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A smart sewer asset information model to enable an 'Internet of Things' for operational wastewater management

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ABSTRACT

Real-time prediction of flooding is vital for the successful future operational management of the UK sewerage network. Recent advances in smart infrastructure and the emergence of the Internet of Things (IoT), presents an opportunity within the wastewater sector to harness and report in real-time sewer condition data for operation management. This study presents the design and development of a prototype Smart Sewer Asset Information Model (SSAIM) for an existing sewerage network. The SSAIM, developed using Industry Foundation Class version 4 (IFC4) an open neutral data format for BIM, incorporates distributed smart sensors to enable real-time monitoring and reporting of sewer asset performance. Results describe an approach for sensor data analysis to facilitate the real-time prediction of flooding.

1. Introduction

Effective wastewater management plays a critical role in both flood hazard mitigation and public health through the prevention of disease. Wastewater is generated through domestic, agricultural and industrial processes, and requires treatment to remove anthropogenic contaminants prior to reuse or release back into the natural water cycle [1]. Sewerage networks comprise the physical infrastructure of pipes, manholes, pumps, screens and channels that convey wastewater to sewerage treatment works for cleaning [2,3].

In many countries, notably the United Kingdom (UK) and the United States of America (USA), there is a legacy of extensive lengths of sewerage networks constructed during the 19th and early 20th Century; a time when civil engineers combined surface water and effluent flows. Today, legacy sewerage systems in old established cities, such as New York and London, represent, in practice, mixed networks i.e. of interdependent surface water, foul and combined sewers [4]. With dynamic populations with changing habits, climate change and a legacy of ageing assets, sewerage networks are subject to capacity and resilience issues, which have been widely reported [5–10]. Flooding, which often leads to pollution incidents due to the prevalence of mixed flow sewerage systems in older cities, is of primary concern [1]. Flooding arises from the overtopping of manholes or drainage gullies, following the exceedance of design capacity or surcharging of a system after a heavy rainfall event; as a consequence of blockages; or as discharge from Combined Sewer Overflows (CSO). CSO act as 'release valves', expelling flow into watercourses to prevent the overload of sewerage network and treatment processes during a storm event. CSO are proven to contribute to concentrations of contaminants in receiving watercourses [11–14], and in both the USA and UK are subject to control policy [15,16].

Sewerage networks receive surface water from catchment areas, which are contributing areas of land where precipitation collects and drains. Sewerage networks can be considered a man-made element introduced to a catchment's hydrological cycle, and like natural rivers or streams, sewerage network infrastructure is subject to variation in water velocity and depth [17]. Discharge, or the volume of water flowing along a sewer pipe each second, is variable, because the duration and intensity of precipitation events occurring in catchments change temporally. Thereby, in an operational sewerage network it is possible for hydraulic flow behaviour to change from open channel flow to pressurised-conduit flow, depending on a catchment's response to a

Abbreviations: BIM, Building Information Modelling; CCTV, Closed-circuit Television; COBie, Construction Operations Building Information Exchange; CSO, Combined Sewer Overflow; D2S, Device to Server; GIS, Geographic Information System; ID, Identification Device; IDW, Inverse Distance Weight; IFC, Industry Foundation Class; IoT, Internet of Things; KPI, Key Performance Indicator; OGC, Open Geospatial Consortium; SSAIM, Smart Sewerage Asset Information Model; SWMM, Storm Water Management Model; UKWIR, United Kingdom Water Industry Research; XML, eXtensible Markup Language; XSD, XML Schema Definition

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rainfall event [17]. Much research work has been completed on modelling the complexities of sewer systems [18,19]. Recent work has considered the complexities of modelling different overland flow or runoff with sewer systems [20,21]; the integration of urban drainage models into wider environmental systems [22]; and approaches to model surcharge discharge from flooding manhole covers lifted under pressure during a rainfall event [23]. Modelling software for the hydraulic simulation of sewerage networks, is now numerous and widely available, and adopted in general drainage practice. In the UK, such commercial simulations are likely to be based upon the Lloyd-Davies Rational Method [24] or the Wallingford Procedure [25]. In the USA, there is the sophisticated US Environmental Protection Agency Storm Water Management Model (SWMM) [26,27]. SWMM can account for time varying rainfall, the antecedent wetness of a catchment, and has the capacity to consider local development impact controls to reduce runoff, such as the introduction of green roof schemes. Sewer capacity and flows are often modelled for discrete parts of the network, to facilitate design proposals for sewer extensions to service new developments, or to characterise hydraulic flow behaviour following a significant or problematic rainfall event. Furthermore, recent research has considered the use of sensors to monitor and predict, the occurrence and duration of overflow discharges from CSO [28,29]. This work assessed the capacity of combined sewer systems (CSS) by monitoring, for several months, the durations of overflow from individual CSO structures incorporated in CSS against rainfall event data. The statistical probability of overflow is determined for a CSS network with several CSO, whose chronological order of overflow has been observed using sensors [28].

Modelling the hydraulic performance of a complete operational sewerage network requires up-to-date rainfall event data, including duration and spatial distribution across a catchment, along with current asset condition information [18]. To facilitate modelling, data from a network of different sensors is required including: precipitation gauges, water level, water velocity and water quality sensors. The Internet of Things (IoT), presents an opportunity, within the wastewater sector to harness and report in real time both environmental and condition phenomena. This advance has the potential to facilitate proactive, and ultimately, self-managing operational performance across large sewerage networks. The IoT concept embraces a vision of ubiquitous network societies [30], where sensors, actuators, displays and other computer elements are distributed seamlessly into real world infrastructure to contribute to the creation and management of Smart Cities. The IoT represents a future where Internet traffic will no longer be dominated by human interaction; instead with flows between semi-autonomous devices taking prominence [31]. Applied to the wastewater sector, the IoT encapsulates wastewater sewerage network asset information models with integrated, distributed smart sensing objects, which would facilitate real-time reporting of asset condition, precipitation events, water velocity and level, with a view to mitigating flooding. Smart objects have been defined as having the capability to sense, store, communicate and make decisions about measurements made by sensors associated with them [32]. Morandi et al. [33] highlight that the integration of smart technology into infrastructure requires methods both for virtualising objects in the digital domain and for capturing the properties of smart objects for value-added services to users. This paper presents and validates a prototype Smart Sewerage Asset Information Model (SSAIM), with an extendable common data structure, for use as a tool for prediction and strategic operational decision-making via smart object integration. The study has been completed in collaboration with Northumbrian Water, a large water and sewerage service company in England. The company provides wastewater services for two million properties, via 437 sewerage treatment works, 683 sewerage-pumping stations and 15,484 km of sewers.

2. Scope of the research

This research presents the design and implementation of a prototype SSAIM, to facilitate real-time operational performance information for asset delivery managers employed in the wastewater sector. The prototype models a 5 km^2 sample area of the sewerage network in the centre of Newcastle upon Tyne, a principal city under Northumbrian Water's management. The sample area was selected for study arbitrarily by Northumbrian Water, as being the central business district for Newcastle Upon Tyne. The main goal of the prototype is to enable an integrated SSAIM within a single platform, providing real-time information, and building towards the capacity to predict aspects of sewerage network performance. The SSAIM will permit managers to reach network wide, proactive operational and maintenance decisions based on both asset condition (e.g. age or criticality) and real-time performance (e.g. flood status or presence of gas). SSAIM has the capacity to support, with appropriate resourcing, improved responses to network emergencies, and to inform capital renewal and maintenance programmes. Furthermore, a requirement of the research has been to test the viability of integrating the wastewater company's existing disparate data, some GIS based, into the SSAIM prototype. Previous research reported by UKWIR [34] found that the development of data systems for the UK sewerage industry, had lagged behind those for clean water sector due to the continuance of an 'agency' system within the UK until the early 1990s. Following privatisation in 1991 after the Water Act 1991 [35], the new water and sewage companies transferred more advanced data structures, developed originally for clean water to sewerage networks. Typically, these approaches spatially collate information on above and below ground assets and allow for the implementation of work management, incident reporting and mitigation systems [34]. Consequently, asset data are often held on a series of systems that are not necessarily integrated, nor have they been developed for specific wastewater management requirements. Finally, following the requirements under Section 102 of the Water Industry Act 1991 [36] for wastewater companies in the UK to adopt and subsequently maintain new sewers and apparatus, the SSAIM also needs to be easily extendable with data compatibility across the sewer companies' suppliers.

Interoperability is key for all modern systems, where discrete systems are to be integrated into bigger ones to enable solutions that provide better control of the data and more effective management. To achieve acceptable levels of interoperability it is important to use standards, if they exist, and only extend them if necessary for a specific specialist domain. The SSAIM prototype was developed using Industry Foundation Class version 4 (IFC4) [37], the most recent version of IFC an open data format for BIM, which is also published as BS ISO 16739:2013 [38]. The IFC4 conceptual data schema and exchange file format has the capacity to hold definitions relating to: project structures, physical and spatial components, analysis items, processes, resources, controls, actors and context definitions. By way of a brief definition, IfcActors represent people or organisations, whilst IfcControls is an abstract generalisation of all concepts that control the utilisation of products, processes or resources. Crucially, IFC4 is a semantic data model, which means that spatial relations (such as the connections between pipes and manholes for example) are represented by class definitions, as are their non-spatial characteristics and relationships. This means that IFC4 has powerful visualisation and simulation capability. The structure of a SSAIM requires this IFC4 capability, defining data relationships such as those between physical assets, customers, observed asset performance, events and legal status. The design and implementation of the SSAIM is described further below.

3. Information modelling and processing

At present a specific domain does not exist in IFC4 for defining data concepts regarding wastewater. Therefore, to develop the prototype it