sewer's condition is deemed worthy of rehabilitative action. In addition, the lack in human ability to evaluate problems of a conflicting and complex nature makes the optimal specification of rehabilitation strategies within a catchment an almost impossible manual task to achieve. However, via the introduction of a multi-objective optimisation tool to the problem, a unique methodology capable of quantifiably appraising optimal rehabilitation strategies is developed.

An appraisal of the model's effectiveness and suitability has been conducted on a catchment case study provided by South West Water, UK. The catchment rehabilitation strategy, produced manually using engineering best practice, was evaluated by the rehabilitation cost model developed in this study at £186,500. In comparison, the optimisation model identified equally beneficial solutions, as defined by the aforementioned Objective Functions 1 and 3, at a cost of only £82,300 and £69,000, respectively. Whilst the global optimality of the solutions identified cannot be guaranteed, the model clearly demonstrates the ability to converge towards optimal solutions which would otherwise be over looked through manual interpretation of the data

alone. Therefore, given the resounding improvement over the manual specification of sewer rehabilitation strategies, coupled with the ability of the optimisation tool to use widely available condition data, this study further reinforces the need to effectively integrate such Hydroinformatic tools into business-as-usual processes within the UK sewerage industry.

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