Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Keeping drinking water crystal clear		
Period when the underpinning research was undertaken: 2013–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Boxall, J.	Professor of Water Infrastructure Engineering	2000–present
Husband, P. S.	Research Fellow	2003–present
Collins, R.	Senior Lecturer	2013–present
Furnass, W.	Senior Research Software Engineer	2016–present
Douterelo Soler I.	Post-Doctoral Fellow	2010–present
Fish, K.E.	Post-Doctoral Researcher	2013–present
Period when the claimed impact occurred: August 2013–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Sheffield's research has uncovered and validated the key synergies between in-pipe hydraulics, material accumulation processes and the role of microbial biofilms in drinking water discolouration. Working with 13 major UK water companies, we have demonstrated that discolouration can be operationally managed by planned hydraulic conditioning. Application of the research to the operation of 2,686km of UK trunk mains delivered over £411m in cost-savings in operational and capital expenditure. It has enhanced water service delivery in the UK, the USA, the Netherlands, and Spain, and improved compliance with drinking water standards. Knowledge from the research has been included in international best practice guidelines.

2. Underpinning research (indicative maximum 500 words)

The Water Distribution Systems Group led by Professor Joby Boxall has an impressive track record in research associated with the Prediction and management Of Discolouration in Distribution Systems (PODDS). Since 2013, research funded by a consortium of 13 UK water companies, representing 77% of the UK's water distribution network, has focused on discolouration associated with trunk mains.

Sheffield's research concept is that discolouration is not due to sediments but accumulated layers of particulate material on pipe walls that are released when the flow shear stress exceeds their hydraulically conditioned strength. Testing using a unique full-scale laboratory system at Sheffield has enhanced this understanding. This testing demonstrated that microbial colonisation of the pipe wall was controlling material accumulation and that managing the in-pipe flows limits the accumulation of particles within the extracellular polymeric substances of pipe wall biofilms and so can ultimately control discolouration levels **[R1]**.

Combining these insights with analysis and simulation of over a 1000 field and laboratory applications (primarily in the UK, but also in Australia, the Netherlands, US, Spain, and Portugal), linked common behaviour in real-world discolouration events to microbially-based

processes for the first time. By having the micro-scale knowledge that biofilms are integral to in-pipe material accumulation, discolouration events can be simulated at the macro-scale; this means that water companies can develop holistic, long-term network operational strategies **[R2]**.

Trunk mains are critical assets where discolouration events can affect millions of downstream customers. Prior to 2013 there was no accepted understanding of discolouration risks from trunk mains or strategies for controlling them, and conventional physical interventions were disruptive and often reliant on the construction of millions of pounds worth of alternative supply routes.

Sheffield's research focused on developing operational PODDS strategies supported by improved modelling tools, which were then validated with all the water company consortium members.

- A flow conditioning strategy applied to an in-service cast iron trunk main with a known discolouration risk demonstrated that the managed removal of accumulated material was possible without serviceability or quality risk. It also confirmed the re-accumulation of material and in this case that the maximum discolouration risk may reoccur in just over 2 years. This enabled the collaborating water company to propose a maintenance plan that reduced discolouration risk using 'operational flow conditioning' at periodic intervals to improve asset condition and network resilience without requiring the trunk main to be decommissioned for invasive cleaning **[R3]**.
- Understanding and refining flow conditioning was achieved through an 18-month study subjecting 10 km of live trunk main, of known discolouration risk, to a series of innovative trials. Carefully controlling the rate of layer mobilisation through managed flow increases proved that these new approaches and supporting models could be used to deliver proactive PODDS operational strategies **[R4]**.
- These successful applications led to improved network monitoring at six further operational sites, supported by the development of turbidity measurement equipment to detect discolouration [http://blog.atiuk.com/nephnet-goes-strength-strength-2]. Importantly, modelling was shown to be able to simulate the measured turbidity responses accurately at all sites. Outputs from this collaborative process helped overcome sector risk aversion for interventions on critical high-risk infrastructure, by building confidence amongst the water suppliers, and subsequently through communications with the relevant regulators **[R5]**.

The insights and data from the aforementioned trials led to the development and validation of a Variable Condition Discolouration Model (VCDM). By combining material accumulation and regeneration knowledge, with previously verified mobilisation predictions, the ability to accurately simulate discolouration behaviour over many years is facilitating long-term scenario and maintenance planning with cost benefit analysis **[R6]**. Driven by industry requests, an online VCDM tool was launched in 2020 (https://vcdm.shef.ac.uk/).

In summary, the application of PODDS operational strategies has transformed the management of discolouration in trunk mains. It has been enabled by the combination of improved fundamental understanding **[R1, R2, R4]**, new modelling tools **[R6]**, monitoring approaches **[R5],** and new operational strategies **[R3]**.

3. References to the research (indicative maximum of six references)

University of Sheffield staff and students in **bold**

R1. **Fish, K. E., Collins, R., Green, N. H., Sharpe, R. L., Douterelo, I.,** Osborn, A. M., & **Boxall, J. B.** (2015). Characterisation of the Physical Composition and Microbial Community Structure of Biofilms within a Model Full-Scale Drinking Water Distribution System. *PLoS ONE, 10*(2), e0115824. https://doi.org/10.1371/journal.pone.0115824. Cited by 44.

R2. **Husband, S., Fish, K. E., Douterelo, I.,** & **Boxall, J.** (2016). Linking discolouration modelling and biofilm behaviour within drinking water distribution systems. *Water Supply, 16*(4), 942–950. https://doi.org/10.2166/ws.2016.045. Cited by 9.

R3. **Furnass, W. R., Mounce, S. R., Husband, S., Collins, R. P.,** & **Boxall, J. B.** (2019). Calibrating and validating a combined accumulation and mobilisation model for water distribution system discolouration using particle swarm optimisation. *Smart Water, 4*(1), 3. https://doi.org/10.1186/s40713-019-0015-z. Cited by 2.

R4. Sunny, I., **Husband, P. S.,** & **Boxall, J. B. (**2020). Impact of hydraulic interventions on chronic and acute material loading and discolouration risk in drinking water distribution systems. *Water Research, 169*, 115224. https://doi.org/10.1016/j.watres.2019.115224. Cited by 4.

R5. **Husband, S.,** & **Boxall, J. (**2016). Understanding and managing discolouration risk in trunk mains. *Water Research, 107*, 127–140. https://doi.org/10.1016/j.watres.2016.10.049. Cited by 18.

R6. **Husband, S.,** & **Boxall, J.** (2014). Predictive water quality modelling and resilience flow conditioning to manage discolouration risk in operational trunk mains. *Journal of Water Supply: Research and Technology-Aqua, 64*(5), 529–542. https://doi.org/10.2166/aqua.2014.042. Cited by 5.

4. Details of the impact (indicative maximum 750 words)

Our research has enabled a step-change in the long-term, network-wide identification and management of drinking water discolouration from trunk mains. The resulting far-reaching, multi-national impact is described below.

Economic impact

The 13 major UK water companies in the consortium have realised considerable financial savings as a direct consequence of Sheffield's research. In 2016, Northumbrian Water and Scottish Water published the first publicly available examples of impact from the application of a PODDS operational strategy to selected trunk mains systems. Following training and workshops delivered by the University of Sheffield based on the research **[R5, R6]**, Northumbrian Water adopted the PODDS operational strategy for 350km of water mains, achieving a 90% cost reduction versus traditional mains cleaning: from £170/m to £17/m. The Chief Executive stated, "*The research has delivered a new understanding of the root causes of discolouration in water networks that will revolutionise industry procedures*" **[S1]**. Similarly Scottish Water announced that PODDS has achieved "*the same customer outcome, but at lower cost & service risk"* and reported capital programme savings of £15m by moving to PODDS based strategies and away from invasive mains-cleaning interventions **[R4, S2 p.6&7]**. Building on these examples, the trunk mains conditioning approach was more widely adopted by the other members of the

consortium. The scale and complexity of application varies by company and trunk main system but collectively they estimated that Sheffield's research has been applied to 2,686 km of pipes, 12.5% of their trunk main networks at an average saving of £153/m of pipe. In total, adoption of PODDS operational strategies has mitigated £411m of capital and operational expenditure since August 2013 **[S3]**.

The UK Drinking Water Inspectorate (DWI) imposes significant financial penalties on water companies for failing to meet their contractual customer contact performance targets, e.g. £6m in one year for one company (Yorkshire Water Annual Performance Report, 2018-2019, pp.62-63). Within the impact period adoption of PODDS strategies by the consortium members has been central to their achieving more than 35% drop in customer contacts regarding water discolouration and has therefore reduced the risk of financial losses based on poor regulatory compliance **[S3]**.

UK water companies include the use of PODDS operational strategies in their five-year Asset Management Plans (AMP) (used by The Water Service Regulation Authority (Ofwat) to set customer prices) - evidencing a clear impact on the strategic business planning process within regulated UK water companies **[S3]**.

Water industry suppliers, such as hydraulic modelling software companies and monitoring equipment manufacturers, have also integrated Sheffield's research into their products **[R3, R6]**. For example, Sheffield's accumulation and release models are a core feature in DNV GL's (Norway) Synergi Water software. DNV GL [text removed for publication] Head of Customer Excellence stated "*The Turbidity Modelling tool in our Synergi Water software is directly based on the PODDS model [...] Synergi Water is at the forefront of market-driven development, an accomplishment that has been considerably supported by the work of Professor Joby Boxall and his team*" **[S4]**. Furthermore, the Director of the international electrochemical sensor manufacturer ATI commented, "*The PODDS models underpinned the NephNet turbidity monitor. [...] as a result of Sheffield's work ATI has also developed two new products and is very involved with Smart Water worldwide."* The two new products developed are ChlorNet and the smart sensor system MetriNet that have sales approaching £2.0m **[S5]**.

Impact on public services

Delivery of safe drinking water is a vital public service, which has been significantly enhanced by the application of the PODDS operational strategies, allowing companies to undertake real time, remote discolouration management. The water company consortium have stated that Sheffield's research has enabled them "to more efficiently meet regulatory requirements for larger sections of the mains network". PODDS strategies have been applied to 2,686 km of UK trunk mains, where even small discolouration events can adversely impact millions of customers **[S3]**.

Impact on policy and practitioners in the national and international water industry

Sheffield's research has improved the UK water industry's long-term regulatory compliance and adherence to Ofwat's strategic goals. The DWI, serving England and Wales, and the Drinking Water Quality Regulator (DWQR) in Scotland have [text removed for publication] PODDS strategies **[S6, S7]**. In 2015, PODDS mains conditioning strategies were formally disseminated to 29 DWI inspectors covering all regions. The DWI Principal Inspector stated, *"This upskilling of the DWI inspectors has been critical in providing a common understanding between water companies and the DWI around this topic, thus allowing quicker assessment, understanding and sign off by our inspectors when dealing with responses to incidents, proposed solutions and their*

AMP7 submissions" **[S6]**. PODDS strategies feature in a Manual of Practice of the American Water Works Association (AWWA), which is utilised worldwide as a guide for best and approved industry practice standards **[S8 p.157]**. Sheffield's modelling tools are available as an extension to the US Environmental Protection Agency's water distribution systems modelling software (EPANET) where it has been used in discolouration risk analysis and flushing plan design for main supply pipes for a New Jersey city (USA), and flushing work in Valencia (Spain). KWR, an independent Dutch water research institute has incorporated advice on PODDS strategies within best practice guidance disseminated to 9 out of the 10 Dutch drinking water companies **[S9]**.

In summary, by increasing the understanding of trunk mains discolouration and by providing modelling tools to simulate network condition, identifying deterioration rates, and crucially providing tried, tested, and data driven cost-effective PODDS operational strategies has significantly alleviated risks of material release and hence discolouration events. Build-up of organic and inorganic substances is recognised as both endemic and inexorable **[R1,R2]**, but the PODDS approach enables effective operational interventions to manage such build-up and hence water discolouration.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Water & Wastewater Treatment Online article reporting the use and impact of PODDS operational strategies by Northumbrian Water. September 2016. (Accessed 16th June 2020). https://wwtonline.co.uk/news/northumbrian-source-to-tap-approach-reduces-water-discolouration

S2. Article in Scottish Water Vision magazine (pdf only) highlighting the use and impact of PODDS operational strategies by Scottish Water. June 2016. (pp.6&7).

S3. Combined confidential testimonial from the consortium water companies (2020). Corroborates a) scale of PODDS application across their networks, b) economic impact, c) customer complaint reduction & d) business/corporate impact. (signatories representing Affinity Water, Bristol Water, Dwr Cymru Welsh Water, Northumbrian Water Group, Scottish Water, Severn Trent Water, South Staffs Water, South West Water, Southern Water, United Utilities, and Yorkshire Water).

S4. Confidential testimonial from the Head of Customer Excellence at DNV GL (2020). [text removed for publication].

S5. Confidential testimonial from the Director at ATi (2020). Corroborates that PODDS strategies have underpinned their turbidity monitors and their associated sales figures.

S6. Confidential testimonial from the Principal Inspector at DWI (2020). [text removed for publication].

S7. Confidential testimonial from the Operations Team Leader at DWQR (2020). [text removed for publication].

S8. Chapter 5 reprinted from M58 Internal Corrosion Control in Water Distribution Systems, Second Edition (ISBN 9781625762023) by permission. Copyright © 2017 the American Water Works Association. (Page 157).

S9. Confidential testimonial from the Manager Knowledge Group Water at KWR (2020). Corroborates the use of and dissemination of PODDS to 90% of Dutch water companies.