Northumbria Research Link

Citation: Edmondson, Vikki, Cerny, Martin, Lim, Michael, Gledson, Barry, Lockley, Steve and Woodward, John (2018) A smart sewer asset information model to enable an ‘Internet of Things’ for operational wastewater management. Automation in Construction, 91. pp. 193-205. ISSN 0926-5805

Published by: Elsevier

URL: https://doi.org/10.1016/j.autcon.2018.03.003 <https://doi.org/10.1016/j.autcon.2018.03.003>

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/id/eprint/33751/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University’s research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher’s website (a subscription may be required.)

Northumbria University NEWCASTLE

CUSTOMER SERVICE EXCELLENCE CSE UniversityLibrary

Automation in Construction 91 (2018) 193–205

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

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

Vikki Edmondson[a,*], Martin Cerny[a], Michael Lim[a], Barry Gledson[a], Steven Lockley[b], John Woodward[c]

[a] *Department of Mechanical and Construction Engineering, Northumbria University, Newcastle Upon Tyne, United Kingdom*
[b] *Department of Architecture and Built Environment, Northumbria University, Newcastle Upon Tyne, United Kingdom*
[c] *Department of Geography, Northumbria University, Newcastle Upon Tyne, United Kingdom*

ARTICLE INFO

Keywords:
Wastewater management
Internet of Things
IFC4
Sewerage networks

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

* Corresponding author at: Northumbria University, Ellison Place, Newcastle Upon Tyne NE1 8ST, United Kingdom.
E-mail address: vikki.edmondson@northumbria.ac.uk (V. Edmondson).

https://doi.org/10.1016/j.autcon.2018.03.003
Received 31 July 2017; Received in revised form 25 February 2018; Accepted 1 March 2018

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

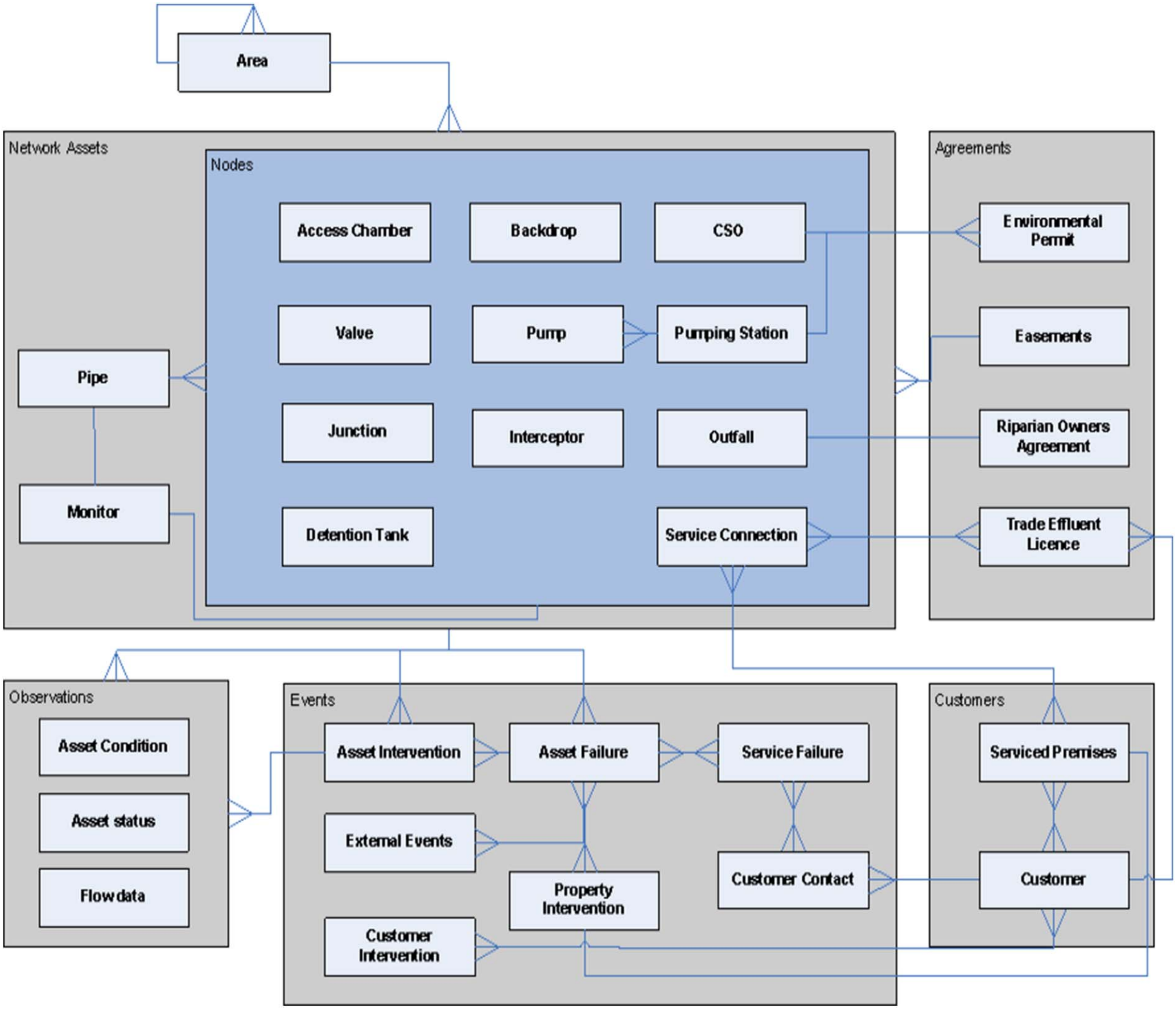


Fig. 1. UKWIR best practises entity relationship data model [34]. *The thirty individual entity definitions such as 'Backdrop', 'Service Failure' or 'Customer' are illustrated in light grey boxes. The entity definitions are grouped into five domains (Network Assets, Agreements, Observations, Events and Customers) illustrated in dark grey, which reflect specialisation of operational processes within a wastewater company. A wastewater 'Area' has physical 'Network Assets' which consists of 'Pipe' entities which are connected to 'Nodes', and 'Monitor' an entity recording water level or velocity. There are eleven special types of 'Nodes' entity, some of which can be associated with legal 'Agreements' reflected in the model by 'Environmental Permit', 'Easement', 'Riparian Owners Agreement' and 'Trade Effluent Licence' entities. A special type of 'Node' is 'Service Connection' which could be a connection for foul water, surface water or trade effluent, which are included within the attributes of the entity. 'Service Connection' has a relationship with 'Customers' which contains two entities dealing with customer information - 'Customer' which will have attributes covering customer address or billing details and 'Serviced Premises' which will, as the name suggests, store attributes associated with the building premises. 'Customer' entity is connected to 'Customer Contact' which is within 'Events', and is intended to cover reported customer problems such as blockages or flooding incidents. Consequently 'Events' contains entities associated with asset and service failures, and repair interventions. Finally, 'Asset Intervention' within 'Events' is linked to 'Observations' which contains entities covering time-series data relating to the operational status of individual assets.*

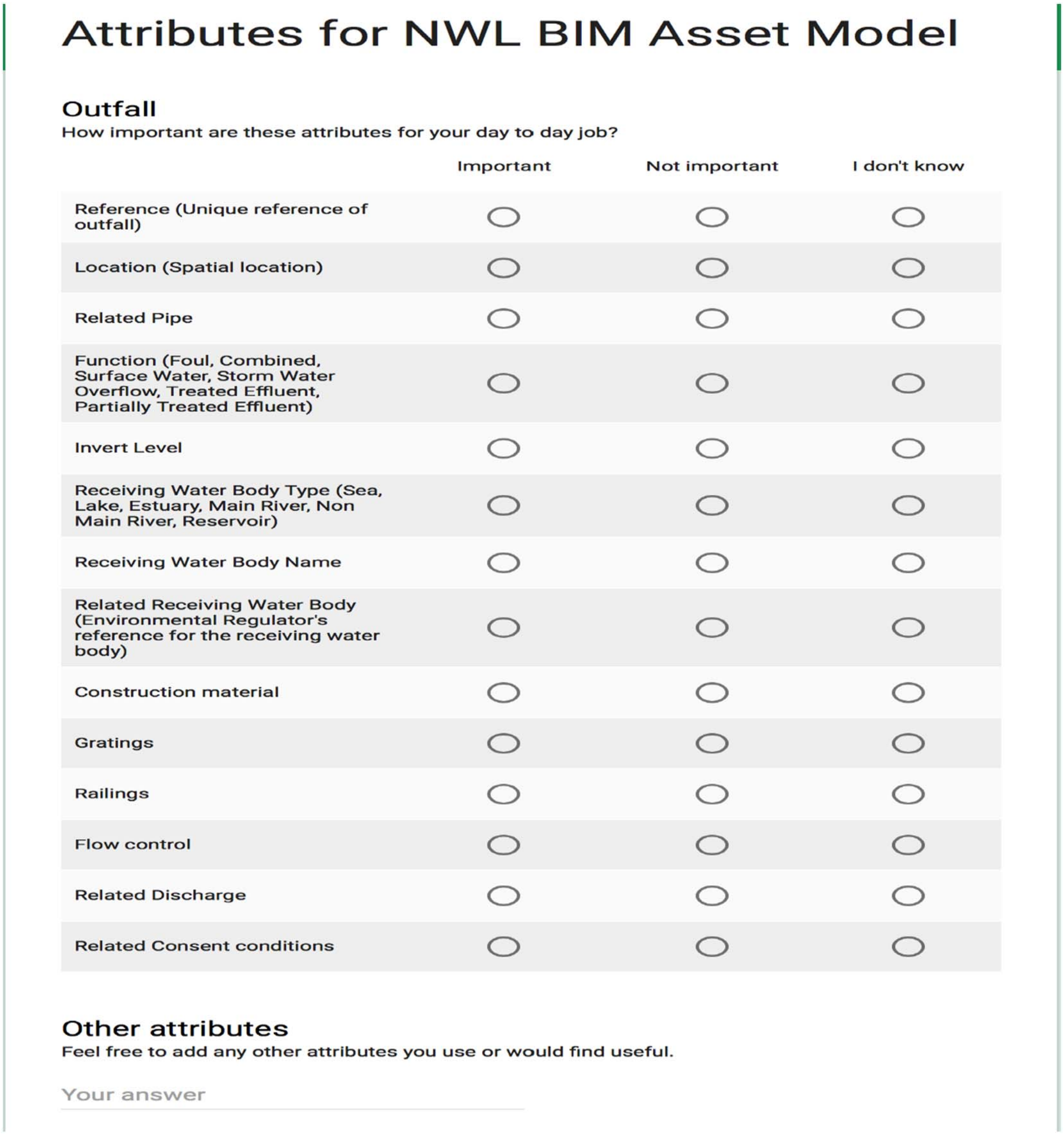
has been necessary to define an information model for the SSAIM, and to map the resulting entities and relationships to IFC4 data types. Upon completion of the mapping exercise, an existing GIS asset data model from Northumbrian Water has been integrated into the SSAIM, prior to the development of a web application to serve as a user interface.

3.1. Development of an information model and subsequent IFC4 data backbone for the prototype SSAIM

When evaluating existing domains such as the wastewater sector to develop an information model, it is important to integrate any recognised existing data structures used by industry. The first collective defined data standard for sewer asset information was published in 1980 [39]. The STC25 report established a series of fifteen simple data forms to define sewer assets, like manholes or pipes, and corresponding condition data, such as incidence of sewer collapses or blockages. UKWIR [34] published a more comprehensive data model in 2014, as part of a review of the wastewater industry to promote more effective sewerage data. Fig. 1 illustrates the entity relationships for the proposed model. This model, comprises 30 entities, with 300 attributes, and forms the basis of the information model for the SSAIM and the IFC4 backbone.

The model makes provision for the physical assets of the sewerage system such as manholes, pipes and pumping stations (referred to as 'Network Assets' Fig. 1), and their associated derived data such as hydraulic capacity or criticality of service. The model holds customer details e.g. address, billing details (referred to as 'Customer' Fig. 1) and also captures event data for the sewerage system such as asset failure (e.g. blockage or collapse) and service failure (e.g. flooding or pollution). In order to harness IoT applications, the SSAIM also includes 'observations' with its information model (refer to Fig. 1). Observation data represents real-time data collected from the sewerage network such as water level or pump status.

The applicability of the model as a virtual representation of the sewerage network, and as a means to support asset delivery programme management, was tested in workshops. A group of six operational users was drawn from senior managers responsible for wastewater in the Asset Planning, Asset Delivery and Asset Operation subdivisions of



Attributes for NWL BIM Asset Model

Outfall

How important are these attributes for your day to day job?

	Important	Not important	I don't know
Reference (Unique reference of outfall)	○	○	○
Location (Spatial location)	○	○	○
Related Pipe	○	○	○
Function (Foul, Combined, Surface Water, Storm Water Overflow, Treated Effluent, Partially Treated Effluent)	○	○	○
Invert Level	○	○	○
Receiving Water Body Type (Sea, Lake, Estuary, Main River, Non Main River, Reservoir)	○	○	○
Receiving Water Body Name	○	○	○
Related Receiving Water Body (Environmental Regulator's reference for the receiving water body)	○	○	○
Construction material	○	○	○
Gratings	○	○	○
Railings	○	○	○
Flow control	○	○	○
Related Discharge	○	○	○
Related Consent conditions	○	○	○

Other attributes

Feel free to add any other attributes you use or would find useful.

Your answer

Fig. 2. An example survey sheet for the entity ‘Outfall’. *An outfall is a structure discharging treated or untreated effluent into a body of water. The sheet describes in the furthermost left column, the proposed attributes for the entity ‘Outfall’, to be considered by the workshop members. The attributes are expressed for accessibility of the survey in layman's English rather than in IFC4 data schema. At the bottom of the sheet the workshop members are prompted to add any additional attributes. Such attributes might be considered essential for service delivery, required for regulatory reporting or necessary to meet company policies.*

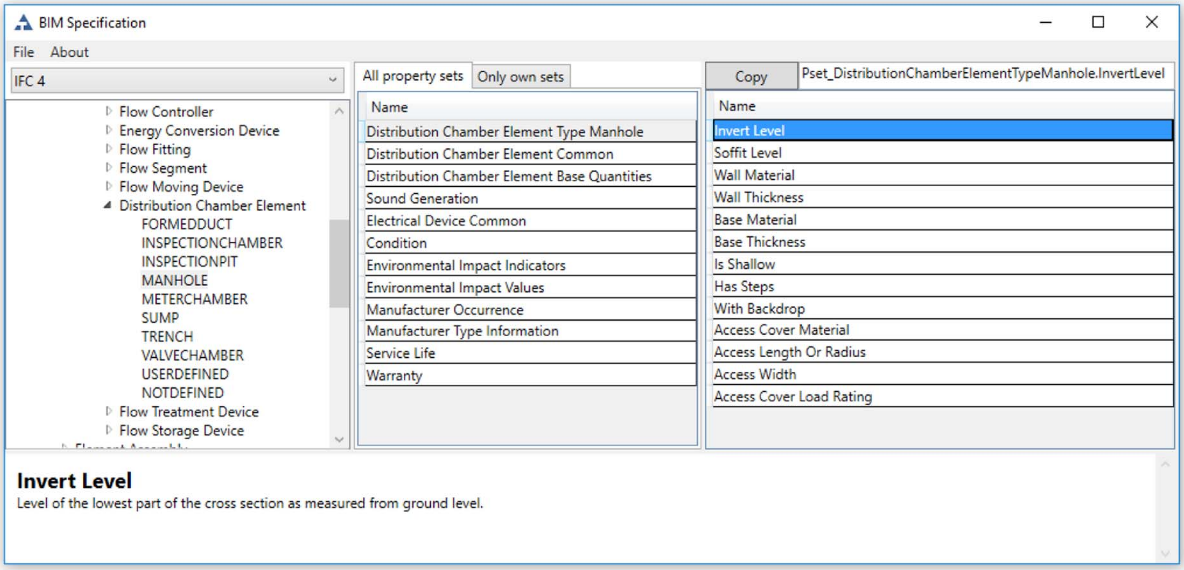
Northumbrian Water. A complete review of the attributes contained in the proposed model for each entity was facilitated by the research team, using a survey presented to the whole group. Workshop members were asked to collectively indicate the importance of an entity's attributes to their division's day-to-day procedures, with responses structured as ‘Important’, ‘Not Important; or ‘I don’t Know’. The operational users were also asked to identify, for each entity, any additional or missing attributes considered necessary to complete their daily activities. Fig. 2, serves as an example of the survey material, and details the attributes that the research team requested that the operational users consider for an ‘Outfall’ entity. The workshops principally affirmed the proposed entities and attributes based on UKWIR [34] as ‘Important’, with users occasionally requesting additional attributes which were incorporated into the model. For example, users requested that the attribute ‘Flap Valve’ be added to the ‘Outfall’ entity and that the attribute ‘Grating’ be renamed ‘Trash Screen’.

The survey approach adopted aimed to prompt exploratory dialogue between users as they reached collective decisions on attributes. This discussion helped to clarify operational terminology, define typical search enquires, and illustrate both obvious and hidden requirements for the SSAIM. Some functional requirements for the SSAIM were captured and noted during the sessions, such as the desire to immediately view an engineering drawing associated with a sewerage asset directly in the SSAIM's dialogue screen (refer to Fig. 12). Furthermore, the group were asked to complete a ranking exercise of proposed user expectations for the SSAIM based on UKWIR [34], to be considered for later formulation into functional requirements. A sample of the user expectations considered are given in Fig. 3. Whilst the final ranking ascribed to this list remains commercially sensitive, an outcome from the exercise was an instruction by the group to focus the prototype SSAIM development initially on the real-time prediction of sewerage asset performance in terms of flooding. The group defined a 5 km^2 study area within the centre of Newcastle upon Tyne as the location for the prototype SSAIM.

Following the completion of the workshops the final agreed conceptual entities were mapped to the closest corresponding entity in IFC4, and custom fields built to specify the asset type. The exercise of mapping the conceptual object schemes against descriptive attributes already defined in IFC4 involved reviewing a large library of predefined properties. To facilitate this work, an enhanced mapping tool [40] has

User Expectations for the Future Utilisation of Data Contained within the SSAIM
• To inform operational intervention option selection and planning.
• To calculate asset residual life.
• To understand the risk of asset or service failure.
• To understand network hydraulic performance and the risk of sewer asset flooding in near or real-time
• To manage asset energy consumption
• To respond to customer contact with near or real-time information on interventions or asset performance
• To determine environmental performance of assets in near or real-time
• To monitor the effectiveness of planned preventative maintenance of assets
• To identify and locate asset and service failures in near or real-time

Fig. 3. A sample of the user expectations considered for the future functionality of the SSAIM based upon UKWIR [34] *These expectations represent user aspirations for the utilisation of the data within the SSAIM.*



IFC 4

- Flow Controller
- Energy Conversion Device
- Flow Fitting
- Flow Segment
- Flow Moving Device
- Distribution Chamber Element
  - FORMEDDUCT
  - INSPECTIONCHAMBER
  - INSPECTIONPIT
  - MANHOLE
  - METERCHAMBER
  - SUMP
  - TRENCH
  - VALVECHAMBER
  - USERDEFINED
  - NOTDEFINED
- Flow Treatment Device
- Flow Storage Device

Pset_DistributionChamberElementTypeManhole.InvertLevel

Name
Distribution Chamber Element Type Manhole
Distribution Chamber Element Common
Distribution Chamber Element Base Quantities
Sound Generation
Electrical Device Common
Condition
Environmental Impact Indicators
Environmental Impact Values
Manufacturer Occurrence
Manufacturer Type Information
Service Life
Warranty

Name
Invert Level
Soffit Level
Wall Material
Wall Thickness
Base Material
Base Thickness
Is Shallow
Has Steps
With Backdrop
Access Cover Material
Access Length Or Radius
Access Width
Access Cover Load Rating

Invert Level
Level of the lowest part of the cross section as measured from ground level.

Fig. 4. Illustration of property and browser user interface [40,41]. *The left column contains a summary index of explanatory definitions which describe the property sets available in IFC4. The middle column is a list of IFC4 property sets, and the right column is a list of the data types contained with a property set. The data types shown are for the property set called 'Pset_DistributionChamberElementTypeManhole' which represents a manhole.*

been created to load property sets published by buildingSMART as XML definitions with published XSD schema [41], and to restructure them to simplify finding potential matches. The tool is based upon the principles of inheritance; predefined property sets are defined as being applicable to certain entities within the inheritance hierarchy of IFC4 entities. Accordingly, the tool assists browsing through definitions, which are both defined on the specific level and inherited from other levels of the hierarchy. An example of the user interface for the tool is illustrated in Fig. 4; the standard properties defined for a manhole in IFC4 are portrayed.

Fig. 5, illustrates the final mapped IFC4 entities and relationships for the SSAIM conceptual model. Mapping of the UKWIR based information model has also been checked against the Construction Operations Building Information Exchange (COBie) data schema to facilitate interoperability, and to safeguard flexibility to extend the SSAIM with additional data from suppliers. COBie is focused on data handover for assets. It consists of predefined templates of entities for information exchange between stakeholders. COBie was originally developed in the USA for buildings, but BS 1192-4:2014 [42] extends its definition for infrastructure and contains recommended attributes specific to new and existing infrastructure assets that apply to sewerage networks. COBie data-structure definition is based on a sub-set of IFC4, and information can be exchanged in several formats including IFC, XML and spreadsheet.

Once mapped, validation of each data entity within the final IFC4 data schema of the SSAIM has been achieved using the freely available validation routines from xBIM Toolkit [43]. The IFC4 standard defines data constraints that must be met in order to create a legitimate IFC4 model, which is checked automatically by the validation routines for the SSAIM. Upon completion of the validation routines the SSAIM was populated with GIS data from Newcastle Upon Tyne, a principal city in the North East of England. The complexity of integrating GIS data with BIM has previously been explored [44,45]. The supplied GIS data was represented as a 2D topological network, with wastewater features presented as points and lines and their relations based on spatial proximity or identity. Within the GIS, semantic data are attached to the geometric features as relational tables, so for example sewer pipe shape and pipe invert levels are accessible in attached database tables. As a

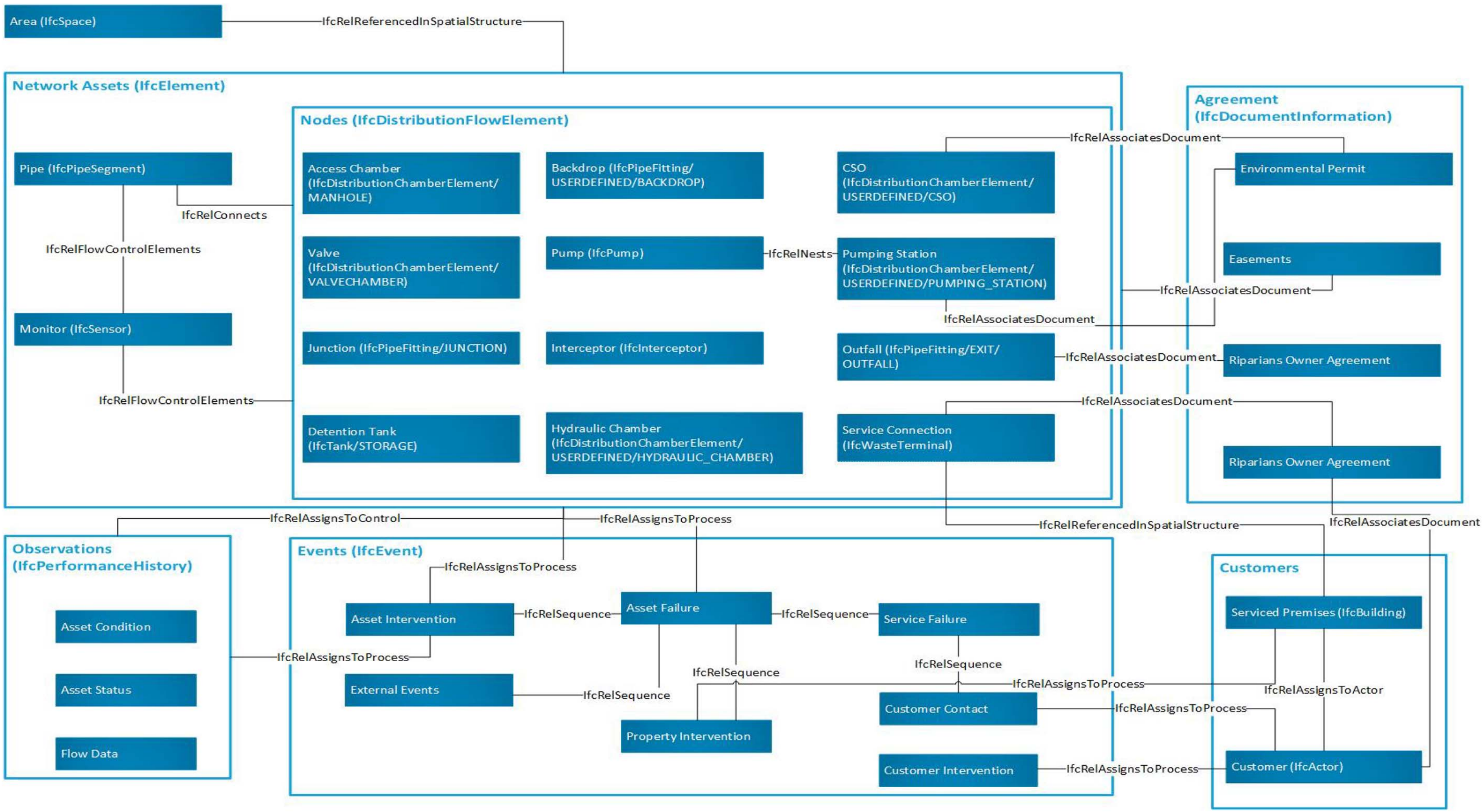


Fig. 5. Mapping between UKWIR and IFC4 entities and relationships. *All the IFC4 relationship definitions which handle for example the assignment of document information between entities (e.g. 'IfcRelAssociatesDocument') and the sequence of relationship processes (e.g. 'IfcRelSequence') are given in black. The mapped IFC4 entity types follow the original information model entity descriptors (refer to* Fig. 1*) and are prefixed with 'Ifc…'* e.g. *the entity 'Pump' is mapped in IFC4 to the entity definition 'IfcPump'. All 'Events' entities will be mapped to instances of 'IfcEvent', 'Observations' to 'IfcPerformanceHistory', and 'Agreement' entities to instances of 'IfcDocumentInformation'.*

consequence of the data investigation, the relationship between spatial data and semantic information, such as pipe shape, are integrated. The known location and identity of assets within the two networks (the GIS asset model and the SSAIM) allows for the construction of the 3D geometry for the SSAIM. Parametric definitions inferred from the semantic data were combined with positional and 2D data from GIS to create 3D geometry for the SSAIM. As IFC4 BIM models keep semantic information and the geometric representation of an object as strictly independent concepts, it would be possible to create the IFC4 SSAIM without geometry. Within IFC4 most of the relations that are based on position or spatial relations can be represented as semantic data. For example, within the SSAIM the topology of the pipe network is represented in IFC4 as an objectified relationship IfcRelConnectsWithRealizingElement. This data schema was used to represent the relation between two connected pipes and a manhole chamber, and thus realises the connections. This is a ternary relation, which allows topological network analysis without any actual geometry being involved.

The populated SSAIM was inserted into a three-dimensional digital model of the urban core of Newcastle Upon Tyne [46]. The city model, developed based upon aerial photogrammatery and terrestrial laser scanning survey techniques, has been implemented in AutoCad (.DWG) file format. The model has been converted as part of the development of the prototype SSAIM to an IFC4 model, utilising functions from the xBIM Toolkit. The original AutoCAD (.DWG) model was already classified into several layers representing various city features like grass areas, roads, pavements, buildings, bridges and others. These were mapped to IFC4 as closely as possible utilising some of the new entity types available in IFC4 such as IfcGeographicElement or IfcCivilElement. The geometry of the model was already created as a 3D mesh, so IFCTraingulatedFaceSet was efficiently used to store the data. The triangulated geometry was also used later to add elevation to the supplied 2D GIS sewerage asset network using an Inverse Distance Weight (IDW) interpolation. The final prototype SSAIM contains IFC4 objects representing buildings as well as terrain (refer to Fig. 6); this places the SSAIM in a spatial context and, more significantly, increases the future functionality of the model (refer to Section 4.0).

3.2. Connectivity of smart sensors to SSAIM

A number of different types of monitoring technologies exist for sewerage applications. Four of particular importance to the prototype SSAIM, for wide sewerage network monitoring outside the boundaries of wastewater treatment plants, are precipitation gauges, water level, water velocity and water quality sensors. Precipitation gauges record local rainfall or snowfall and the latest are now aerodynamically designed to reduce undercatch arising from wind action. Water quality sensors typically incorporate biosensors to detect pollutants such as ammonia, nitrogen and phosphorous in sewage [47,48]. Water level and water velocity sensors are typically mounted at a fixed position in a manhole chamber, and can make use of ultrasonic emissions, pressure transducers, radar or laser technology to take measurements. For water level sensors, pressure transducer technology is more frequently and widely deployed. Ultrasonic level sensors, as a consequence of their cost and power consumption, are often used only at strategic locations in a sewerage network. Locations such as, but not limited to: points in the catchment which have experienced previous flooding problems; upstream and downstream of major storm overflows; or near major junctions on a main sewer, which are significantly influenced by the effect of sub-catchment flow. Water quality, level and velocity sensors are required to be intrinsically safe, waterproof and increasingly benefit from advances in battery technology and zero power sensing [49] offering the potential for extended lives of two to three years. The final achieved battery life of the sensor will be influenced by operating temperatures, transmission frequency, the power management features of the sensor and the required pattern of data readings. Many of these sensors utilise location technologies such as GPS modem, GSM Short Message Service (SMS) or Cell_ID with triangulation to send data readings to web based cloud servers.

The IoT architecture for the SSAIM will adopt a device to server protocol (D2S). IoT architecture can consist of three layers - a sensing layer, network layer and application layer [50]. The SSAIM represents the application layer which will enable, algorithms to model the real-time or near time hydraulic performance of a sewerage network. The sensing layer will consist of water level, water velocity, water quality sensors and precipitation gauges which will use wireless telemetry [51]

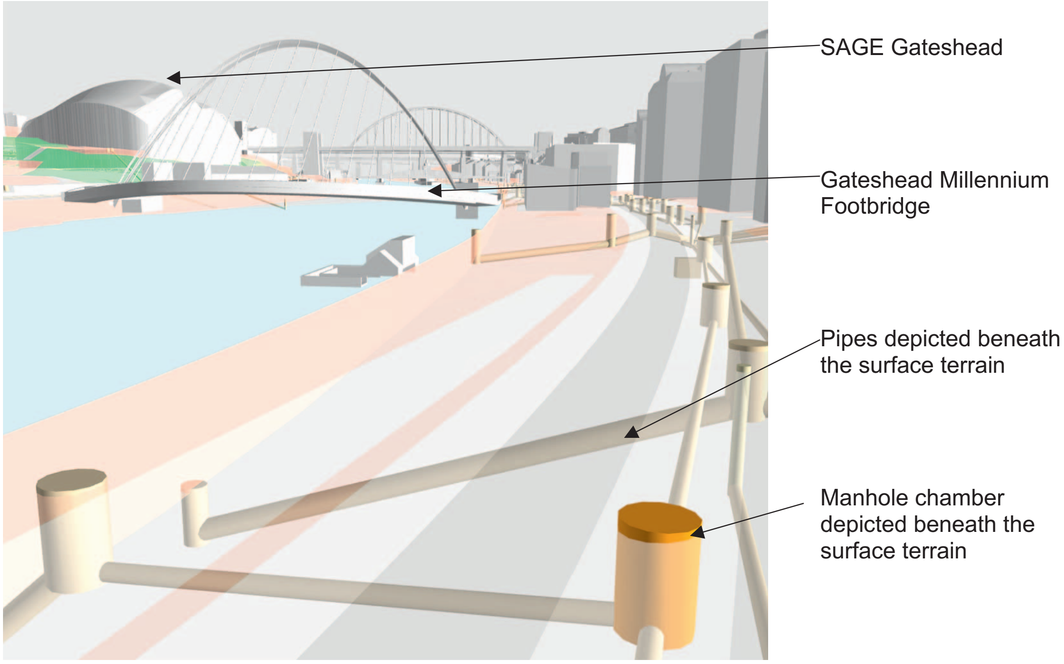


Fig. 6. A three-dimensional view of part of SSAIM in the context of the city model of Newcastle upon Tyne [46]. *The pipes and manhole chambers are displayed beneath the surface terrain. Massing for buildings are depicted based upon the converted city model; notably the landmark structures of the Gateshead Millennium Footbridge and SAGE Gateshead are visible.*

to communicate to a web-based cloud server. The web-based cloud server represents the network layer, with the SSAIM IFC4 schemas mapped to Open Geospatial Consortium (OGC) standard Sensor Model Language (SensorML) and Sensor Alert Standard (SAS) [52], in order to allow discovery of new sensors, sensor locations, observation processing, sensor alerts and task assignment. OGC is an open standard, utilising eXtensible Markup Language (XML) schemas to support web-based accessible sensor networks. Information is contained in XML schemas about a sensor's control interface to enable automated communication with the sensor for various purposes (for example, to determine its state and to issue commands or access stored or real-time data). The SSAIM communicates with the web-based sensor system, interprets the XML data and maps it to IfcPerformanceHistory for a chosen observation; and thus enables real-time monitoring and measurement. The IFC4 backbone of the SSAIM does enable some flexibility of sensor connectivity. The native language of the sensor could either be transposed directly to IFC4, or the SSAIM can be linked to external sensor data through the OGC sensor web-based platform. To achieve a direct connection, sensor measurement data is assigned within IFC4 to an IfcPerformanceHistory class and then to a particular asset entity in the SSAIM (for example IfcPipeSegment). Entities are able to hold data tables of appropriate measurements, such as pipe water level or flowrate. This approach is sufficiently robust to allow for monitoring on a daily or bi-daily basis. If more frequent monitoring is required (hourly or even by the minute), then connection to a web-based sensor platform such as OGC is more efficient.

3.3. Development of a web based user interface

As the IoT inherently consists of many independent components forming a heterogeneous network, interoperability is an essential requirement for any part of the network. The most basic communication between components could require a complete snapshot of datasets for a defined geographical region of interest. For data exchange, efficient data size and the existence of a documented and open data schema is important. A benefit of IFC4 over GIS based data architecture, is that it is an open data schema, and the memory requirements are generally less demanding, enabling larger volumes of data to be accessible. Fig. 7 shows a comparison between the IFC4 STEP 21 [53] data representation and the ESRI Shapefile ® [54] which is a common way to share GID datasets. The original GIS data provided by Northumbrian Water for Newcastle Upon Tyne city centre was 95 MB in ESRI Shapefile format, whilst the IFC4 based SSAIM complete with 3D geometric representation was only 11.2 MB in STEP21 physical file, without the city model.

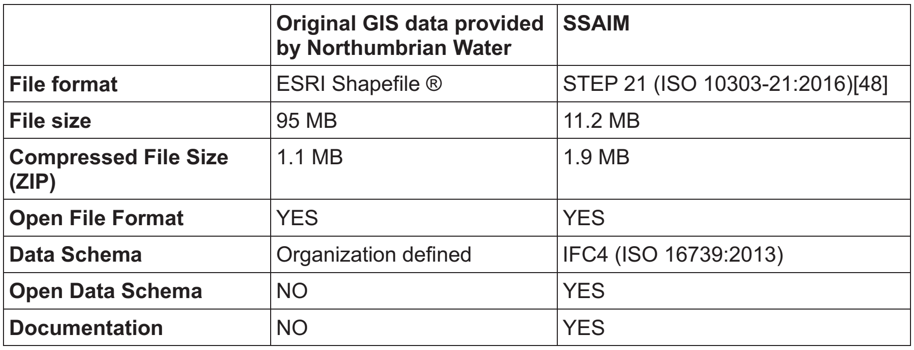
The ESRI Shapefile ® is often used as a format for data transfer. It is a meta format consisting of a set of files, where the three main files are *.shp for geometry, *.shx for spatial index data, and *.dbf or dBASE file used for database records relating to geometry objects where the structured order of records is important. Data in the original supplied dBASE table for Newcastle was sparse, but the table was configured to use the maximum size of all database records, resulting in oversized database tables. Whilst it is possible to optimise the records, the encountered configuration is often the default for this kind of data. The configuration is the reason why the compressed file size of the data, given in Fig. 7, is 1.16% of the size of the original file. In comparison, the IFC4 based SSAIM was saved as a STEP 21 physical representation, which having an ASCII file, only uses as much space as is necessary for the actual data content; and thereby the uncompressed file size was smaller (refer to Fig. 7).

A STEP 21 file is essentially an object database with one entity on every line, that contains references to other entities, using a numeric key that is unique within a single file and data using base data types. To make the data available for a random access, by the SSAIM, the xBIM Toolkit was used. The xBIM Toolkit converts the STEP 21 file into a single file ESENT database [55] which contains the original data, and a persisted index for the local identities of instances of entities as well as for the inverse relations defined in the IFC4 schema. The inverse relations essentially define queries for obtaining data and enforce referential integrity of data.

A web application has been developed as a user interface for the prototype SSAIM to allow the flexibility to view the model on both computers, and handheld portable mobile devices for site based operatives. To make the data available as a general purpose web service the xBIM Toolkit can preprocess geometric presentation information into wexBIM format [56]. The xBIM Toolkit makes use of modern web technologies such as WebGL [57] (HW accelerated graphics rendering), HTML5 [58] (a set of JavaScript APIs for advanced data presentation and user experience), Angular2 web application framework, Bootstrap4 [59] presentation framework and OWIN authentication framework [60] to build the web application. The final SSAIM application can run in any modern web browser, is platform independent and does not require any plugins to be installed.

The use of a persisted index representation of the IFC4 SSAIM model, using the ESENT database as a persistence layer, allows efficient bidirectional navigation of the data. Using this approach means that the SSAIM only loads in memory the part of the model necessary to create the response to a query or request. The availability of data schema definitions and documentation with the SSAIM is crucial to achieving the initial desired level of operable performance of the web based model and, later, interoperability with connected devices through the IoT. Accordingly, the operable performance of the web-based prototype SSAIM in terms of speed of data access and memory utilisation was subject to some initial stress tests.

The tests considered the 5 km^2 study area representing the centre of Newcastle; an area encompassing 3199 nodes or manholes, and 3345 pipes. The tests were completed on a computer with the specification indicated in Fig. 8, and were designed and run as a single threaded task. The results in terms of the time and memory utilisation are given for five operations as described in Fig. 9 for two hundred independent runs. Fig. 9 indicates that for a cool data access to the SSAIM, from when a



	Original GIS data provided by Northumbrian Water	SSAIM
File format	ESRI Shapefile ®	STEP 21 (ISO 10303-21:2016)[48]
File size	95 MB	11.2 MB
Compressed File Size (ZIP)	1.1 MB	1.9 MB
Open File Format	YES	YES
Data Schema	Organization defined	IFC4 (ISO 16739:2013)
Open Data Schema	NO	YES
Documentation	NO	YES

Fig. 7. Summary comparison of the specification for the file and data formats of the original supplied GIS data and the SSAIM.

Operating System	Microsoft Windows 10 Enterprise
System Model	MacBookPro11,4
System Type	x64-based PC
Processor	Intel64 Family 6 Model 70 Stepping 1 GenuineIntel ~2800 Mhz
Physical Memory	16,260 MB

Fig. 8. Specification of the PC used to complete the tests on the operable performance of the prototype web-based SSAIM.

computer or mobile device is first triggered after shut down, it takes 544 milliseconds to access the data utilising 6.9 MB of managed memory. The data access figure reduces to 128 milliseconds with the managed memory requirement remaining the same, where a computer or mobile device is left on i.e. a hot data access. To complete a search for an entity such as a pipe using a known asset ID, takes 167 milliseconds and 0.05 MB of incremental managed memory. Note here the memory is incremental, meaning that it represents the additional memory consumed on top of that required to activate the SSAIM to read. If all the properties of an element are required, such as indicated in Fig. 11, then the typical time taken to access the data is 55 milliseconds with 2.1 MB of incremental managed memory consumed. Finally, the time taken to transverse the complete network reachable from a single node or manhole is in the order of 410 millisecond, necessitating 0.3 MB of incremental managed memory. The ability to find associated elements connected to an element of choice is useful for display functions in a dialogue screen, and when making wider data enquires, for instance related to the properties of elements comprising a drainage sub-catchment. The initial stress test results indicate that the prototype SSAIM operable performance, in terms of speed and memory consumption, is promising for a server side deployment as a back end for REST [61] or other form of web service, as well as for the an IoT message protocol endpoint enabling real or near-real-time applications. Testing the speed of communication of the SSAIM with sensors using the proposed OGC forms later work.

Fig. 10 shows the landing page for the SSAIM web-base application after a user has been authenticated. The landing page shows the city model and network features of the SSAIM. The buildings and terrain visibility can be switched off if a user is only interested in the sewerage network itself. Once a user clicks on any network asset within the SSAIM the left panel presents all the related information. The SSAIM provides searchable, direct and easy access to a large variety of operational and maintenance information, including but not limited to: asset properties (refer to Fig. 11); related engineering drawings or documentation (refer to Fig. 12); CCTV footage showing pipe condition (refer to Fig. 13); real-time sensor data; customer details; and related sewer event information (refer to Fig. 14) such as flooding or odour. Direct, onsite access to all relevant information via mobile devices for onsite management, has been identified by Northumbrian Water as a critical element for supporting improved customer satisfaction.

4. Potential future applications and conclusions

With predicted changes to rainfall patterns and intensity, the resilience of sewers against flooding is an increasing concern to wastewater companies. Sewerage network management demands an indication of network wide hydraulic behaviour, with the capacity to visualise and predict flood performance, in order to anticipate surcharging of manholes and inlets as well as discharge events from CSO. The SSAIM IFC4 semantic backbone facilities, for the first time, the 'reverse-engineering' of traditional hydraulic sewer design approaches (capacity calculations based on a design storm and estimated runoff from a serviced area [24–27,63]), to determine the likelihood of flooding in real-time. The semantic relations that encapsulate the IFC4 SSAIM mean that the prototype does not need to perform any geometric analysis. Therefore, the SSAIM, has the capability to efficiently complete network wide post-processing analysis tasks in real time with low computing requirements. Additionally, as the SSAIM was developed using IFC4 an open BIM data standard, it facilities data exchange with other open BIM schema software tools, belonging to wastewater suppliers or property developers. This means that the model is extendable, with the possibility to add virtual sections of sewerage network to the model, to coincide with newly constructed physical assets. Supplied IFC4 data might represent an extension to the network to serve a new residential development. The extendibility of the SSAIM facilitated by the open BIM data standard, creates the future possibility to research testing or validating the impact of a proposed extension to an existing sewerage catchment (designed using capacity calculations), within a real-time operational sewerage model. Following the development of the IFC4 backbone of the SSAIM presented here, future work will initially

Ref	Description of Operation	Performance Measured	Value	Standard Deviation of Results Computed from 200 Single Threaded Task Runs
1	Cool data access (includes creation of static metadata cache)	Time	544 ms	11 ms
		Memory	6.9 MB	0 MB
2	Hot data access (uses cached static metadata – and considers the case of the service continuously running)	Time	128 ms	5 ms
		Memory	6.9 MB	0 MB
3	Search for an entity by its asset evidence ID	Time	167 ms	38 ms
		Memory increment	0.05 MB	0 MB
4	Request for 1 element with all its 39 properties	Time	55 ms	1 ms
		Memory increment	2.1 MB	0 MB
5	Traversal of complete network reachable from a single node (2613 pipes)	Time	410 ms	33 ms
		Memory increment	0.3 MB	0 MB

Fig. 9. Summary of the operational tests with corresponding results completed upon the SSAIM. *Tests were run as a single threaded task. The results for the time taken to complete an operation are presented in milliseconds (ms), with memory requirements given in megabytes (MB). As the XBIM Toolkit is implemented as a. NET library [62], the memory measured represents the managed memory footprint. Additional system memory will be used by the. NET runtime, but this depends in factors out of the control of the executing code. The 'Memory Increment' reported for operations three to five, represents the additional memory consumed on top of that required to activate the SSAIM to read.*

Northumbria Water

Sewerage Asset Information Model

This web application is a prototype representing potential of BIM model being used as an Asset Information Model. Sewage network presented in this application was generated as a parametric model from Northumbria Water GIS database for the area in the center of Newcastle upon Tyne and Gateshead.

To give a spatial reference and context city model is provided to show terrain and buildings in the city. This model is a property of Northumbria University and was aquired for the Virtual Newcastle Gateshead project.

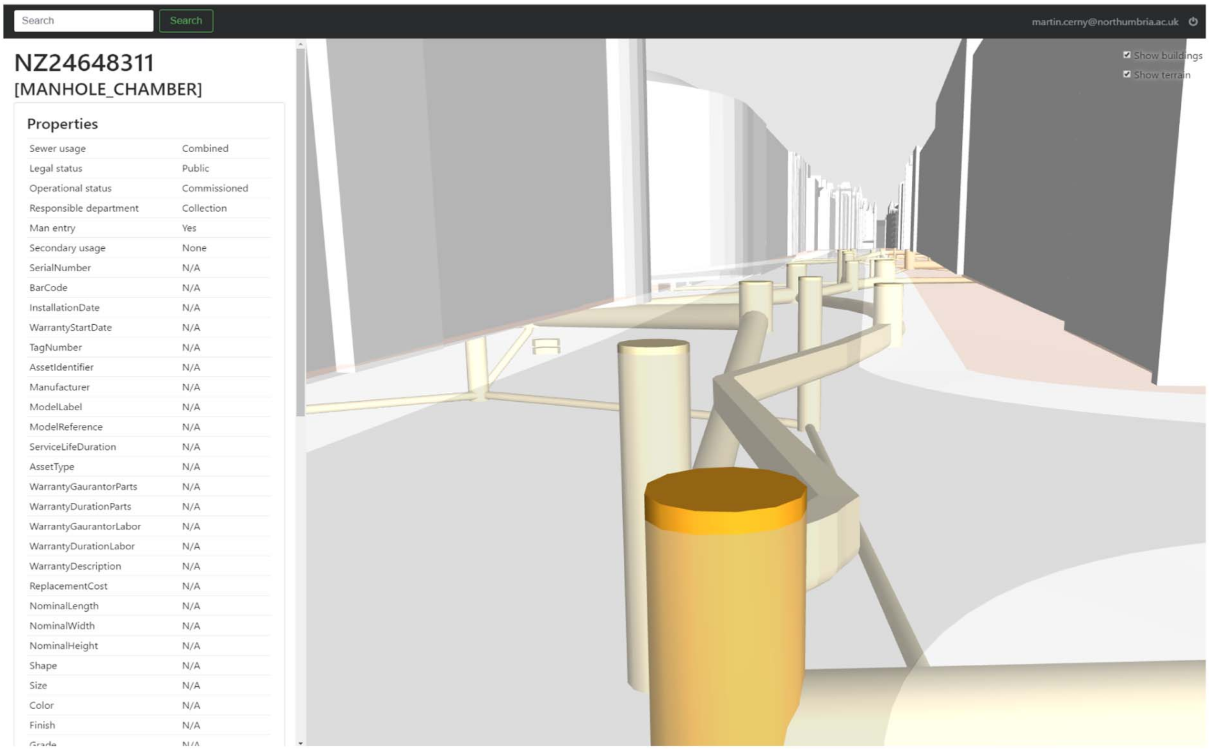
City terrain data was used to bring original 2D GIS data up to terrain. Depth of chambers and pipes was used to set up height of node features and depth of pipes. Precission and quality of the prototype model presented in this application is inherited from the quality of original GIS data set. Where there were no data available for a specific GIS feature (node or line), values were derived from other connected features or assumptions were made based on common or minimal required values.

Process of parametrized data creation was developed to be repeatable so once the original dataset is improved enhanced and improved data model can be created. XBIM toolkit was used to create the BIM model in IFC format (ISO 16739:2013) and to validate resulting data to be fully compliant with IFC4 Add1 data schema requirements.

3D visualization which is part of this prototype is also based on xBIM Toolkit technologies using WebGL and other modern web technologies. All parts of xBIM Toolkit are freely available as an Open Source and are mostly developed by BIM Experts at Northumbria University. xBIM Toolkit is developed under CDDL license which allows for full commercial use of the toolkit and as such is being used actively in more than 90 projects worldwide where more than 60 of these projects use it in a mission critical scenario.

Click on any pipe or manhole to get more information about it...

Fig. 10. Landing page of the SSAIM web application. *The main part of the screen displays the three-dimensional city model and sewerage network, which can be explored using standard zoom features.*



NZ24648311

[MANHOLE_CHAMBER]

Properties

Sewer usage	Combined
Legal status	Public
Operational status	Commissioned
Responsible department	Collection
Man entry	Yes
Secondary usage	None
SerialNumber	N/A
BarCode	N/A
InstallationDate	N/A
WarrantyStartDate	N/A
TagNumber	N/A
AssetIdentifier	N/A
Manufacturer	N/A
ModelLabel	N/A
ModelReference	N/A
ServiceLifeDuration	N/A
AssetType	N/A
WarrantyGaurantorParts	N/A
WarrantyDurationParts	N/A
WarrantyGaurantorLabor	N/A
WarrantyDurationLabor	N/A
WarrantyDescription	N/A
ReplacementCost	N/A
NominalLength	N/A
NominalWidth	N/A
NominalHeight	N/A
Shape	N/A
Size	N/A
Color	N/A
Finish	N/A
Grade	N/A

Fig. 11. Example of an asset with the properties dialogue box open from the SSAIM. *The main part of the screen displays a section of sewerage network with a manhole chamber in the foreground. The manhole chamber has been selected by the user and accordingly has been highlighted in orange. The left-hand side dialogue box presents all the related properties or attributes of the selected manhole. Where a property records 'N/A', this indicates that the data relating to the property, has not yet been collected and stored by the wastewater company for the particular selected asset.*

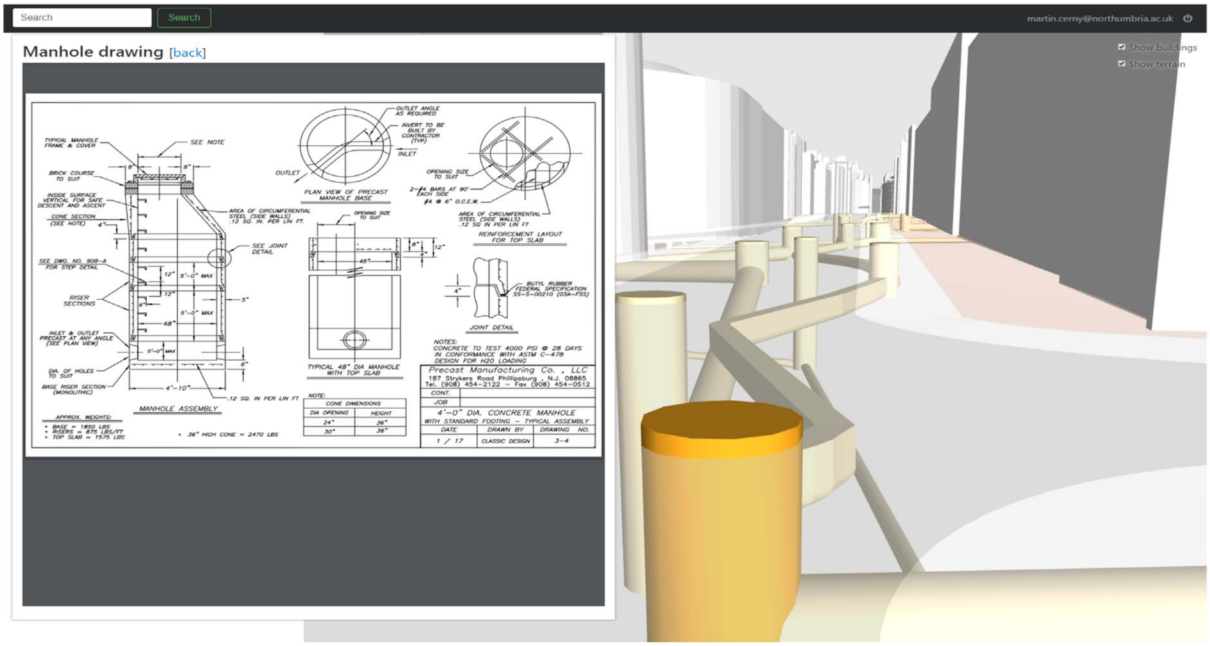


Fig. 12. Example of manhole asset with an engineering drawing open within the SSAIM dialogue box. *The main part of the screen displays a manhole chamber within the sewerage network. The left-hand side dialogue box presents the as-built engineering drawings for the manhole.*

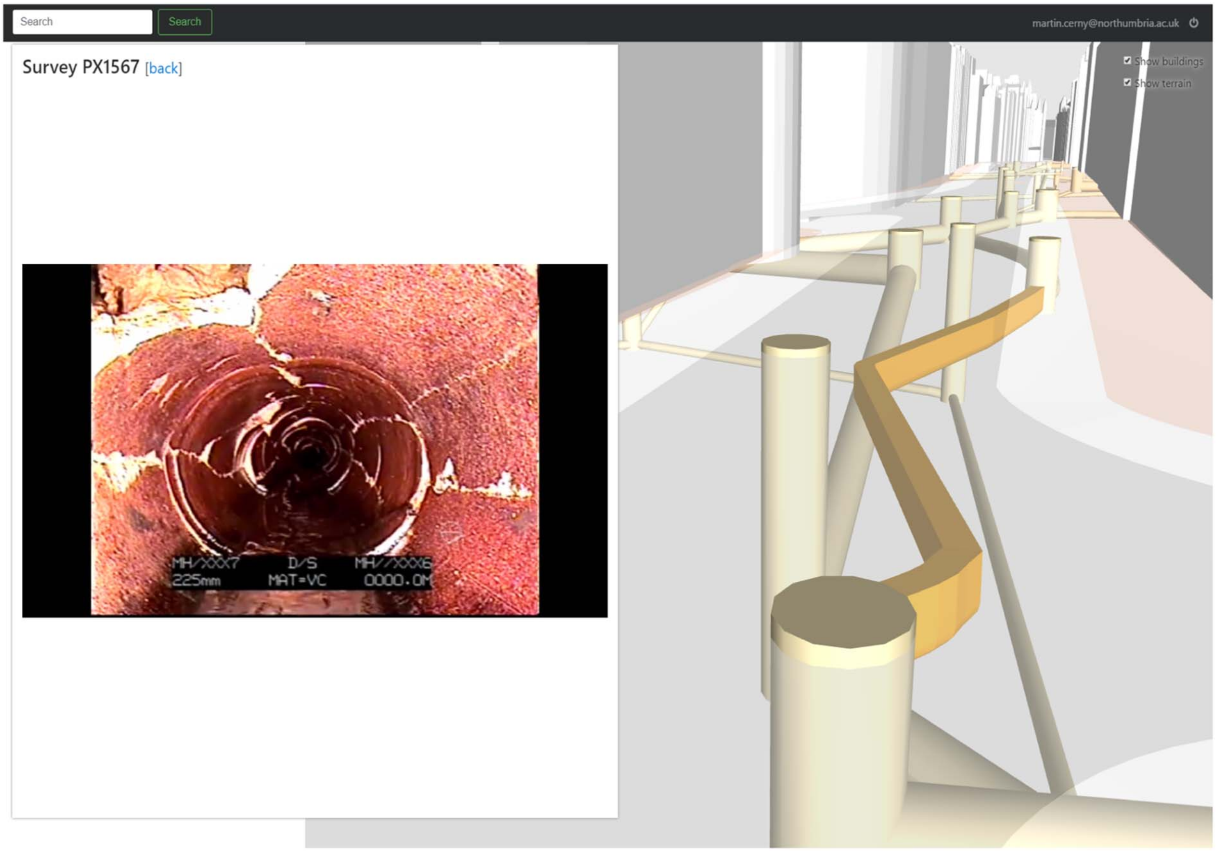
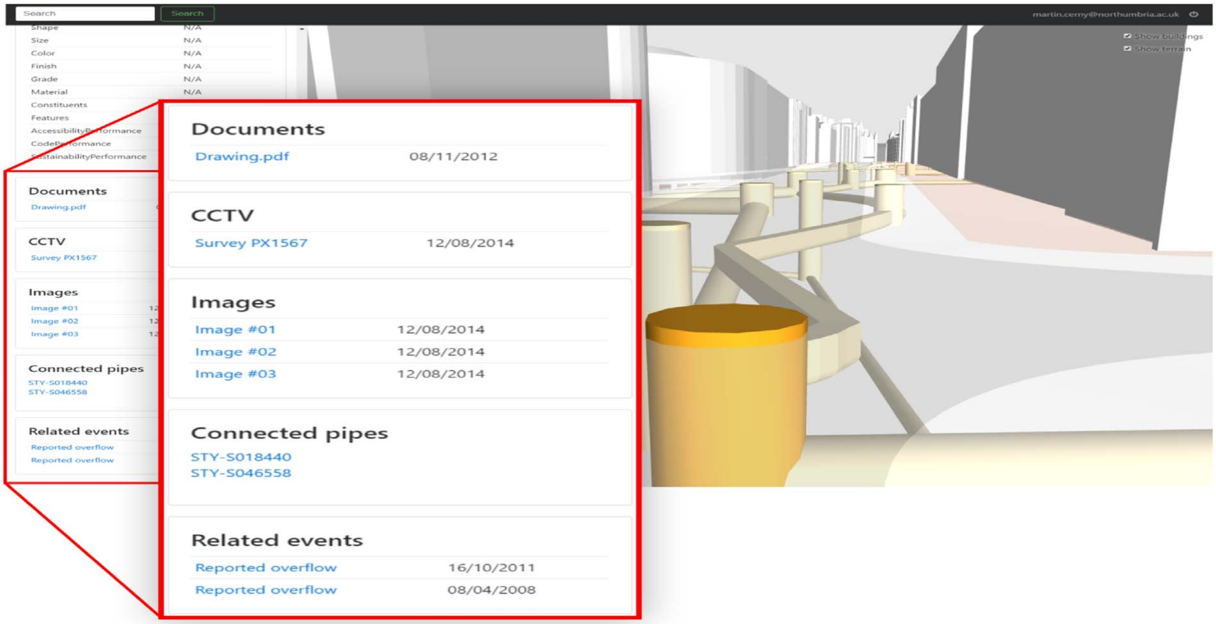


Fig. 13. Example of pipe asset with a CCTV Video footage open in the SSAIM dialogue box. *The main part of the screen displays a section of sewerage network zoomed in upon a pipe. The left-hand side dialogue box presents the CCTV survey footage of the selected section of pipe for the user to view.*

concentrate on the programming of algorithms and analysis to support (near-) real-time sewer flood prediction utilising sensor data.

As part of the next phase of the SSAIM project, real time rainfall intensities will be calculated from precipitation sensors positioned across the sewerage network. Utilising hydraulic analytical approaches which can simulate the variable conditions of open channel and pressurised pipe flow which occur in a sewerage network [17], it is possible to calculate potential sewer water levels from intensity data. This is made possible through the inclusion within the SSAIM of the city model's real terrain and thereby the contributing service areas for pipes.



Shape	N/A
Size	N/A
Color	N/A
Finish	N/A
Grade	N/A
Material	N/A
Constituents	
Features	
AccessibilityPerformance	
CodePerformance	
SustainabilityPerformance	

Documents

Drawing.pdf	08/11/2012

CCTV

Survey PX1567	12/08/2014

Images

Image #01	12/08/2014
Image #02	12/08/2014
Image #03	12/08/2014

Connected pipes

STY-S018440
STY-S046558

Related events

Reported overflow	16/10/2011
Reported overflow	08/04/2008

Fig. 14. Example of a manhole asset dialogue box detailing event and other information. *The main part of the screen displays a section of sewerage network and the selected manhole chamber. The left-hand side dialogue box illustrates the information options available to the user after scrolling down to the bottom of manhole properties list depicted in* Fig. 11. *The user may view documents associated with the manhole (refer to* Fig. 12), *CCTV (refer to* Fig. 13) *or obtain properties of connected pipes and related events such as the dates when the manhole surcharged. Real or near-time observation data, such as water velocity or water level, will also be available for manhole chambers fitted with sensors.*

The calculated potential water levels can be compared with the real-time rates of water level rise obtained from the sensor network, and an estimation of the likely time to flood achieved. Similarly, the SSAIM allows a sewer pipe water level, based upon maximum capacity, to be compared with a real-time water level obtained via a sensor; triggering an alert beyond a set margin of safety prior to flooding. Furthermore, in dry weather conditions the historic daily water level can be related to a real-time water level, to identify a potential blockage where a water level sensor records a significantly large deviation. As a consequence of the structure of the SSAIM and its connection to the IoT, it would be possible to share and disseminate flood likelihood data to stakeholders, aiding flood mitigation measure for example. An IoT for wastewater management will enable a more proactive approach to operation of the sewerage network, playing a part in the battle to reduce flooding and pollution incidents. The established SSAIM enables an integrated platform for wastewater network data, facilitating accessibility and efficiency and better informing key decision making tasks. There remains though much potential to expand the IoT for wastewater management; the deployment of actuators to manage discharge is just one example for further research.

Acknowledgements

The work presented in this paper is part of the on-going development of a SSAIM for Northumbrian Water Limited, whose support with this research project is acknowledged.

References

[1] J.E. Drinan, F. Spellman, Chapter 11: wastewater sources and types in water and wastewater treatment, A Guide for Non-engineering Professional, 2nd Edition, CRC Press, Boca Raton, 2013, pp. 139–143 (ISBN 13: 978-1-4398-5400-6).

[2] D.E.McNabb. Chapter 6: water and wastewater utilities in public utilities, Old Problems New Challenges. 2nd Edition. Edward Edgar Publishing Limited. Northampton, Massachusett, pp 121–131 (ISBN 13: 978-1785365522).

[3] F. Bloetscher, Utility Management of Water and Wastewater Operators, American Water Works Association, Denver, CO, 2011 (ISBN 13: 987-1583218235).

[4] D.J. Van, A. McLean, I. Tsoulou, Y. Gao, T. Evans, Water Infrastructure in New Jersey's CSO Cities: Elevating the Importance of Upgrading New Jersey's Urban Water System, May 2014 [Online] Available at http://www.njfuture.org/wp-content/uploads/2014/04/VanAbs_Urban-Water-Infrastructure-Report-Revised-Final-June-2014.pdf, (2014) , Accessed date: 9 December 2017.

[5] L. French, V. Samwinga, D. Proverbs, The UK sewer network: perceptions of its condition and role in flood risk, Flood Hazards: Impacts and Responses for the Built Environment, CRC Press, Boca Raton, FL, 2011, pp. 75–88 (ISBN 13:978-1439826256).

[6] J.A.E. Veldhuis, F.H.L.R. Clemens, G. Sterk, B.R. Berends, Microbial risk associated with exposure to pathogens in contaminated urban flood water, Water Res. 44 (9) (2010) 2910–2918, http://dx.doi.org/10.1016/j.watres.2010.02.009.

[7] F. Cherqu, A. Belmeziti, D. Granger, A. Sourdril, P. Le Gauffre, Assessing urban potential flooding risk and identifying effective risk-reduction measures, Sci. Total Environ. 514 (2015) 418–425, http://dx.doi.org/10.1016/j.scitotenv.2015.02.027.

[8] M. Grum, A.T. Jørgensen, R.M. Johansen, J.J. Linde, The effect of climate change on urban drainage: an evaluation based on regional climate model simulations, Water Sci. Technol. 54 (6–7) (2006) 9–15, http://dx.doi.org/10.2166/wst.2006.592.

[9] L. Nie, O. Lindholm, G. Lindholm, E. Syversen, Impact of climate change on urban drainage systems a case study in Fredrikstad, Norway, Urban Water J. 6 (4) (2008) 323–332, http://dx.doi.org/10.1080/15730620802600924.

[10] A.O. Hlodversdottir, B. Bjornsson, H.O. Andradottir, J. Eliasson, P. Crochet, Assessment of flood hazard in combined sewer systems in Reykjavik city centre, Water Sci. Technol. 71 (10) (2015) 1471–1477, http://dx.doi.org/10.2166/wst.2015.119.

[11] P. Weyrauch, A. Matzinger, E. Pawlowsky-Reusing, S. Plume, D. Seggern, B. Heinzmann, K. Schroeder, P. Rouault, Contribution of combined sewer overflows to trace contaminant loads in urban streams, Water Res. 44 (15) (2010) 4451–4462, http://dx.doi.org/10.1016/j.watres.2010.06.011.

[12] J. Passerat, N.K. Ouattara, J. Mouchel, V. Rocher, P. Servais, Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River, Water Res. 45 (2) (2011) 893–903, http://dx.doi.org/10.1016/j.watres.2010.09.024.

[13] A.S. Madoux-Humery, S. Dorner, S. Sauvé, K. Aboulfadi, M. Galarneau, P. Servais, M. Prévost, Temporal variability of combined sewer overflow contaminants: evaluation of wastewater micropollutants as tracers of fecal contamination, Water Res. 47 (13) (2013) 4370–4382, http://dx.doi.org/10.1016/j.watres.2013.04.030.

[14] A. Hata, H. Katayama, K. Kojima, S. Sano, I. Kasuga, M. Kitajima, H. Furumai, Effects of rainfall events on occurrence and detection efficiency of viruses in river water impacted by combined sewer overflows, Sci. Total Environ. 468–469 (2014) 757–763, http://dx.doi.org/10.1016/j.scitotenv.2013.08.093.

[15] OFWAT, Key Indicators – Guidance, [Online] Available at http://www.ofwat.gov.uk/wp-content/uploads/2015/12/prs_web_kpiprintable.pdf, (2015) , Accessed date: 9 December 2017.

[16] United States of America Environmental Protection Agency, Combined sewer overflow (CSO) control policy, notice, Fed. Regist. 59 (75) (1994) 18688–18698 [Online] Available at https://www.epa.gov/sites/production/files/2015-10/documents/owm0111.pdf , Accessed date: 9 December 2017.

[17] B.C. Yen, N. Pansic, Surcharge of Sewer Systems. WRC Research Report, 149 (1980) [Online] Available at http://web.extension.illinois.edu/iwrc/pdf/149.pdf , Accessed date: 9 December 2017.

[18] J. Marsalek, T.O. Barnwall, W. Geiger, M. Grokker, W.C. Huber, A.J. Saul,

W. Schilling, H.C. Torno, Urban drainage systems: design and operation, Water Sci. Technol. 27 (12) (1993) 31–70 [Online] Available at http://wst.iwaponline.com/content/27/12/31 , Accessed date: 9 December 2017.

[19] J. Marsalek, D. Sztruhár, Urban drainage: review of contemporary approaches, Water Sci. Technol. 29 (1–2) (1994) 1–10 [Online] Available at http://wst.iwaponline.com/content/29/1-2/1 , Accessed date: 9 December 2017.

[20] T.J. Chang, C.H. Wang, A.S. Chen, A novel approach to model dynamic flow interactions between storm sewer systems and overland surface for different land cover in urban areas, J. Hydrol. 524 (2015) 662–679, http://dx.doi.org/10.10.16/j.hydrol.2015.03.14.

[21] I. Fraga, L. Cea, J. Puertas, Validation of a 1D-2D dual drainage model under unsteady part-full and surcharged sewer conditions, Urban Water J. 14 (1) (2014) 74–84, http://dx.doi.org/10.1080/157306X.2015.1057180.

[22] P.M. Bach, W. Rauch, P.S. Mikkelsen, D.T. McCarthy, A. Deletic, A critical review of integrated urban water modelling – urban drainage and beyond, Environ. Model. Softw. 54 (2014) 88–107, http://dx.doi.org/10.1016/j.envsoft.2013.12.018.

[23] A.S. Chen, J. Leandro, S. Djordjevic, Modelling sewer discharge via displacement of manhole covers during flood events using 1D/2D SIPSON/P-DWave dual drainage simulation, Urban Water J. 13 (2016) 830–840, http://dx.doi.org/10.1080/1573062X.2015.1041991.

[24] D.E. Llloyd-Davies, The elimination of storm water from sewerage systems, Minutes of Proceedings of the Institution of Civil Engineers, 164 1906, pp. 41–67, , http://dx.doi.org/10.1680/imotp.1906.16637.

[25] Standing Technical Committee on Sewers and Water Mains, Design and analysis of urban storm drainage: the Wallingford procedure, Principles, Methods and Practice, Vol. 1 NWC, London. UK, 1981(ISBN 10-0901090271).

[26] W.C. Huber, L.A. Rossman, R.E. Dickinson, V.P. Singh, D.K. Fervert (Eds.), EPA Storm Water Management Model, SWMM5 Chapter 14 in Watershed Models, CRC Press, Boca Raton, FL, 2006(ISBN 13: 978-0-8493-3609-6, ISBN 10: 0-8493-3609-0).

[27] United States Environmental Protection Agency, Storm Water Management Model User's Manual Version 5.1, [Online] Available at https://www.epa.gov/water-research/storm-water-management-model-swmm, (2015) , Accessed date: 9 December 2017.

[28] A. Montserrat, L.I. Bosch, M.A. Kiser, M. Poch, L.I. Corominas, Using data from monitoring combined sewer overflows to assess, improve, and maintain combined sewer systems, Sci. Total Environ. 55 (2015) 1053–1061, http://dx.doi.org/10.1016/j.scitotenv.2014.10.087.

[29] D. Zhang, G. Lindholm, H. Ratnaweera, Use long short-term memory to enhance internet of things for combined sewer overflow monitoring, J. Hydrol. 556 (2018) 409–418, http://dx.doi.org/10.1016/j.jhydrol.2017.11.018.

[30] M. Weiser, R. Gold, J.S. Brown, The origins of ubiquitous computing research at PARC in the late 1980s, IBM Syst. J. 38 (4) (1999) 693–696, http://dx.doi.org/10.1147/sj.384.0693.

[31] The Internet of Things, International Telecommunication Union, [Online] Available at https://www.itu.int/net/wsis/tunis/newsroom/stats/The-Internet-of-Things-2005.pdf, (2005) , Accessed date: 9 December 2017.

[32] G. Kortuem, F. Kawsar, V. Sundramoorthy, D. Fitton, Smart objects as building blocks for the internet of things, IEEE Internet Comput. 14 (1) (2010) 44–51, http://dx.doi.org/10.1109/MIC.2009.143.

[33] D. Miorandi, S. Sicari, F. De Pellegrini, I. Chlamtac, Internet of things: vision, application and research challenges, Ad Hoc Netw. 10 (2012) 1497–1516, http://dx.doi.org/10.1016/j.adhoc.2012.02.016.

[34] B. Baffoe-Bonnie, I. Dawes, J. Hulance, C. Kelliher, M. Kowalski, F. Moy, N.R. Orman, F. Pearce, Ensuring service delivery through best practice management of sewerage data, UK Water Industry Research Limited, 2014 Report Number 14/SW/01/9. (ISBN 10: 1 84057 727 4).

[35] Great Britain, Water Act 1991, The Stationary Office, London, 1991 [Online] Available at https://www.legislation.gov.uk/ukpga/1991/56/pdfs/ukpga_19910056_en.pdf , Accessed date: 9 December 2017.

[36] Great Britain, Water Industry Act 1991, The Stationary Office, London, 1991 [Online] Available at https://www.legislation.gov.uk/ukpga/1991/56/pdfs/ukpga_19910056_en.pdf , Accessed date: 9 December 2017.

[37] Building Smart, Industry Foundation Classes Release 4 (IFC4), [Online] Available at https://www.buildingsmart-tech.org./ifc/IFC4/final/html/link/basic-context-information.htm , Accessed date: 9 December 2017.

[38] BS ISO 16739:2016, Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries, British Standards Institute, 2016 (ISBN 13: 978 0 580 94091 0).

[39] National Water Council, The Standing Technical Committee Report Issue 25 Sewers and Water Main Records, [Online] Available at http://www.ofwat.gov.uk/wpcontent/uploads/2015/11/prs_inf_simsup1.pdf, (1980) , Accessed date: 9 December 2017.

[40] Cerny, M. Property and Quantity Set Browser, Open Source BIM. (n.d.). [Online] Available at: https://github.com/martin1cerny/BIM-Library-CZ/tree/english (Accessed 9th December 2017).

[41] BuildingSmart. IFC4 XML Definitions of Property Sets. (n.d.). [Online] Available at: http://www.buildingsmart-tech.org/xml/psd/PSD_IFC4.xsd (Accessed 9th December 2017).

[42] British Standard Institute, PAS 1192-4: 2014. Collaborative production of information Part 4: fulfilling employers information exchange requirements using COBie, Code of Practice, 2014 (ISBN 13: 978 0 580 85255 8).

[43] S. Lockley, xBIM Toolkit eXtensible Building Information Modelling, n.d.. [Online] Available at: http://docs.xbim.net/ (Accessed 9th December 2017).

[44] J. Irizarry, E.P. Karan, F. Jalaei, Integrating BIM and GIS to Improve the Visual Monitoring of Construction Supply Chain Management Automation in Construction, 31 (2013), pp. 241–254, http://dx.doi.org/10.1016/j.autcon.2012.12.005.

[45] R. de Latt, L. van Berlo, Integration of BIM and GIS: the development of the City GML GeoBIM extension, in: T.H. Kolbe, G. König, C. Nagel (Eds.), Advances in 3D Geo-Information Sciences, Springer, 2010, pp. 211–225 (ISBN 13: 978-3-642-12670-3).

[46] E.M. Thompson, M. Horne, S. Lockley, M. Cerny. Towards an information rich 3D city model: virtual Newcastle Gateshead integration. In CUPUM 11 12th International Conference on Computers in Urban Planning and Management. 5th to 8th July 2011, Alberta. Canada n.d. [Online] Available at: http://nrl.northumbria.ac.uk/5795/ (Accessed 9th December 2017).

[47] Y.J. Yang, R.C. Haught, J.A. Goodrich, Real-time contaminant detection and classification in a drinking water pipe using conventional water quality sensors: techniques and experimental results, J. Environ. Manag. 90 (2009) 2494–2506, http://dx.doi.org/10.1016/j.jenvman.2009.01.021.

[48] J. Umetsu, Instrumentation Control and Sensor Technology for Sewerage Treatment Plants, [Online] Available at http://www.fujielectric.com/company/tech_archives/pdf/45-04/FER-45-04-126-1999.pdf, (1999) , Accessed date: 9 December 2017.

[49] B. Stark, UB20M High-Voltage, Low-Threshold, Ultra-Low Power Voltage Detector for Energy Harvesting, RF Power Transfer and Event-Driven Sensing, University of Birmingham, 2017 [online] https://www.bristol.ac.uk/media-library/sites/engineering/research/eem-group/zero-standby/UB20M_Datasheet_Rev.1.5.pdf , Accessed date: 18 December 2017.

[50] L. Atzori, A. Lera, G. Morabito, The internet of things: a survey, Comput. Netw. 54 (15) (2010) 2787–2805, http://dx.doi.org/10.1016/j.comnet.2010.05.010.

[51] A. Stanford, A. Nipper, MQTT (n.d.) [Online] Available at: http://mqtt.org (Accessed 9th December 2017).

[52] M. Botts, G. Percivall, C. Reed, J. Davidson, OGC Sensor Web Enablement: Overview and High Level Architecture, OGC 07-165r1 [Online] Available at http://docs.opengeospatial.org/wp/07-165r1/#sensor-model-language-sensorml-encoding-standard-1.0-2007, (2013) , Accessed date: 9 December 2017.

[53] ISO 10303-21: Industrial automation systems and integration – product data representation and exchange – part 21: implementation methods: Clear Text Encoding of the Exchange Structure n.d. [Online] Available at: https://www.iso.org/standard/63141.html (Accessed 9th December 2017).

[54] ESRI, ESRI Shapefile Technical Description, [Online] Available at https://www.esri.com/library/whitepapers/pdfs/shapefile.pdf, (1988) , Accessed date: 9 December 2017.

[55] Codeplex. Essent Managed Interface (n.d.) [Online] Available at: https://managedesent.codeplex.com/ (Accessed 9th December).

[56] xBIM, Creating WexBIM File for a Web Presentation, [Online] Available at http://docs.xbim.net/examples/creating-wexbim-file.html , Accessed date: 9 December 2017.

[57] D. Jackson, J. Gilbert, Web GL Specifications, [Online] Available at https://www.khronos.org/registry/webgl/specs/test/1.0/, (June 28 2017) , Accessed date: 9 December 2017.

[58] I. Hickson, R. Berjon, S. Faulkner, T. Leithead, E.D. Navara, E. O'Conner, S. Pfeiffer, HTML5 A Vocabulary and Associated AIPs for HTML and XHTML. W3c Recommendations 28th October 2014, [Online] Available at http://www/w3/org/TR/hrml5/ , Accessed date: 9 December 2017.

[59] Bootsrap 4 Getting Started – An Overview of Bootstrap, Including How to Download and Use it, Some Basic Templates and Examples and More. n.d.. [Online] Available at: https://v4-alpha.getbootstrap.com/getting-started/introduction/ (Accessed 9th December 2017).

[60] H. Sun, P. Thiagarajan, R. Anderson, Owin OAuth 2.0 Authorization Server, [Online] Available at https://docs.microsoft.com/en-us/aspnet/overview/owin-and-katana/owin-oauth-20-authorization-server, (2014) , Accessed date: 9 December 2017.

[61] R.T. Fielding, Chapter 5 – Representational State Transfer (REST) in Architectural Styles and Design of Network-Based Software Architecture, Doctoral Dissertations University of California, 2000 ([Online] Available at), https://www.ics.uci.edu/~fielding/pubs/dissertation/rest_arch_style.htm , Accessed date: 9 December 2017.

[62] Microsoft, NET Standards, [Online] Available at https://docs.microsoft.com/en-us/dotnet/standard/net-standard , Accessed date: 9 December 2017.

[63] U.K. Water, Sewers for adoption, in: 7th Edition (Ed.), A Design and Construction Guide For Developers, WRc Publications, Swindon, 2012(ISBN 13: 978 1 898920 65 6).