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An optimised total expenditure approach to sewerage management

Ben Ward MSc, CEng, MICE, MIAM
Research Engineer, AECOM, Exeter, UK; Research Engineer, Centre for Water Systems, University of Exeter, Exeter, UK

Maciej Kawalec MSc
Graduate Engineer, AECOM, Exeter, UK; Research Engineer, Centre for Water Systems, University of Exeter, Exeter, UK

Dragan Savić MSc, PhD, CEng, FREng, FICE, FCIWEM
Head of Engineering and Director of the Centre for Water Systems, University of Exeter, Exeter, UK

It is generally accepted by Ofwat, the water industry regulator for England and Wales, that the current investment planning system whereby capital and operational expenditure are accounted for separately is complex and burdensome. In a move towards realising a total expenditure approach, a previously successful sewer rehabilitation optimisation model has been adapted to provide a mechanism for users to evaluate the trade-offs that exist between the capital and operational benefits associated with different sewer rehabilitation schemes. A series of geographic information system tools has been integrated within the model to help prioritise high-benefit sewer rehabilitation schemes by evaluating the potential serviceability improvements that can be realised in addition to the purely structural condition improvements. As a result, the new sewer rehabilitation model can be referred to as a strategic decision support tool that is capable of helping sewerage engineers and planners in the evaluation of different intervention programmes of work. The benefits of adopting this approach are demonstrated in a UK sewerage case study that uses a multi-objective genetic algorithm to consider the three-way trade-off that exists between minimising investment cost against maximising asset life (capital benefit) compared with proactively addressing serviceability problems (operational benefit).

Notation

B_{pr}	number of blockage paper/rag incidents recorded
B_{ro}	number of blockage roots recorded
C_o	number of collapse incidents recorded
C_{pa}	number of partial collapse incidents recorded
C_{po}	number of potential collapse incidents recorded
i	individual sewer
N	total number of sewers in catchment
P	probability of a serviceability event occurring from a collapse
PR	private business costs
Ref	operational performance measure reference
SE	social/environmental costs
S_i^0	structural condition score for sewer asset i
S_i^1	structural condition score for sewer asset i post-rehabilitation
T_1	earliest incident observation year
T_2	latest incident observation year

1. Introduction

Sewer rehabilitation planning is currently a slow and repetitive process that often requires the decision-maker to review condition inspection information when deciding on the best course of intervention techniques (Yang and Su, 2006). During this process, it is highly unlikely that the decision-maker will attempt to evaluate the strategic business benefits surrounding the investment decisions from a catchment-wide or network-wide perspective. This is due to the complexities associated with being able to quantify the change in risk of failure or serviceability improvements that can be achieved through different combinations of rehabilitation strategies. Halfawy and Baker (2009) define sewer network renewal planning as a process that establishes the most appropriate and cost-effective intervention action for each pipe segment in the network. The approach draws similarities to the cost and reliability trade-off concept observed by Dandy and Engelhardt (2006) for potable water mains replacement, whereby the objectives for optimal sewer rehabilitation planning are also conflicting. This implies that rehabilitation solutions that vastly improve the structural condition of an asset would typically have high associated costs. Therefore, to permit effective planning and investment to occur, it is important that decision-makers understand and appreciate the cost–benefit trade-off between different rehabilitation solutions and the possible combinations of these solutions that can be delivered across a catchment.

Over the past two decades, researchers and practitioners have begun to utilise the availability of standardised CCTV sewer inspection information (NASSCO, 2001; WEF *et al.*, 2009; WRc, 2004) to formulate reliable and repeatable approaches to predict the future condition of sewerage assets (Baik *et al.*, 2006; Kathula *et al.*, 1999). Wirahadikusumah *et al.* (1999) recognised that the defect coding outputs produced by these condition inspection methods are the single most important element of information used by planners, contractors and consulting engineers to help ascertain the current condition of sewerage assets. In support of this statement, more recent hydroinformatic tools are also founded on these standardised inspection formats as they seek to support the rehabilitation decision-making process (Baur *et al.*, 2005). Similarly, the availability of ever-increasing computational power, when coupled with inspection information, has allowed for the application of optimisation algorithms to identify cost-effective intervention options and inspection timings for complex networks (Berardi *et al.*, 2009; Halfawy *et al.*, 2008; Ugarelli and Federico, 2010; Yang and Su, 2006).

Despite the success of the above research works, which have all contributed in some way towards improving sewer rehabilitation planning, criticism has focused on the lack of transparency and user interaction with the tools, which are often referred to as black box systems (Marsalek *et al.* 1996). It is also evident that none of the above methodologies allow the decision-maker to adopt a truly strategic vision of the trade-offs that exist between different rehabilitation schemes at an asset or catchment level. This understanding of the trade-offs that exist between different solutions is particularly valuable in the current economic climate in which rehabilitation budgets are constrained, in turn forcing decision-makers to prioritise assets for investment.

2. Proposed total expenditure approach using optimisation techniques

It is generally accepted by Ofwat that the current system in which capital expenditure (capex) and operational expenditure (opex) are accounted for separately is complex and burdensome. It has also been reported that the water industry currently exhibits a bias towards capex rather than opex (Engelhardt and Turner, 2011; Ofwat, 2011a; Utility Week, 2012). The problem with this type of bias is that utility providers are being financially incentivised to invest in capital schemes instead of more operationally related solutions, almost irrespective of which option is better suited to addressing the problem (Ofwat, 2011b). In light of the above, it is widely foreseen that the UK water industry will begin to evaluate investment on a total expenditure (totex) basis. To assist in this transition, a previously successful sewer rehabilitation optimisation model (Ward and Savić, 2012) has been modified to adopt a totex approach to the problem of strategic sewer rehabilitation. This approach allows the user to consider the trade-offs that exist between the capital and operational benefits of different intervention strategies. It was deemed more appropriate to present the problem as a trade-off between capex and opex benefits rather than evaluating schemes for their combined operational and capital benefits (i.e. totex). Representing the problem as a multi-objective trade-off is well suited to the application of optimisation-based algorithms because it ultimately provides greater flexibility to the decision-maker.

Optimisation is a technique that represents a problem so that a mathematical procedure can be applied to solve it. Generally speaking, optimisation tools look either to maximise or minimise the objective function(s) by changing the decision variables of the problem. These decision variables are changeable to form a solution within the limits of the problem's constraints, which are used to impart reality and/or to ensure that only desirable solutions are found. Nicklow *et al.* (2010) recognised how genetic algorithms have become a mature technology in the water and wastewater industry because of their ability to solve complex network management and planning problems by mimicking natural evolution.

In order for a multi-objective genetic algorithm to be applied to the problem of optimal sewer rehabilitation specification, a decision environment is used to formulate the problem in terms of the aforementioned objective functions, decision variables and constraints. This environment structures the raw data into an organised and interpretable sewer rehabilitation matrix. This is subsequently used by the model to converge on optimal solutions using a well-established multi-objective genetic algorithm (Savić *et al.*, 2011). Table 1 shows the organised data structure alongside the corresponding possible range of values for each field, and Table 2 provides an example for a short CCTV survey that has been translated ready for analysis by the genetic algorithm. Essentially, the structure is formed by assigning individual rows to every defect observation in the condition survey. This is done through interrogation of an industry standard CCTV survey format, the *Manual of Sewer Condition Classification* 4th edn (MSCC4) (WRc, 2004).

The position of the defect along the sewer, the defect code and its corresponding score (as shown in fields 1, 3 and 4 of Table 1) are extracted directly from the conventional MSCC4 CCTV inspection report. The decision variable field is added by the model for use by the genetic algorithm to select between different solutions. It may take the form of one of four potential

Field	Description	Range of values
1	Position along the pipe: m	[0–length]
2	Decision variable	[0–3]
3	Defect code	[code]
4	Observed defect score S^0	[score]
5	Post-rehabilitation defect score S^1	[score]
6	Maximum repair length: m	[position–position+1]
7	Patch or lining (yes/no)	[0–2]
8	Contiguous lining (yes/no)	[0–1]

Table 1. Optimisation data structure

values – 0 represents no rehabilitation, 1 represents a patch repair, 2 represents lining from the upstream manhole towards the downstream manhole and 3 indicates lining from the downstream manhole upwards. The post-rehabilitation defect score (S^1) is calculated as the sum total of the remaining defect scores after rehabilitation (i.e. the unremediated defects).

Unlike in previous work by the authors (Ward and Savić, 2012), the model described in this paper presents the problem in a much more computationally efficient manner. Rather than assigning decision variables to each 1-m section of the sewer to indicate whether the section is being repaired (1) or not (0), the decision variables are now only applied to defective sections of the sewer. Figure 1 is provided to help visualise the improved search space in the new model by means of the removal of sections of pipework where structural defects have not been observed. It is important to note that, despite condensing the problem from a modelling perspective, the logical repairs that span healthy sections of pipework (i.e. contiguous re-lining lengths between defects) can still be selected by the optimisation algorithm. This also demonstrates how the solutions can span other decision variables that are essentially 'turned-off' from consideration by the model when contiguous lining would encompass them. This is achieved by means of the use of a set of logical rules set up in fields 7 and 8 of Table 1.

This new representation of the problem has delivered a significant improvement in processing performance that has enabled the tool to produce an array of optimal rehabilitation solutions for individual assets within seconds. These solutions each present a trade-off between asset life preservation (capital benefit) against rehabilitation cost, thus allowing the tool to be used as a 'real-time' decision support system that quickly identifies the performance and cost of all feasible rehabilitation solutions. At this point the engineer is presented with an array of optimised solutions for each asset that he/she can override. For example, the repair methodology could be changed from a trenchless to an excavated solution or additional repairs could be added to the set of solutions identified by the genetic algorithm alone. The final stage of the model uses these outputs to develop an asset management strategy by optimising a set of network-wide rehabilitation schemes from the preselected rehabilitation solutions identified for each individual asset. The approach uses the same multi-objective genetic algorithm as before, but with a third objective function introduced at asset level to evaluate the operational performance benefits of different schemes. The third objective function is developed using a series of geographic information system (GIS) tools to interrogate historical operational and maintenance activities when determining the potential benefits associated with the restoration of one asset over another. Therefore, the output from the second phase of optimisation is a trade-off between investment cost against asset life preservation (capex) compared with serviceability improvements (opex).

Once the user has selected a scheme (defined as a group of assets for rehabilitation within a catchment), this selection of assets and the necessary remedial activity for each asset (i.e. rehabilitation length and technique) is fed back by means of a semi-automated process to the commercially available geospatial asset management tool InfoNet (http://www.innovyze.com/products/infonet/). InfoNet is used to host the utility provider's corporate sewerage asset database, which is eventually overlaid with the asset-specific rehabilitation information as identified by the optimisation algorithm, thereby showing what assets to rehabilitate and the extent and nature of each rehabilitation solution.

2.1 Defining optimal rehabilitation solutions

The global objective of any infrastructure network rehabilitation programme is typically to improve performance or increase the network's reliability (Sitzenfrei *et al.*, 2011). However, the

Position along the pipe: m	Decision variable	Defect code	Observed defect score, S^0	Post-rehabilitation defect score, S^1	Maximum repair length: m	Patch or lining (yes/no)	Contiguous lining (yes/no)
1·5	0	H	80	0	1·5	0	1
2·1	1	CC	10	0	2·5	1	1
3·3	3	FC	40	0	3·5	0	1

Table 2. Sample problem representation for a single sewer length

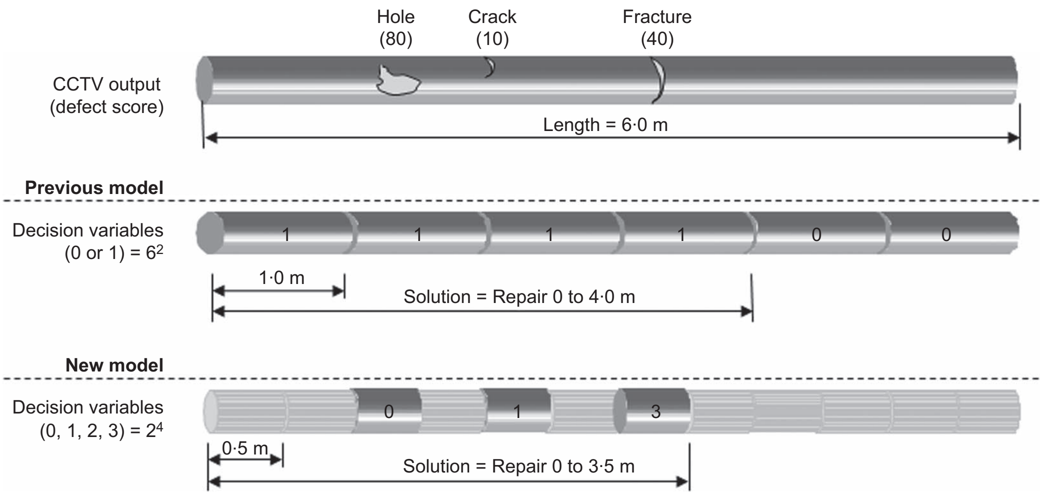

Figure 1. Comparison of modelled solution search space

problem of how best to represent network performance is a topic that has generated much variance between different models and the published literature (Fenner, 2000). This is mostly due to the complexity of the problem in conjunction with the fact that network performance is often interpreted differently by different stakeholders.

Here, three objective functions are used to evaluate the benefits and trade-offs of different rehabilitation solutions at catchment, or network, level

- maximise asset life (objective function 1)
- minimise investment cost (objective function 2)
- proactively address serviceability problems (objective function 3).

The processes undertaken to calculate objective functions 1 and 2 are well documented by Ward and Savić (2011) and remain largely unchanged in the new model.

Objective function 1 (Equation 1) considers a simplified approach to the problem of quantifying network improvement. It builds on previous work undertaken in clean water distribution planning by Halhal *et al.* (1997), in which the authors assumed that any length of pipe replaced in the network would provide for an improvement in overall water quality, thus allowing the total length of water mains replaced to be representative of the network's water quality improvement. Similarly, the sum of the observed defect scores (S^0) from the coded CCTV condition inspection report for each sewer (i) are used here to represent the current condition of a catchment or network with N sewers. It also assumes that an improvement in a sewer's structural condition can only be obtained by interventions to remediate the observed defects. Therefore, the structural score post-rehabilitation for each sewer (S^1) is simply the sum of the structural defect scores that remain unaltered by the rehabilitation solution. As a result, any change to this total can be used to quantify the total benefit provided by the rehabilitation strategy being implemented.

1.

$$\text{Structural improvement} = \sum_{i=1}^{N} [S_i^0 - S_i^1] \quad i = 1, 2, \ldots, N$$

The second objective function focuses on minimising construction costs. Therefore, it is of fundamental importance that the cost of each rehabilitation strategy is calculated accurately to ensure that the comparison of different strategies is representative of the actual delivery costs that will be incurred. To account for local cost differences between different utility providers and/or different rehabilitation contractors, the model presented in this paper was developed with the flexibility to include bespoke cost models into its analysis. The case study reported in Section 3 uses an audited cost model provided by South West Water that distinguishes between the type of repair, repair length, sewer diameter and the above-ground conditions for excavated solutions (i.e. highway, verge or grassland). Minor modifications have been made to the cost model to account for contractor mobilisation costs and economies of scale for consecutive repairs, which were omitted from the previous model.

Objective function 3 is a new feature that has been introduced in the model to help decision-makers adopt a more sustainable asset management practice by considering the serviceability improvements that different rehabilitation schemes could offer in the network (Ugarelli *et al.*, 2010). This third objective function was integrated by means of a series of bespoke GIS tools that are run within ESRI ArcGIS software. These tools are used to help account for the geospatial nature of serviceability incidents when determining and quantifying the operational benefits of different rehabilitation solutions (e.g. the prevention of a future flooding and/or pollution event resulting from a collapse). The assessment is first made by evaluating the spatial proximity of historic serviceability incidents to the sewer being considered for rehabilitation. As a general rule, the further away an incident is from the pipe being considered represents a lower likelihood of the incident being related to that pipe. Therefore, a GIS buffering exercise is used to reduce the risk of collecting events that fall outside the sphere of a sewer's influence. An adjustable buffer size is used depending on the address point density: areas of high address point densities are assigned smaller buffer sizes to reduce the risk of selecting events that are occurring on adjacent streets, whereas the buffer size is increased in areas of low address point density (e.g. rural areas) to recognise the fact that public sewers will often be further away from the properties they immediately serve.

The GIS model then applies a logical set of criteria, depending on the type of incident that the rehabilitation solution is thought to resolve, to establish the perceived avoided private cost (PR) associated with the rehabilitation scheme. A confidence factor of 0·5 is applied to the avoided private costs associated with each of the incidents recorded as 'blockage paper/rag' (B_{pr}) and 'potential collapse' (C_{po}), thereby demonstrating less certainty that the rehabilitation solution will in fact address these incidents. Incidents recorded as 'blockage roots', 'partial collapse' and/or 'collapse' are assigned a confidence factor of 1·0 to signify a higher level of certainty that these incidents will be directly addressed and prevented from occurring in future (Table 3).

The annualised frequency of an incident occurring each year is calculated from historic recorded event data, and it is assumed that the historic frequency of occurrence would proceed at the same rate if a rehabilitation solution were not specified. This is accounted for in Equation 2, which calculates the total period of time that each incident has been experienced for and then allows for the cost–benefit of the rehabilitation scheme to be represented as an annualised benefit value

$$\text{2.}\quad \text{Annual operational benefit}(£/\text{year}) = \sum_{x=1}^{5} f_x\left[\frac{\Sigma \text{PR}_x}{T_{2x}-T_{1x}}\right] \quad x=1,2,\ldots 5$$

In addition to resolution of these annualised incidents, additional one-off benefits are realised through the prevention of sewer failure. The one-off costs arising as a direct result of sewer failure are quantified in monetary terms under two categories – private (PR) and social/environmental (SE) costs. Private costs are those that are incurred by the business in response to a sewer failure and include all costs incurred to remedy the collapse. These are typically well understood and can be derived from an assessment of historic costs. Social/environmental costs are those that are incurred by society and/or the environment as a result of a collapse (e.g. disruption to traffic or pollution of a water course). These costs are typically more difficult to define and water utility providers often refer to guidance set out by the Environment Agency (EA, 2003) to help quantify the environmental impact or they rely on customer willingness to pay information linked to operational performance measures (OPMs) (Heather and Bridgeman, 2007; Willis *et al.*, 2005). To apply these costs to each rehabilitation scheme, Equation 3 is used in conjunction with Table 4, which gives consideration to the unique characteristics and spatial proximity of each sewer to other infrastructure and environmental features. A list of probabilities P and costs assigned to the prevention of an OPM associated with a sewer collapse are listed in Table 4. Costs are calculated using

$$\text{3.}\quad \text{Collapse cost}(£) = \sum_{\text{Ref}=\text{A}}^{\text{J}} \left[P_{\text{Ref}}(\text{PR}_{\text{Ref}} + \text{SE}_{\text{Ref}})\right] \quad \text{Ref} = \text{A,B,}\ldots\text{,J}$$

Incident reference, x	Incident	Probability of incident resolution, f	Cost per incident, PR: £
1	Blockage paper/rag, B_{pr}	0·5	1000
2	Blockage roots, B_{ro}	1·0	1500
3	Collapse, C_o	1·0	15 000
4	Partial collapse, C_{pa}	1·0	10 000
5	Potential collapse, C_{po}	0·5	500

Table 3. Operational benefit costs by incident type

OPM	Ref	Measure	Frequency per collapse, *P* (1:)	Criteria	Cost per event: £000	
					PR	SE
Traffic disruption						
	A	All	1	All sewers	20 000	
	B	A road	1	All sewers beneath A roads		100 000
	C	B road	1	All sewers beneath B roads		50 000
	D	Minor road	1	All sewers beneath minor roads		10 000
Flooding						
	E	Internal event	0·01	All sewers in densely populated areas	5000	100 000
	F	External event	0·05	All sewers in densely populated areas	1000	8000
	G	A Road flooding	0·1	All sewers beneath A roads	1000	15 000
	H	B Road flooding	0·1	All sewers beneath B roads	500	5000
Pollution						
	I	Category 2 event	0·004	All foul/combined sewers <625 mm diameter	10 000	1000 000
	J	Category 3 event	0·004	All foul/combined sewers >625 mm diameter	3000	50 000
	K	EA prosecution	0·5	Conditional probability per pollution event for foul/combined sewers that results in EA prosecution	20 000	
	L	Bathing water pollution	0·2	Conditional probability per EA prosecution for foul/combined sewers within 200 m of special site	10 000	300 000
	M	Shellfishery pollution	0·2		10 000	50 000
	N	Biodiversity and heritage pollution	0·2		5000	200 000
Customer contact						
	O	Call	50	Average number of customers affected per collapse	20	10
	P	Letter	0·05	Conditional probability per customer call that results in a letter	50	

Table 4. Operation performance measures (OPMs), probability of occurrence and costs. Costs shown are for indicative purposes only; all applicable costs are additive if any of the preceding criteria are valid

Therefore, when the annualised savings associated with the resolution of historic serviceability incidents are combined with the one-off costs avoided by the prevention of a sewer collapse, a monetary value that reflects the annual operational expenditure and the avoided serviceability costs is assigned to each rehabilitation solution. Assuming that the resolution of historic serviceability incidents will last for 25 years, then the third objective function, operational benefit, is expressed as

4.
$$\text{Operational benefit}(\pounds) = \text{Avoided collapse cost} + (\text{Annual operational benefit} \times 25)$$

3. Case study

A new methodology for optimising sewer rehabilitation has been developed. It uses conventional CCTV data to identify which sewers to rehabilitate and the extent and nature of the rehabilitation required, while also considering the serviceability benefits that different rehabilitation schemes bring to the customer. The study was commissioned by the UK water utility South West Water with the aim of embedding sewer network performance, as a decision-making criterion, into the previously successful sewer rehabilitation model developed by Ward and Savić (2012). The 2012 study documents the benefits associated with using a multi-objective optimisation model to evaluate the trade-offs between structural condition improvement (objective function 1) and cost (objective function 2). An appraisal of the model's effectiveness demonstrated its capability of identifying equally beneficial solutions for approximately 50% of the construction value when compared with manually produced solutions. A number of limitations and challenges were identified by the authors when considering its use as a day-to-day decision support tool, namely solution resolution, run time and lack of consideration of improvements in sewer network performance that different rehabilitation schemes can offer (e.g. by means of the resolution of historic incidents or by mitigating sewer collapse risk).

The new model presented in this paper improves on all of these limitations, while retaining the underlying principles of the original work. The challenge of embedding sewer network performance into the decision-making framework was achieved by means of the use of advanced geospatial information technology to quantify network performance improvements associated with different rehabilitation schemes across a catchment. A third objective function is added to the 2012 model to represent this new decision-making criterion. By introducing this new objective function, the model now considers sewer rehabilitation from a total expenditure perspective by actively promoting solutions that offer direct serviceability benefits for customers and therefore reduced operational costs for utility providers. These optimal serviceability solutions were also found to outperform the original engineering solution from a capital expenditure perspective in their own right.

Integration of this new objective function – alongside the vastly improved computational processing time – has established the model as a feasible and truly strategic decision support tool that can be used for optimal sewer rehabilitation planning. For some time, the water industry has recognised the need for more sustainable and comprehensive sewerage asset management methodologies due to increasing customer and political pressures in conjunction with tightening regulations (Fenner *et al.*, 2000). Heightened financial costs due to the reactive nature of the work, damaged business reputations and the increased likelihood of social and environmental impacts all justify the use of this type of approach, which is receiving increasing support (Ofwat, 2006; UKWIR, 2002).

4. Conclusions

Decision-making and planning for sewerage asset renewal/rehabilitation is a process that seeks to evaluate the condition of an asset, its risk of failure and the cost of remediation, and to understand serviceability improvements that could be achieved through different interventions. Typically, the objectives of a rehabilitation programme are conflicting, implying that interventions that vastly improve the structural condition or serviceability of an asset typically have high associated costs. Therefore, to permit effective planning and investment, it is important that decision-makers understand the cost–benefit trade-offs that exist between different schemes.

Historically, the specification of sewer rehabilitation solutions has been a tedious manual process that is highly subjective due to its dependency on engineering interpretation. It is also a process that is often undertaken in isolation (i.e. on a pipe-by-pipe basis) with little consideration given to the global asset management strategy. The shortcomings of this approach can largely be attributed to the complexity of the global asset management problem, whereby the interaction between multiple assets across a network is too complex to tackle without the aid of decision support tools that are often seen as a luxury rather than a necessity.

As the water industry in the UK continues to mature, attitudes and customer expectations are changing. This is in turn driving change in asset management best practice across water and wastewater infrastructure. One example of this is that greater emphasis is being placed on the need to deliver proactive rehabilitation programmes that improve serviceability performance for customers at low cost. In order for the industry to respond to this change, truly optimal rehabilitation investment programmes that are capable of considering the upfront trade-offs that exist between different schemes need to be delivered.

The optimisation model presented here uniquely considers sewerage asset rehabilitation from a global perspective. It quantifiably evaluates and optimises numerous rehabilitation solutions such that the decision-maker is presented with an understanding of the trade-off solution space between high-benefit/low-cost solutions and the optimal solutions that lie within that search space. The model has successfully demonstrated its capability of identifying these optimal solutions, which are presented to the decision-maker as a list of sewers to rehabilitate along with the extent and nature of the rehabilitation required, depending on the elected solution. However, by integrating operational benefits into the decision-making process, the model now considers sewer rehabilitation from a total expenditure perspective. The advantage of this approach is that the decision-maker is directed towards rehabilitation solutions that deliver ongoing serviceability benefits to customers while also outperforming any originally developed engineering solution from a capital expenditure perspective.

The proposed model is one example of how the water industry is beginning to capitalise on advancements in information technology and asset management best practice. However, more work needs to be done to integrate optimisation techniques and geospatial analysis better into the day-to-day decision-making philosophy across the industry. It is no longer acceptable to invest in infrastructure that will not yield direct benefits to customers, and the authors have successfully demonstrated one approach to ensure the delivery of optimised rehabilitation programmes.

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