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Costing of strategies for long-term trunk main discolouration management

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ABSTRACT

Material continually accumulates throughout drinking water distribution systems, as a result episodic maintenance is essential to mitigate uncontrolled mobilisation leading to water quality failings. Focussing on discolouration as the primary issue observed by consumers, this risk is of particular significance in trunk mains that can supply large downstream populations. Long-term total costs are for the first time investigated here by considering future operational and capital interventions to sustain a defined hydraulic capability that limits the discolouration response. To achieve this, accumulation and mobilisation profiles of pipe wall material is simulated using the open source Variable Condition Discolouration Model (VCDM) to develop Pareto trade-off curves between discolouration resilience and maintenance intervention frequency and magnitude. As the rate at which material accumulates is considered a function of water quality, operational savings that could accrue from reduced maintenance following capital investment, such as water treatment upgrades, are also investigated. With the complexity, size and ageing nature of water distribution system infrastructure, the ability to forecast network discolouration behaviour and hence costs is vital for long-term delivery of safe water at least cost to customers.

1. Introduction

Water suppliers are required to have a comprehensive understanding of contamination risks and to effectively control such risks to ensure access to safe and reliable drinking water of good aesthetic quality that is affordable to customers (The Bonn Charter for Safe Drinking Water, 2004; IWA, 2004). The vast, buried, ageing infrastructure of drinking water distribution systems (DWDS) and the complexity of reactions and interactions that occur within them presents one of the greatest challenges to managing such risks.

Particles and dissolved substances remain in drinking water irrespective of treatment. During transit through the distribution system changes in water quality occur, including pipe wall accumulation of material due to physico-chemical and microbiological processes. Hydraulic conditions within distribution systems are typically turbulent allowing particles in the water to come into contact with the pipe wall where cohesive forces, together with microbiological activity in the form of biofilms, cause accumulation leading to a ubiquitous and persistent discolouration risk (Husband and Boxall, 2011; R L Sharpe et al., 2019). Hydraulic disequilibria, where shear forces exceed normal operating maximums such as from changes in demand, valve operations, rezoning or bursts, can lead to mobilisation of this wall bound material, causing discolouration and associated water quality failings including metal concentration exceedances (Cook and Boxall, 2011). Discolouration is a well-known aesthetic water quality issue that often leads to consumer complaints worldwide (Husband et al., 2010).

It is necessary to manage material accumulations within networks such that operators are confident that planned, or unplanned, hydraulic changes will not result in uncontrolled, observable material mobilisation. With hydraulics governing the discolouration response, discolouration resilience is hence defined here as the ability to withstand increased hydraulic forces without mobilising material at concentrations constituting a discolouration risk to customers. For a given diameter and roughness pipe discolouration resilience is hence quantified in terms of the flow rate above which sufficient material would be mobilised to cause observable discolouration. Discolouration resilience is particularly relevant for large diameter transmission (trunk) mains due to their critical location in the network and typically high numbers of downstream consumers. Failure to maintain these assets to have resilience against likely flow events (i.e. ensuring that material does not accumulate such that likely hydraulic events cause observable discolouration) can therefore have significant and widespread consequences, damaging water utility reputation and consumer confidence. In the UK financial penalties or incentives are also levied by regulators based on water companies' annual performance (DWI, 2016).

Water utilities employ various invasive operational maintenance

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strategies to manage the discolouration risk of accumulated material including ice pigging, air scouring and swabbing (Ellison, 2003; Friedman et al., 2012). These interventions however are typically complex and require specialist equipment, as a result making them expensive, whilst also nominally requiring the pipe to be taken out of service thereby disrupting supply and customer service. In downstream networks flushing is usually a preferred option due to its simplicity. Irrespective of intervention type, studies consistently report material re-accumulating (Husband et al., 2010; Blokker and Schaap, 2015a). Therefore, one-off interventions are not a sustainable solution for managing long-term discolouration risk. A key factor in effectively managing this recurrent discolouration risk is the required frequency of operational interventions, specifically how discolouration risk changes over time. This information is necessary to determine the magnitude and frequency of intervention needed to achieve a desired level of discolouration resilience, which is critical for quantifying long-term operational costs.

The rate at which material accumulates is known to be linked to the water quality (Boxall et al., 2003; Vreeburg et al., 2008; Husband and Boxall, 2011; Blokker and Schaap, 2015a). This is a function of the final treated water, but also then how the water quality changes during transit, with pipe material and internal surface condition being key factors. For example, unlined cast iron pipes can contribute to water quality changes by acting as a source of material through corrosion by-products, increasing the rate of accumulation both for themselves and the downstream network. Hence, discolouration risk can also be partially managed by capital options such as upgrades to water treatment works or replacing/relining corroding pipes. With every network unique, the abililty to quantify the impact of such capital investment on the frequency of required operational interventions against ongoing discolouration resilience is essential to establish optimal management strategies.

The aim of this paper is to demonstrate how to design least-cost long-term operational interventions to achieve a desired level of discolouration resilience and how this is affected by capital investments that improve water quality. Given the complexity of such modelling, attention is focused on application to trunk mains where cost and consequences of discolouration are greatest.

2. Background

2.1. Rehabilitation intervention and discolouration risk

Selection of drinking water pipe rehabilitation techniques in the UK is primarily driven by the short-term benefits and cost (Marlow et al., 2015). However, for cost optimisation, it is sensible to account for all relevant costs and benefits throughout the DWDS service life. Prior to 1970, infrastructure investment decisions relied heavily on capital cost alone (Boussabaine and Kirkham, 2008). Later, whole life costing (WLC) concepts were developed based on the idea that operational expenditure (OPEX) for any asset maintenance could be higher than its capital expenditure (CAPEX). Several researchers demonstrated WLC approaches for water distribution networks to minimise the total expenditure (TOTEX) that includes both CAPEX and OPEX for a required level of service by maximising desired performance (Conroy and Hughes, 1997; Engelhardt et al., 2002; Jayaram and Srinivasan, 2008; Skipworth et al., 2002). Rehabilitation decision and prioritisation models to address structural performance and water loss have been developed using diverse performance criteria, e.g. burst rate and asset age (Engelhardt et al., 2003), integrating GIS, hydraulic data and breakage models (Tabesh and Saber, 2012), using a cost function based on pipe replacement, rehabilitation, repairs and pumping cost (Kim and Mays, 1994), and pipe failure and replacement cost using Bayesian parameter estimation (Scholten et al., 2014). However, these models focus on structural performance and water quality is not considered.

Decision support tools primarily compare CAPEX investment, e.g. installing new pipe, with ongoing OPEX, e.g. pipe repair, to minimise overall TOTEX. One WLC methodology considered fixed cost periodic flushing of distribution pipes as a general water quality risk mitigation strategy versus lining of unlined cast iron mains (Skipworth et al., 2002). However, apart from this conceptual proposal, no further study using WLC methodologies for discolouration management have been reported.

2.2. Material accumulation rates and maintenance interval

The knowledge and understanding of the factors that influence the rate at which discolouration material accumulates within drinking water distribution systems is key to informing and identifying best TOTEX strategies. Research has shown that material responsible for discolouration accumulates continuously and ubiquitously in distribution systems (Boxall et al., 2001; Blokker et al., 2011; Cook and Boxall, 2011; Husband and Boxall, 2016). Accumulation processes are influenced by a number of sources and factors in water distribution networks such as bulk water quality (Boxall et al., 2003; Vreeburg et al., 2008; Husband and Boxall, 2011; Blokker and Schaap, 2015a), pipe material (Husband and Boxall, 2011), hydraulic conditions (Cook and Boxall, 2011; Pothof and Blokker, 2012), and temperature (Sharpe, R L 2019; Blokker and Schaap, 2015b).

Studies investigating the period for discoloration material to fully re-accumulate have been published for distribution pipes with less than 150 mm (6″) diameter. Husband and Boxall (2011) analysed turbidity data from repeat flushing reported periods between 1.5 to 4.0 years as a function of water quality and pipe material in the UK. Vreeburg et al. (2008) reported 1.5 years using extrapolation from repeated application of the resuspension potential method in the Netherlands. Richardt et al. (2009) developed a flushing decision model based on pipe specific turbidity potential, estimating possible flushing return intervals between 0.5 to 8.0 years. There is little data or publications pertaining to material accumulation rates or return intervals for larger diameter pipes. One of the few studies was carried out as part of validating the Variable Condition Discolouration Model (Sunny et al., 2023). This reported re-accumulation periods of between 1.5 and 2 years, with indications of seasonal variation from three large diameter cast iron trunk mains all fed from a single treatment source.

2.3. Simulation of discolouration processes and behaviour

The material mobilisation process has been described as occurring sequentially from weak to strong shear strength layers, as simulated in the validated Prediction of Discolouration in Distribution Systems (PODDS) model (Boxall and Saul, 2005; Husband and Boxall, 2015 & 2016). However, results from repeated flushing trials have shown accumulation occurring across all layer strengths simultaneously (Husband et al., 2010; Husband and Boxall, 2011). This accumulation across the strength range has been verified in full-scale temperature-controlled laboratory conditions (Sharpe et al., 2019). Repeated flushing has also indicated material accumulating linearly over time (Cook and Boxall, 2011). Modelling to usefully inform long-term discolouration management strategies must capture both mobilisation and accumulation processes. One such model exists, the Variable Condition Discolouration Model (VCDM).

The VCDM simulates long-term discolouration behaviour by tracking both material mobilisation and accumulation simultaneously across a range of discretised shear strength bands. Following development, mobilisation functionality was validated by Furnass et al. (2019) and accumulation functionality was validated in Sunny et al. (2023). The mobilisation process assumes cohesive layers remain in equilibrium conditions with current prevailing hydraulics (τ_i) with mobilisation only occuring due to excess applied shear stress (τ_a) conditions when $\tau_a > \tau_i$. Material accumulation occurs when applied shear is lower than the prevailing hydraulics ($\tau_i > \tau_a$) and is represented by β_r (accumulation period). The model tracks the relative amount of material φ within the range of 0 to 1, where 0 represents no material on the pipe wall, and 1 represents fully developed or maximum amount for a given layer strength (Furnass et al., 2014). β_r represents the time for taken for φ to go from 0 to 1. An open access version of the VCDM for single pipe lengths is available at www.podds.co.uk [accessed July 2023].

2.4. Non-invasive hydraulic based discolouration risk management

Flow conditioning is an in-service trunk main cleaning strategy that was developed by the University of Sheffield in collaboration with leading UK water companies based on a detailed understanding of material accumulation and mobilisation behaviour and confidence in predicting and managing mobilisation response accurately (Husband and Boxall, 2015). Flow conditioning can be described as a controlled in-service flushing process that has the potential to reduce water loss to zero and mitigate risks through hydraulic management. The process involves managed mobilisation of material into the bulk water, nominally below a target value, typically <1 NTU, which is evidenced from carefully monitoring turbidity responses. This maintains a significant safety margin below the 4 NTU prescribed concentration value limit at the customer's taps in the UK. By imposing an excess system shear stress (τ_a-τ_i), material with shear strengths below τ_a are mobilised. The pipe is thus conditioned to τ_a, with further increases in shear stress required to mobilise additional material. Imediately after conditioning flows can be safely incraesed up to τ_a with no discolouration risk. The ability to use multiple flow conditioning steps and manage the response at each stage allows target flows or the desired discolouration resilience to be achieved. These hydraulic steps and durations can be planned using PODDS or VCDM models, together with knowledge of hydraulic history and network properties. It is important to note that flow conditioning does not remove all material, rather a planned level of discolouration resilience is achieved. With continuous material accumulation, periodic repeat flow conditioning is required to preserve the benefits, as with any other possible maintenance intervention. This method has been successfully implemented in trunk main systems across the UK and internationally (Cook et al., 2015; Husband and Boxall, 2015) and its long-term water quality benefits have been demonstrated as part of a treatment-to-tap approach (Sunny et al., 2020).

Flow conditioning is widely applicable across trunk mains, where and whenever it is possible to design and manage hydraulic conditions. Trunk mains can be categorised into two groups for flow conditioning purposes. Those linking network components such as between treatment and service reservoirs that have hydraulic conditions within utility control generally facilitate more straightforward strategies. With the correct infrastructure, conditioning can have effectively zero cost and even be automated (Cook and Husband, 2017). The second type of trunk mains are demand-driven, that more directly supply customers. For demand-driven trunk mains, hydraulic conditions are more temporally dynamic and complex with no buffer or break prior to water being delivered to the consumer. In many cases manual on-site intervention may be required with flow managed by controlled discharge through one or more fire hydrants or other wash out infrastructure; in effect applying flushing to larger diameter pipes. In these circumstances flow conditioning has been commonly planned to coincide with peak daily flows, minimising the additional demand to be discharged.

3. Methods and materials

3.1. Methodology

The ultimate output required is quantification of the trade-off between total long-term costs and the level of discolouration resilience. This is complex with many interacting contributing factors. A given level of discolouration resilience may be achieved by either a more aggressive operational cleaning strategy repeated less frequently, or vice versa. These different strategies come with different costs. Frequency is a function of the accumulation processes and is governed by capital options. Accumulation also decreases the level of discolouration resilience over time, thereby dictating the operational frequency required. Defining a single hydraulic event for desired resilience is also unrealistic. The proposed methodology captures and considers all these factors with the outcome enabling quantification of total costs for different levels of discolouration resilience. This approach allows for the selection of a preferred strategy to achieve a selected discolouration resilience without excessively escalating the total long-term cost.

The methodology is demonstrated here to achieve discolouration resilience in a demand-driven trunk main as these are the dominant type of trunk mains and have complex hydraulic conditions. We assume that the operation intervention of choice is flow conditioning due to it is wide applicability and in-service nature. To aid simplicity of result interpretation, the trunk main system is simplified to an effective single pipe length as is often the case in practice. It is assumed on-site manual hydraulic control is via a standpipe, planned to coincide with daily peak demand (minimising discharged water).

3.2. Modelling using the VCDM

The first stage requires simulating flow conditioning scenarios that keep turbidity below 1 NTU, the prescribed concentration limit at water treatment works in the UK and currently considered acceptable by some UK utilities to intentionally generate within operational networks as part of maintenance. This may initially involve a stepped intervention depending on the level of discolouration resilience required and pipe properties, with repeats being either single or stepped increases depending on the return frequency.

The response to event hydraulic conditions are then simulated to assess the discolouration resilience with an event limit of 4 NTU. When the response exceeds 4 NTU, the prescribed concentration limit at the tap in the UK, discolouration resilience is breached. Events are simulated as instantaneous sustained increases that result in the most rapid and complete mobilisation of material and the highest observable turbidity. By tracking material accumulation and simulating events at increasing time after the flow conditioning, the change in discolouration resilience can be simulated and the frequency for repeat intervention determined as the time just before a 4 NTU response is generated.

To investigate the discolouration risk-return period for varying imposed shear stress interventions, the model was simulated initially for a single fixed discolouration resilience. As different magnitude flow conditioning interventions have different risk-return periods, cost determinations are different for each imposed intervention. The minimum cost to ensure discolouration resilience against a target hydraulic event was assessed from a trade-off curve between intervention magnitude and periodicity. Once the method for identifying the minimum costs for periodicity and magnitude of flow conditioning for a given discolouration resilience was assessed, different discolouration resilience levels informing a true trade off curve, or Pareto front, for cost against discolouration resilience could be explored.

3.3. VCDM modelling of flow conditioning and discolouration resilience

Figs. 1–3 explain how flow conditioning strategy options and the change in discolouration resilience is enabled by the VCDM functionality through tracking of the material quantity for each of the discretised shear strength material layers. The aim is to highlight how flow conditioning strategies can be designed such that whenever an event with imposed shear stress of τ_R occurs, the predicted down stream response is less than 4 NTU.

Fig. 1 shows a situation with no flow conditioning and a hydraulic event at some point in time. The upper plot shows 8-days of a repeating daily shear stress profile, determined from a measured daily flow time series during normal operation, with a peak daily shear stress of τ_D. On

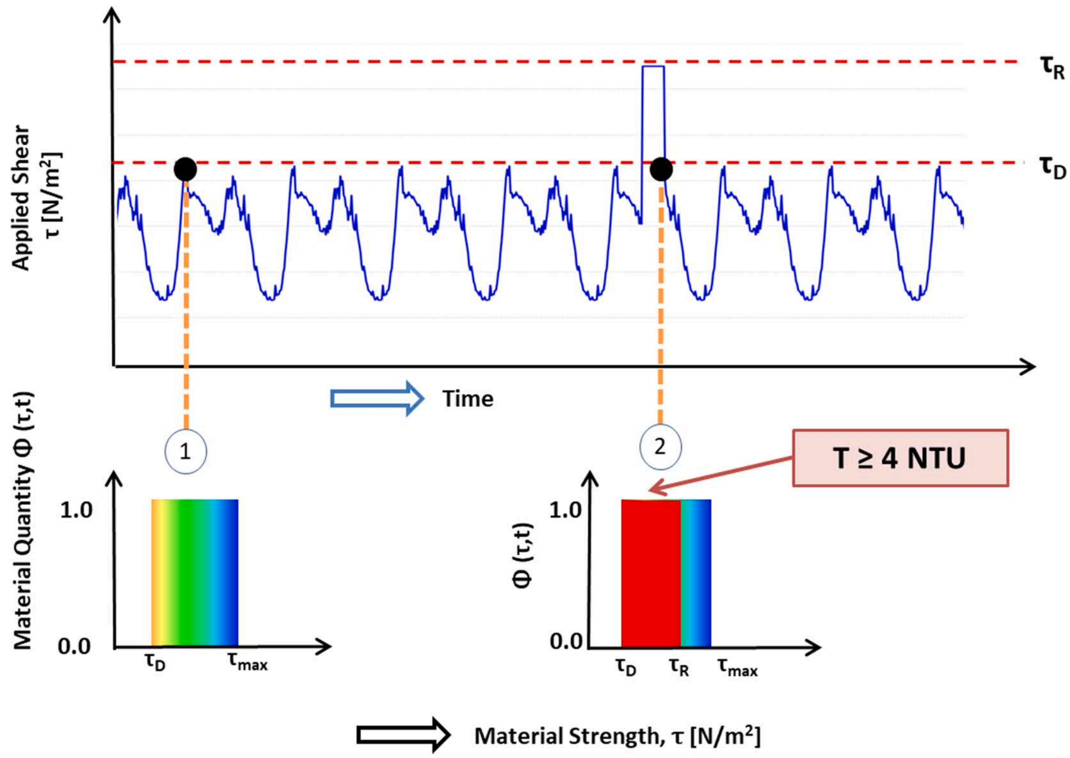

Fig. 1. Applied shear stress profile (N/m^2, upper plot) and cohesive material layer state (φ, lower plots) at given times. τ_D is the maximum daily peak shear stress, τ_R hydraulic event shear stress, τ_{max} simulation specific maximum shear stress. Rainbow colour pallet represents the amount of material held with varying cohesive strength material present on pipe wall for $\varphi = [0,1]$, the red box shows material mobilised due to the hydraulic event.

day 5 a hydraulic event with shear stress τ_R occurrs. The lower plots show snap shot representations of how much material is accumulated at the pipe wall as a function of layer strength. The x-axis shows layer shear strength and the y-axis material quantity between $\varphi = [0,1]$, i.e. no material up to fully developed layers or maximum risk. The amount of material accumulated at each strength is indicated with a graduated colour palette fill, a single colour is not used to avoid misinterpretation of consistent strength. At time point 1, where daily conditions with no change have occurred for a long time, material has fully accumulated at all layer strengths above the daily peak shear stress (and no material with shear strength $< \tau_D$). At time point 2 the red area in the lower plot indicates the material that would be mobilised by event τ_R. Discolouration resilience is breached when this equates to a downstream observable turbidity greater than 4 NTU.

Fig. 2 depicts a design for repeated flow conditioning interventions to guard against observable discolouration due to a future hydraulic event of magnitude τ_R. In many cases the initial flow conditioning operation, following a prolonged period without maintenance, point 1 Fig. 2, may require multiple steps to incrementally remove material and prevent down stream turbidity exceeding the operational intervention target limit of 1 NTU, as shown by point 2 in Fig. 2, total material mobilised indicated by the grey box in the lower plot. At this point all material with layer strengths below τ_c will have been removed from the pipe wall. Post conditioning, material will start to accumulate across all shear strength layers $> \tau_D$, as indicated by point 3 in Fig. 2. The effects of repeated flow conditioning can then be simulated, as shown in this example this is achieved with a single step increase that mobilises material, indicated by the grey boxes, but not generating excessive turbidity (<1 NTU), at points 4 and 5. The interval and magnitude of flow conditioning must prevent a downstream turbidity response >4 NTU whenever a defined event of magnitude τ_R may occur. This risk is highest immediately before the next flow conditioning, as shown in point 6 of Fig. 2, where the L-shaped red marked area represents material mobilised. By maintaining the same magnitude intervention and critical material threshold, an accurate risk-return period, X, for a given configuration can be determined. In reality the period indicated X in Fig. 2 will be far greater than the 3 days shown.

Fig. 3 presents three different flow conditioning designs, one in each of the top 3 plots. The designs show increasingly aggressive flow conditioning and as a result lower return frequency, but with each strategy providing the same level of discolouration resilience. This is shown in the bottom plots as equivalent red areas should a τ_R event occur just prior to planned flow conditioning repeat.

3.4. *Costing framework*

Flow conditioning cost assessment is calculated from two components: a) resource cost to operate the intervention on-site and b) water usage cost. Costs used in this study are representative to reflect possible UK application of the methodology, and are based on the five-year cycle of current UK financial regulation.

To quantify the resource cost, it is assumed that two employees are required on-site, in accordance with common health and safety practices. The work process includes valve management, equipment setup, data collection and health, safety and risk assessments. It was assumed that each trial would require a total of five hours, including all planning, preparation and field work for a minimum one pipe turnover flushing duration. Travel cost to the site has not been included as it is too site-specific. The employee unit hourly cost was taken from the UK national minimum wage of ~10 per hour (www.gov.uk/national-minimum-wage-rates, accessed December 2022). Considering employee pension, overhead management cost, various insurances and travel allowance, it was assumed that resource cost would be 2.25 times unit rate ($2 \times 10 \times 2.25 = £45.0$ per hour).

Since this work is assuming flow conditioning in a demand driven trunk main, water disposal was considered as hydrant discharge, with each site visit generating one volumetric pipe turnover. It was assumed discharge did not incur any disposal / wastewater cost. For the costing

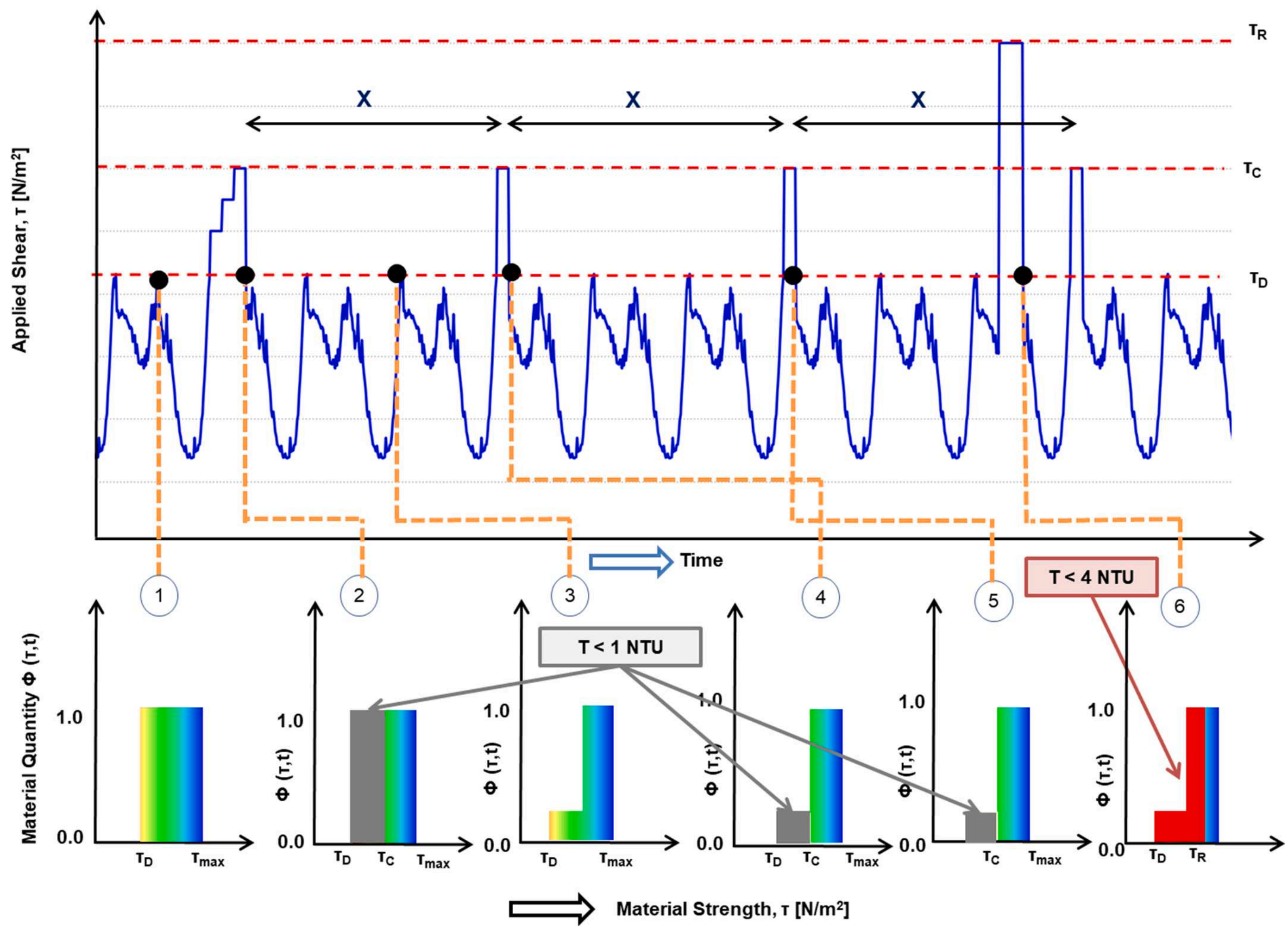

Fig. 2. The conceptual basis of material mobilisation and accumulation for discolouration management decision framework showing applied shear stress profile (upper plot) and cohesive material layer state (φ, lower plot). Rainbow colour pallet represents the varying cohesive strength material present on pipe wall for φ = [0,1], red box shows material mobilised due to the hydraulic event τ_R causing turbidity greater that 4NUT, grey boxes shows material mobilised due to flow conditioning interventions τ_C generating turbidity less than 1NTU. X in the upper plot represents the maintenance return interval.

framework, discharged bulk water cost was determined as 0.84 £/m^3 (Scottish Water, 2013) which included internal maintenance, water treatment and pumping cost.

UK water companies' financial regulatory cycle is currently set at five years and hence for this study a five year design period was selected for cost assessment. To normalise the future cost to its present value, all costs were converted to their net present value (NPV) using a discount rate of 3.5% (Treasury, 2003). The NPV cost was calculated by equation 1;

$$NPV = \sum_{n=0}^{n} \frac{C_n}{(1+i)^n} \tag{1}$$

Where, NPV = Net present value (£), C_n = operational cost at year n (£), i = discount rate (%), n = duration of cash flow (years)

Design and management related cost was excluded from this costing calculation as these are business specific and will be relatively constant across the different operational interventions. Equipment costs such as flushing standpipes, turbidity monitoring equipment, vehicles etc. for flow conditioning was also not included as those are standard water company inventory. The costing framework however could readily be revised to include or exclude costs as required.

3.5. Pareto front assessment for OPEX against discolouration resilience

A cost curve for a fixed level of discolouration resilience can be produced for different flow conditioning strategies by balancing flow magnitude and return frequency, as shown in Fig. 3. However, selecting a pre-defined level of discolouration resilience for a given network is unlikely and is liable to change as networks and demands evolve. To determine a trade-off curve between flow conditioning OPEX and any level of discolouration resilience, a Pareto efficient method was used to generate a set of independent solutions. The true Pareto front was then defined, where the curve represents the best solutions (here minimum cost) for a given level of discolouration resilience.

3.6. Capex interventions

The impact of capital interventions of interest are those aimed to improve water quality, hence decrease the rate at which discolouration material accumulates. As a result, fewer (less frequent) interventions are required to sustain discolouration resilience. This includes improvements to catchments, water treatment works, and upstream pipe replacement or lining. This can be included into the analysis methodolgy by changing the VCDM accumulation period β_r, such that ultimately a set of pareto trade off curves for operational costs against discolouration resilience is produced. The saving in operational costs can then be

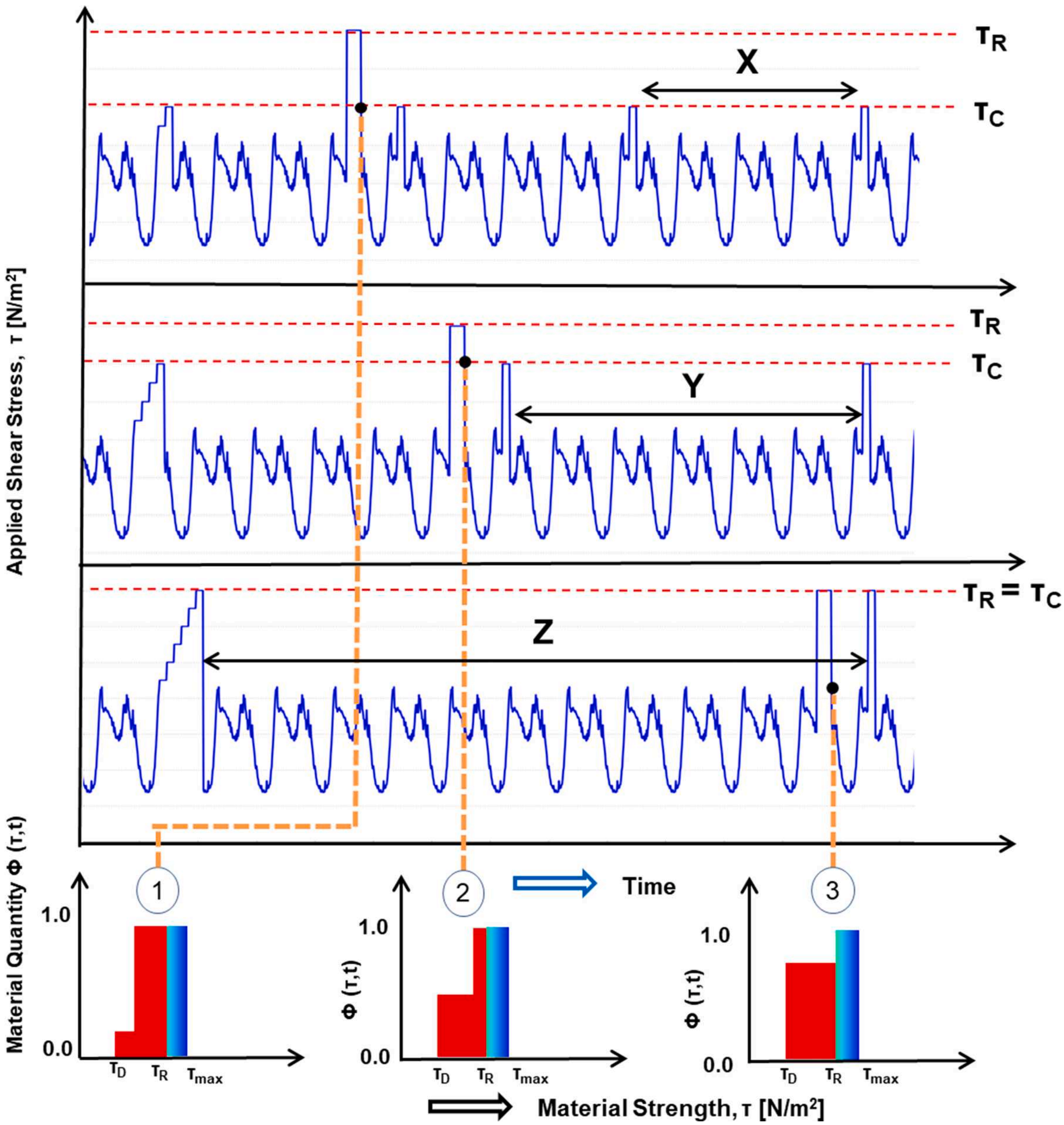

Fig. 3. Discolouration risk management by balancing flow conditioning magnitude and return frequency. Three scenarios are presented, with increasing return frequency (X, Y, Z) and conditioning magnitude from top to bottom. All scenarios provide the same discolouration resilience against hydraulic event τ_R. Lower plot shows cohesive material layers state at given time with rainbow colour pallet representing the cohesive strength material present on pipe and red boxes material mobilised due to the hydraulic events.

compared to the captial options that would achieve the simulated change in accumulation period. The costs and effects of such capital investments are diverse and site specific, making them beyond the scope of the work reported here. The payback periods for such capital investments are likely to be greater than the five-year horizon used, but the analysis can be simply extended through the NPV calculation to estimate such durations.

The accumulation parameter, β_r, was varied across the range of 1.5 to 4.0 years in line with published work (Husband and Boxall, 2011; Vreeburg et al., 2008).

3.7. Sensitivity study

Sensitivity tests were conducted to evaluate the influence of changing the physical characteristics of the trunk main on the obtained Pareto fronts and the resulting solutions. The length and diameter of the trunk main were selected as invariant with time yet both influence water volumes, travel time and durations on site etc. Diameter additionally influences shear stress. The effects of L and D are more readily apparent in the fixed discolouration resilience plots. Extrapolation to moving the Pareto curves is induced from fixed discolouration resilience curves that lift or suppress the Pareto front. Hence sensitivity tests for L and D focussed on the initial trade-off curve developed with a fixed discolouration resilience τ_R and a daily peak shear stress τ_D. Pipe roughness was not included due to its potential variability over time in response to varying hydraulic conditions impacting physical layer state (Sunny et al., 2020).

The effect of accumulation period (β_r) was tested for both fixed discolouration resilience and Pareto front, as β_r may reflect changes in source water quality and inform operational decisions.

3.8. Case study

The methodology is illustarted for application to a 1 km pipe length with an effective internal diameter (ID) of 228 mm (9″) and pipe roughness (k_s) 5 mm, based on a real trunk main of interest. The accumulation return period, which is the time taken to go from no material to fully developed material layer, was selected as 1 year, based on previous findings (Furnass, 2015; Furnass et al., 2014; Husband and Boxall, 2011) and believed to be representative of the surface water source and cast iron pipe material of the real DWDS. A repeating 24-hour diurnal flow profile with a maximum peak of 20 l/s ($\tau_D = 0.55$ N/m^2) was selected for simplification and ease of interpretation. In operational systems, demand profiles vary, which influences the amount of material on the pipe wall. Flow data can be used and input to the VCDM to track the material quantity in the shear strength layers. Discolouration resilience was initially asumed to be required for a sustained 15 l/s above the daily peak flow, totalling 35 l/s ($\tau_R = 1.5$ N/m^2) based on an operational requirement of the real system.

The upstream end of the pipeline on which these simulations is based was a water treatment works, but incoming mass flux of material would still not be zero. With background turbidity known to be < 0.3 NTU from a previous study (Sunny et al., 2020), the simulations were run with a background turbidity of between 0 and 0.3 NTU generated using normally distributed random numbers.

The initial layer profile is an important consideration in VCDM simulations (Furnass, 2015). VCDM simulations were hence run with φ=1.0 at the start for all layers for a period of 3 months (not included here) to develop a stable and realistic profile for the start of the period of interest. The VCDM divides the material layers into a number of discrete bands. Based on previous work this was set to 100, which was found to be more than sufficient with no significant impact on computational time (Sunny et al., 2023).

4. Results

4.1. Applied intervention versus return frequency trade-off curve for a target discolouration resilience

Fig. 4 presents the relationship between the shear stress applied by flow conditioning interventions and return frequency necessary to protect against an event $\tau_R = 1.5$ N/m^2 generating downstream turbidity of 4 NTU or greater. Flow conditioning interventions that induce less than 0.925 N/m^2 cannot protect against the defined event, as this leaves sufficient material in layers between 0.925 and 1.5 N/m^2 that if mobilised would cause a turbidity response in excess of 4 NTU. When the flow conditioning shear stress was greater than the event shear stress (1.5 N/m^2), the return period is constant (105 days). In this example this effect can be seen starting from 1.2 N/m^2. This highlights that flow conditioning (or any other intervention) that removes material held in layers with a shear strength greater than the target discolouration resilience (or just less than, in this case 1.2 N/m^2) has no benefit in the mitigation in this discolouration risk. This is logical because as material accumulation

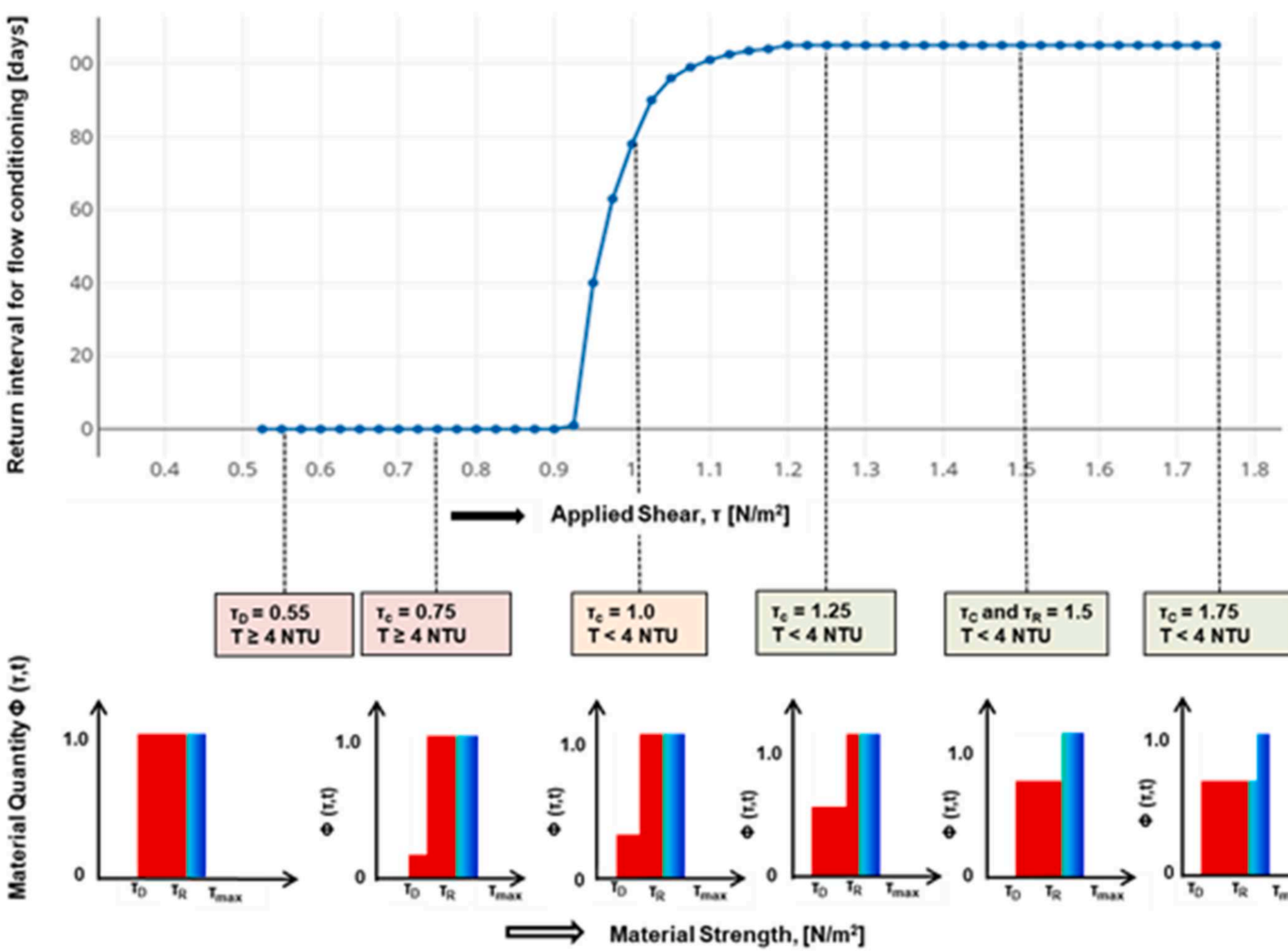

Fig. 4. Top plot is trade-off curve of applied conditioning shear stress and risk-return period with peak daily shear stress $\tau_D = 0.55$ N/m^2 and target discolouration resilience $\tau_{R=}$ 1.5 N/m^2 for a 1 km long 228 mm internal diameter main. Bottom plots represent VCDM material layer condition, with red highlighting the material that would be mobilised if τ_R occurred just prior to intervention, i.e. worst case scenario.

occurs at all strengths simultaneously, it is the amount of material in layers with strength less than imposed by the event (τ_R) that dictate the risk. It is important to note that although the same level of protection can be delivered for all interventions > 0.925 N/m^2, different costs will be associated with different strategies due to return frequencies, duration on site and volumes of water discharged.

4.2. Cost assessment for a fixed discolouration resilience

Fig. 5 presents the operational costs for flow conditioning interventions over a five-year financial period to maintain a discolouration resilience $\tau_R = 1.5$ N/m^2 as defined by the trade-off curve in Fig. 4. The lowest cost from Fig. 5 is found for flow conditioning at 1.125 N/m^2 with return period of 102 days. The cost increases for interventions that imposed shear stress less 1.125 N/m^2 are a result of increasing intervention frequency. Above 1.125 N/m^2 there are step increases in the cost profile due to the need for flow conditioning operations to span over more than one site visit. This is necessary as only a single step can occur per day due to the time to turn over a complete pipe volume based on daily peak only occurring in the morning and step size being limited to not generate downstream turbidity exceeding 1 NTU. With each extra daily visit there are increased staffing and associated water costs.

Fig. 6 presents the percentage cost breakdown of the effective flow conditioning strategies from Fig. 5, showing categories of initial and repeat staffing and water costs. The figure shows that repeated trial resources dominated total cost, always >80%. This is expected due to the number of repeat interventions within the five-year period (the maximum return interval was 105 days). Resource costs in these scenarios are also always 80% or greater than water costs, a result of the minimal discharge volumes required by imposing additional flow to coincide with peak demand.

4.3. Cost assessment for varying discolouration resilience: Pareto front assessment

Using the same method to determine the costs for a single defined discolouration resilience, the minimum cost for different discolouration resilience targets was determined which is shown in Fig. 7. The Pareto front, which represent the set of solutions, shows that intervention costs over five years increases exponentially ($R^2 = 0.98$) with increasing discolouration resilience. A discolouration resilience event imposing 1.25 N/m^2 or less did not create downstream discoloration greater than 4 NTU so no interventions are necessary, and this defines the minimum point. Using Fig. 7, an operator can select a discolouration resilience target for this scenario while considering budget constraints. For example, a discolouration resilience of ~1.9 N/m^2 can be achieved at only 25% of the costs associated with the most expensive option for 2.5 N/m^2 resilience.

4.4. Capital investments

The capital investments of relevance are those that change the rate at which discolouration material accumulates, a parameter in the VCDM model. Fig. 8 shows the effects of changing accumulation period, that is the time taken for material layers to fully develop (φ goes from 0 to 1) on the trade-off curve, effectively creating a family of curves around the original one-year return shown in Fig. 4.

As previously the costs and then the Pareto front can be developed for each of the accumulation periods assumed to occur as a result of different capital investment, as shown in Fig. 9. The 5-year operational costs reduce with increasing accumulation periods (decreasing accumulation rate), retaining an exponential function. This means that the benefits of capital investments, in terms of reduced operational costs, are greatest in situations where a high level of discolouration resilience is necessary. For the most extreme discolouration resilience and greatest improvement in accumulation shown in Fig. 9 (from 1 year to 4 years), this represents an operational saving of approaching £60,000 / 5year cycle for a 1 km length of trunk main. If we assume a system with perhaps 50 km of trunk mains, all with similar potential and linear increase in costs for flow conditioning, that would be a £3 M saving in 5 years. But with treatment works upgrades to improve filtration, membrane upgrades etc., typically costing £10 - £100 M, the capital option would take multiple 5 year cycles to pay back if discolouration management in the trunk main is the only consideration. For lower resilience levels the payback periods are far longer.

4.5. Sensitivity analysis for the impact of length and diameter

A sensitivity analysis investigating pipe length impact on flow conditioning and intervention frequency is shown in Fig. 10. The plot shows as expected that the shorter the length, the longer the return period. This is because in shorter pipes less surface area is available for material

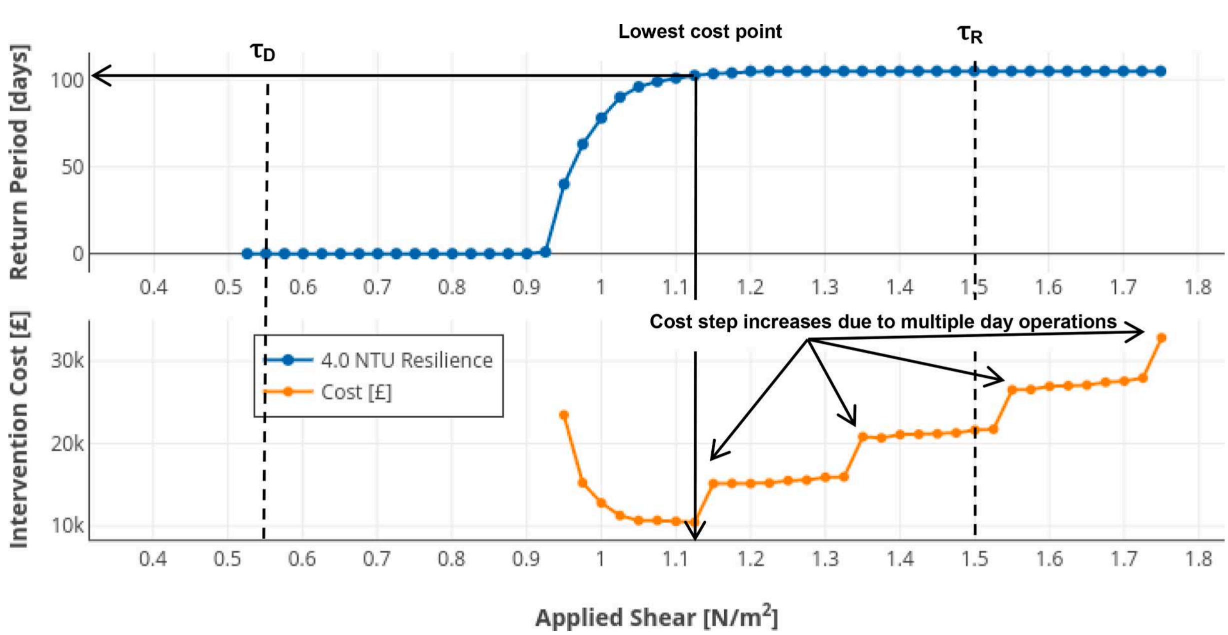

Fig. 5. Five-year intervention cost assessment based on imposed shear stress conditioning and risk-return period for a fixed discolouration resilience of 1.5 N/m^2.

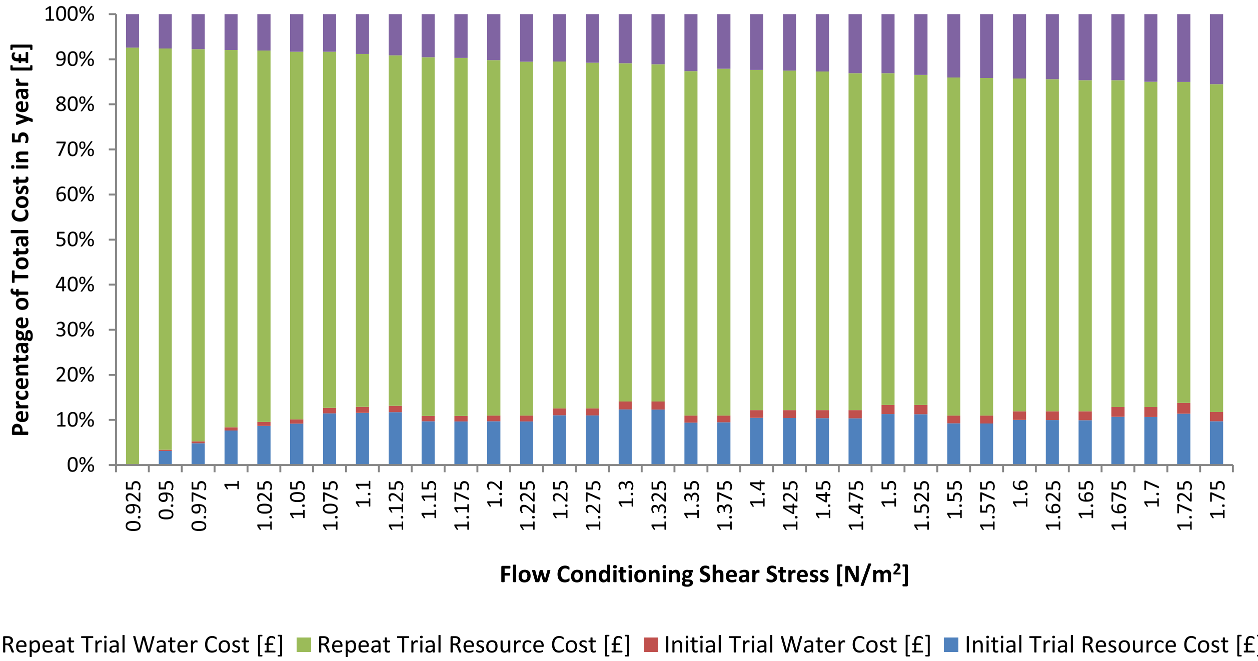

Fig. 6. Cost breakdown for five years of imposed intervention to provide discolouration resilience for a 1.5 N/m^2 event.

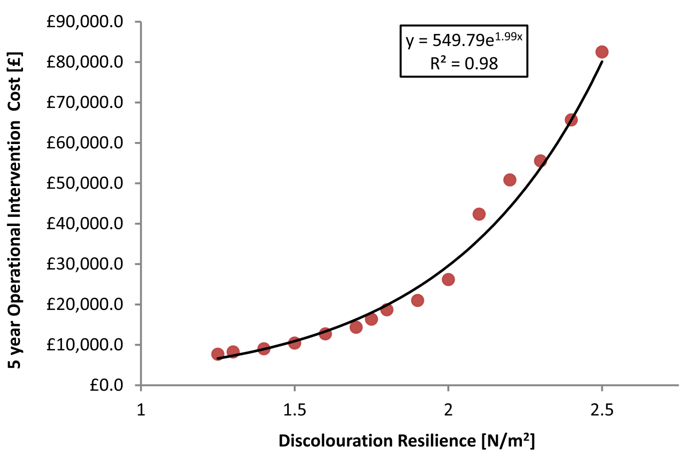

Fig. 7. Operational expenditure (£) for five year period to maintain target discolouration resilience (τ_R) against discolouration resilience using periodic flow conditioning interventions.

accumulation and subsequent erosion (the VCDM assumes uniform accumulation). As a τ_R event mobilises the same amount of material per unit area, irrespective of length, peak turbidity in shorter pipes is associated with the pipe turnover volume. However, when a certain pipe length is reached, all accumulated material of specific strength depending on imposed event can be mobilised before the time taken for a pipe turnover. When this occurs, at around 2 km in the configuration used here, turbidity values plateau at a peak value and hence the return period is similar after a certain length. This suggests that flow conditioning becomes more efficient (the return frequency does not increase) for longer lengths of trunk main. However there are practical limits to this, including the duration required for a turnover of pipe volume and the length over which conditions are suitably consistent to be considered a single pipe length.

The effect of diameter on the trade-off curve for flow conditioning and return period is shown in Fig. 11, showing that the imposed flow conditioning shear stress has reducing impact and longer return periods as diameter increases. This is due to the surface area to volume effect causing greater dilution of material mobilised into the bulk water (the model treats turbidity as an effective concentration). For example, a 200 mm diameter pipe diameter has a twice the surface area to volume ratio than a 500 mm pipe. As the shear stress was maintained constant irrespective of diameter for sensitivity assessment, the flow rate required is much higher in larger diameter pipes compared to smaller ones. As a result, in the scenarios investigated here when an event shear stress is applied in the smaller pipe diameters, the lower the dilution of mobilised material into the bulk flow and the higher the resulting observed turbidity and therefore the return frequency required to manage this.

5. Discussion

5.1. Trade-off diagram and cost assessment

A novel methodology is presented for designing flow conditioning cycles in a demand driven network by considering long-term costs against discolouration resilience. While previous models determined TOTEX based on structural performance, this is the first model that considers discolouration risk as a water quality performance. The estimation of operational expenditure is the most complex and advanced aspect of this model, and it captures the effects of capital investment so that the trade-off for TOTEX can be considered.

The proposed methodology utilises the VCDM model that captures the non-linear relationship between shear stress imposed by flow conditioning and the return frequency necessary to maintain discolouration resilience. This is a result of the complex material layer conditions and accumulation processes that occur on pipe walls throughout distribution systems. A key observation is that more aggressive cleaning does not result in greater discolouration resilience, or persistence of such resilience. This initially may appear counterintuitive, but is logical when considering that material re-accumulates at all strengths simultaneously, as captured in the VCDM functionality. Furthermore, Figs. 4, 10 and 11 demonstrate that varying magnitude interventions can provide the same discolouration resilience, but with significant variation in cost. Fig. 5 highlights how a minimum cost can be defined, the identification of which is non-trivial.

The modelling undertaken utilises standard one-dimensional solutions to describe pipe flow. Like most water quality models, the results

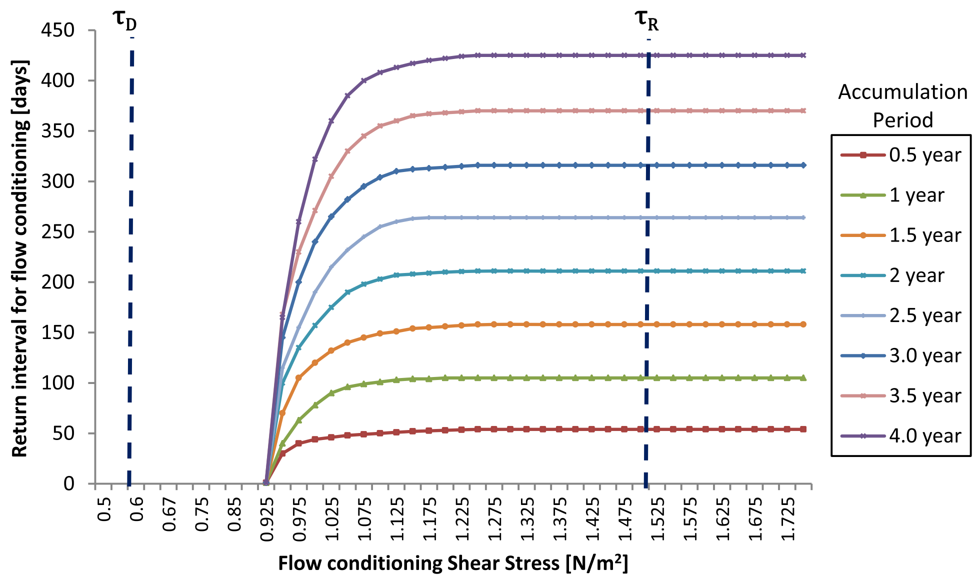

Fig. 8. Effect of changing accumulation period (time for material layers to fully develop, such as due to capital investment) on imposed shear stress and return interval sustaining a discolouration resilience of 1.5 N/m^2.

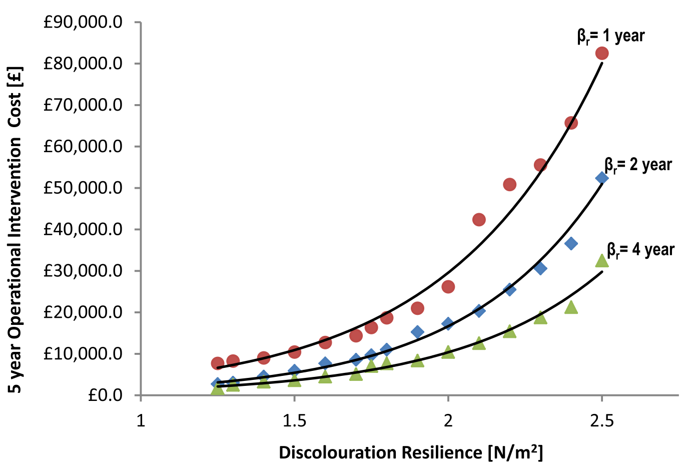

Fig. 9. Accumulation period effect on five-year intervention costs against discolouration resilience.

here are dependant on the accuracy of the representation in the hydraulic model. For this application shear stress is used derived from calculated headloss, not only transport and tracking as with many other water quality applications such as chlorine decay, hence the dependency on hydraulic accuracy is greater. The process of flow conditioning, like flushing or fire-flow testing, does however provide an ideal opportunity to collect hydraulic calibration data if coupled with measurement of flow rate and up and downstream pressures (Boxall et al., 2004). It should be noted that the modelling undertaken is still time consuming and complex and hence is only likely to be justifiable for trunk mains or other pipes with large downstream populations and hence high consequences. Automating or generalising, if possible, could provide effective solutions for smaller pipes.

The parameter of interest throughout this work has been discolouration as it is the key cause of customer dissatisfaction with water quality. The effects of discolouration are dominated by metals, including iron and manganese, and biofilms are also known to play a crucial role in layer development. The methodology reported could therefore be adapted and applied for management of metals and microbial loading. This however would be on a network specific basis, whereas turbidity behaviour has been shown to be ubiquitous.

5.2. Pareto front assessment for cost versus discolouration resilience

A key challenge in discolouration management is the uncertainty of 'the event' that discolouration resilience should be provided against. The Pareto front assessment in Fig. 7 allows for a risk-based approach to balance water quality and costs, which aligns with the approach advocated in the Bonn Water Charter and cascades into governance and regulation. The methodology presented is the first that can be used as a proactive decision support tool informing a discolouration risk based management approach. With suitably validated VCDM modelling, the methodology can be used to develop budgets for discolouration management as part of planning for upcoming fiscal periods such as the UK water industry five-year Asset Management Period (AMP) cycle.

To ensure confidence in making risk-based investment decisions and plans, it is essential to generate a substantial number of solutions within the Pareto front range, allowing for a well-defined Pareto optimal band. The results reported here made use of batched simulations and brute force techniques to enable this. However, automation, such as the inclusion of appropriate search and optimization algorithms, could further reduce the number of simulations required and enable the production of Pareto fronts for pipelines under any design constraints.

In this work the five-year cost profile was shown to be dominated by the intervention return frequency (Fig. 6), which is dictated by the network accumulation rate. While improving treated water quality can reduce the rate of accumulation (Vreeburg et al., 2008), it can be capitally expensive (Postawa et al., 2013). By mapping a Pareto front, this study allows for an assessment of the trade-off between maintenance interventions (OPEX) and potential treatment works investments (CAPEX) over the asset's lifespan (Fig. 7). While previous works showed that both flow conditioning interventions (Sunny et al., 2020) and treated water quality (Vreeburg et al., 2008) can improve downstream network discolouration risk, this work demonstrates that a potential trade-off solution between water treatment upgrades and trunk main maintenance can inform discolouration management in a more robust manner. This is the first proposed WLC model that accounts for the cleaning intervention and Water Treatment Works (WTW) improvement processes to manage discolouration considering TOTEX. With this framework, an operator can find the synergy between WTW upgrade and network maintenace such that discolouration risk can be optmised from WTW to consumer on a network basis.

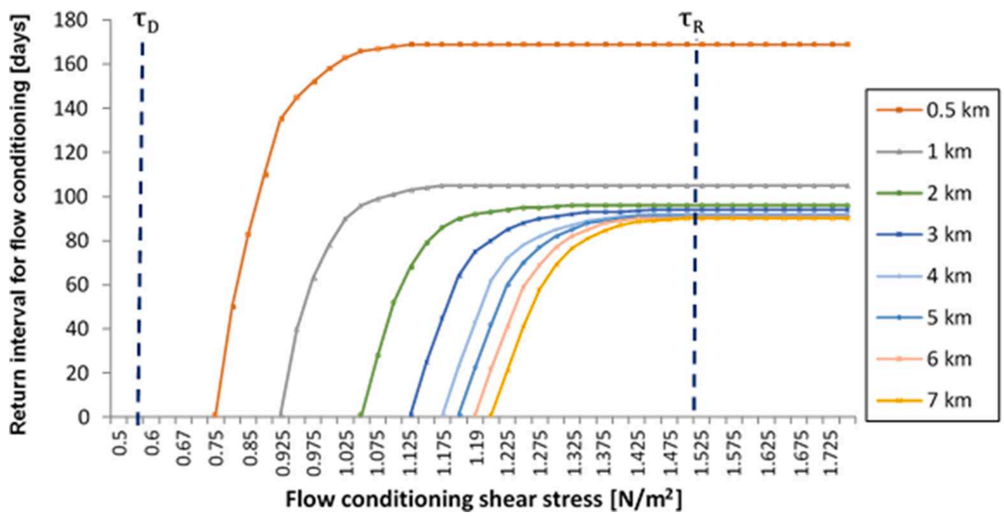

Fig. 10. Sensitivity analysis trade-off curve for varying pipe lengths to achieve a fixed discolouration resilience of 1.5 N/m^2. Idealised model conditions (Fig. 4) length was 1.0 km.

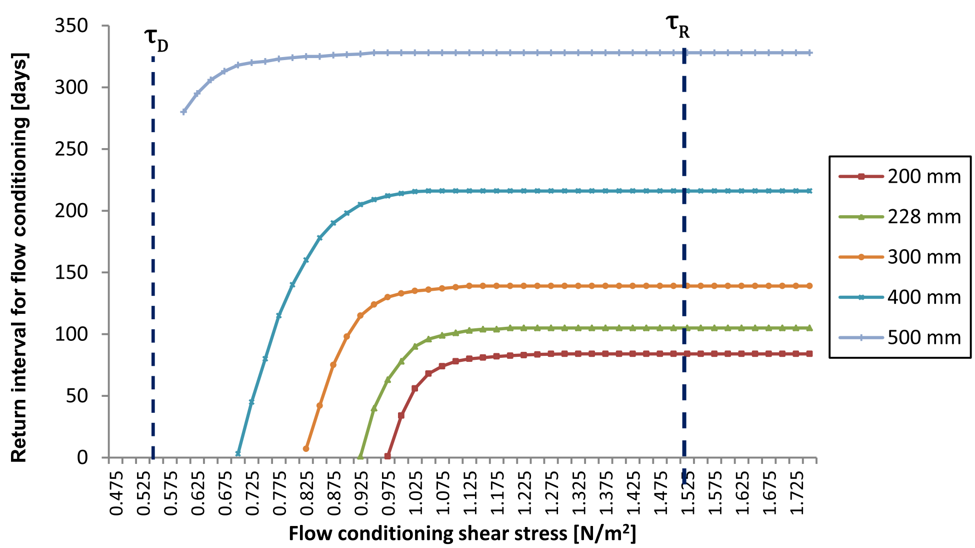

Fig. 11. Sensitivity analysis trade-off curve for varying internal pipe diameter to achieve a fixed discolouration resilience of 1.5 N/m^2. Idealised model conditions (Fig. 4) internal diameter was 228 mm.

5.3. Flow conditioning strategies

Implementation of flow conditioning in a demand-driven network can be more complex and hazardous than non-demand driven mains as it requires manual interventions and they directly supply consumers. While no survey has indicated what percentage of the network comes within this category, it is plausible to assume demand-driven mains could cover up to 50% of the total network where populations are uniformly distributed in a relatively small land area, such as Europe. This indicates the necessity of designing specific interventions for demand-driven systems.

In the demand driven system investigated in this work, the cost of the water discharged is found to be less than 20% for all scenarios, yet this strategy may not be applicable due to reputational or environmental issues. As for non-demand driven mains, it may however be possible to avoid discharging water in some circumstances, such as in looped systems or parallel mains. Valve operations can be used to manage intervention in these cases to control flow direction or balance and magnitude (Cook et al., 2015). Along with managing reservoir fill rates via valve or pump control, these processes can be fully automated by a Programmable Logic Controller (PLC) leaving minimal or no additional resource cost and no water wastage (Cook and Husband, 2017). Such automation processes, equipment and costs are highly situation specific, hence this aspect has not been included within the scope of this work.

5.4. Discolouration resilience for a new or invasively cleaned pipe

The application of the methodology in this paper considered trunk mains that have been operational for some time. The methodology is also relevant for discolouration risk management in new or relined pipes or following an invasive cleaning intervention.

Fig. 12 compares periodic flow conditioning to provide discolouration resilience in a new (or otherwise fully clean) pipe compared to an established pipe, with the difference being in the starting state. A new (or relined) pipe can be simulated in the VCDM by setting initial wall layer condition at $\varphi = 0$, indicating no material present on the pipe wall (Furnass et al., 2014). While this is considered accurate for a new or relined pipe, the initial material condition ($\varphi(\tau,t)$) can remain uncertain after invasive cleaning strategies (e.g. swabbing or ice pigging) (Sunny et al., 2017), and hence setting $\varphi(\tau,t) = 0$ is not necessarily considered

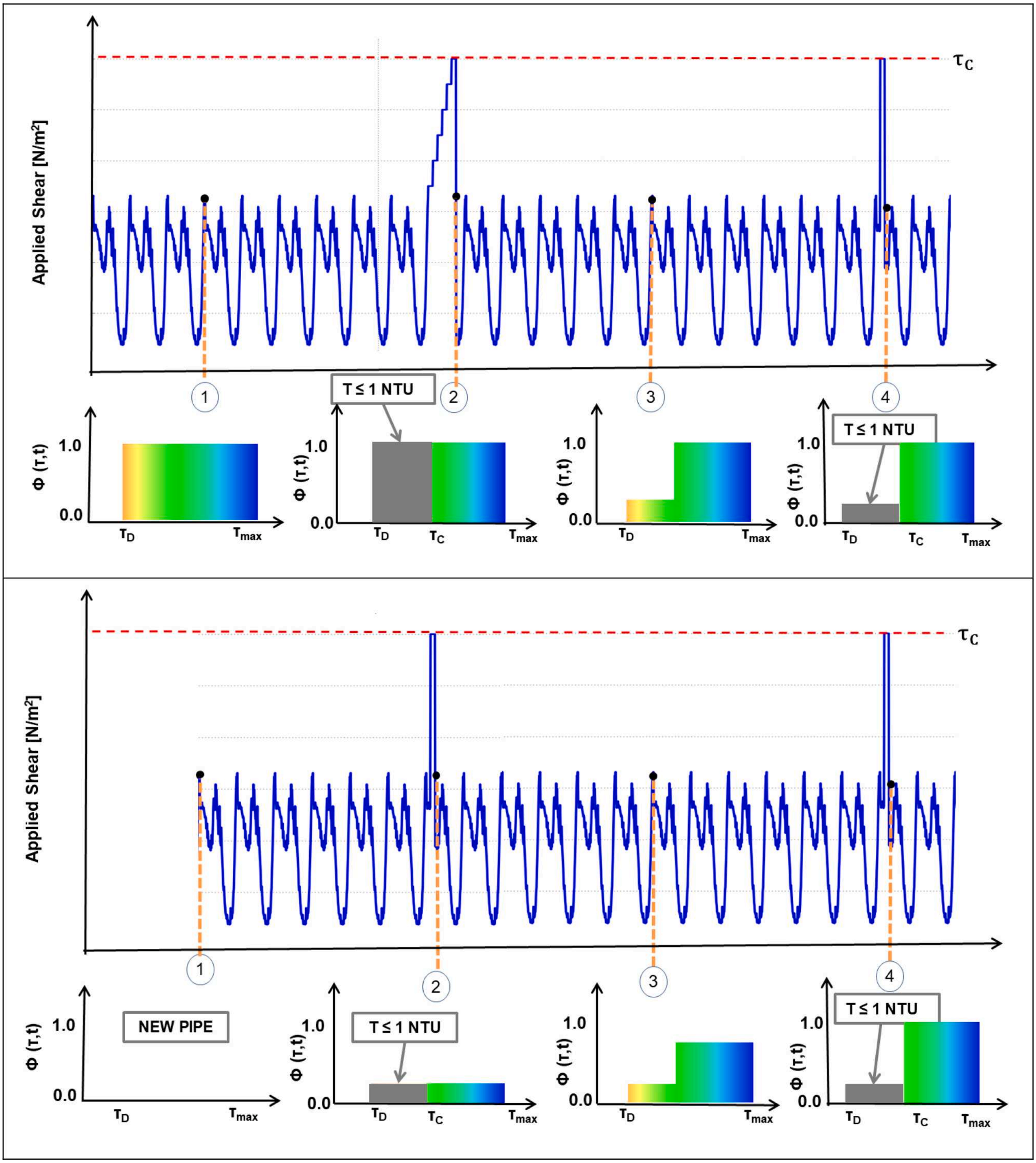

Fig. 12. Managing discolouration risk in established (top) and new (or relined / fully cleaned, bottom) pipe using flow conditioning with turbidity response limited to $\leq$ 1 NTU. Material layer state as represented by the VCDM at specific points shown beneath each plot. Material acccumulation rate is accelerated to aid visual representation.

realistic. In Fig. 12, there is initially no discolouration material on the new pipe, however, over time, material accumulates at all layer strengths simultaneously, regardless of the preceding material legacy or intervention. Fig. 12 then shows how repeated flow conditioning can be used to manage the layers that represent the greatest risk. If this is initially done after one maintenance period from installation there is no need for the stepped flushing that may otherwise be necessary. The cost implications of this are then trivial in the estimates provided here. Following the initial accumulation period, it is important to note that a new pipe poses the same discolouration risk for the design event hydraulics, so additional benefits are short-lived.

The process of material accumulation at all layer strengths simultaneously is a critical conceptual aspect of this work, key to why regular maintenance is necessary and why for efficiency, maintenance should target layers that represent the greatest discolouration risk. These are usually the layers with strength just greater than the normal operating peak hydraulic shear stress, as any small increase in flow can mobilise this material. A key message is that any maintenance is only temporary, long-term discolouration management will be required for all pipes where elevated flows are possible.

5.5. Long-term investment

The resource and financial implications of managing ageing water infrastructure are concerning. AWWA (2012) stated that about $1 trillion in funding would be required over the coming 25 years to effectively manage and deliver clean water considering both aged asset rehabilitation and meeting the demand of growing populations. Such estimates are usually dominated by pipeline asset renewal or replacement costs. This study shows that flow conditioning is a viable long-term maintenance strategy, using only controlled changes in hydraulics, to manage discolouration risk. No specialist tools or rezoning are required for operation and it can potentially be implemented across most networks and pipes conditions. It should be noted that this is only for discolouration resilience, when there are structural issues compromising the continuity of supply and or water loss, replacement, structural lining etc. will still be required.

The proposed methodology in this paper is based on flow conditioning OPEX assessment that then includes the impacts of CAPEX investment through changes to material accumulation periods, allowing some estimation and assessment of TOTEX. A full trade-off between CAPEX and OPEX is not possible due to the specific costs associated with improving water quality and because the resulting change in accumulation period would be is unknown. This is an active area of research (www.PODDS.co.uk, accessed July 2023), but better understanding and quantification is needed in order to help develop holistic discolouration management strategies incorporating different capital and operational intervention types.

6. Conclusion

This paper presents a novel methodology for designing cost-effective long-term trunk main discolouration management strategies. The Variable Condition Discolouration Model (VCDM), which includes simultaneous material mobilisation and accumulation functionality, is used to assess total costs and how the distribution system's operational and maintenance strategies can deliver a desired level of discolouration resilience.

- The work demonstrates how to derive Pareto trade-off curves between applied shear stress, cleaning intervention severity and frequency and water quality as a function of target discolouration resilience.
- Pipe length and diameter trade-off curves for target discolouration resilience show these are site-specific and simulations are required for each pipe system to inform risk proactively.
- The strategic effects of capital investments to improve water quality, with resulting change in material accumulation periods, shows a complex influence on induced shear stress and return period trade-off for both target discolouration resilience and Pareto front curve. This is important emergent behaviour, resulting from the accurate simulation of material accumulation occurring simultaneously at all cohesive layer strengths, within the VCDM.
- The Pareto set solutions provide a unique opportunity to inform holistic management of discolouration risk to achieve a desired level of discolouration resilience, trading off capital (such as upgrading treatment works or pipe replacement) and operational (severity and frequency of cleaning intervention) from WTW to customers tap. The selection of a target discolouration resilience means this is a risk-based approach consistent with the requirements set out in the Bonn Charter.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

No data was used for the research described in the article.

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