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Infrastructure Asset Management: Historic and Future Perspective for Tools, Risk Assessment, and Digitalization for Competence Building

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Abstract: This article aims at analyzing the historic development of infrastructure asset management (IAM) resulting from the increase of challenges over time. Furthermore, it aims at suggesting the corresponding requirements for the enrichment of educational programs to provide the decision makers of tomorrow with the right competences. The evolution of IAM is here described as characterized by three periods introducing an increased complexity of analysis and thereby, a more powerful system for urban water management: (a) Data collection and development of computerized information systems including statistical methods for information management; (b) application of risk analysis including sources of hazards and their consequences; and (c) introduction of a holistic sustainable perspective including governance, social and economic aspects (circular economy), environmental impacts, and the condition of physical assets including digital systems. A variety of competencies are needed to obtain the safe management of urban water systems, in particular for the provision of water services in medium- and large-scale cities. Similar competencies are needed for other infrastructures, like buildings, roads and railroads, and IT systems. The elements of sustainability including risk assessment and digitalization should be incorporated in master programs for civil engineering world-wide. This paper is not designed as a scientific paper, but as inspirational for IAM practitioners and for the development of enriched educational programs of technical universities.

Keywords: education; infrastructure asset management; water; wastewater

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1. Introduction

The aim of this paper is to provide a high level, chronological review of IAM practice in water and wastewater industry and from that reflect on the educational requirements. The authors expect this paper to be inspirational for IAM practitioners and for the development of enriched educational programs of technical universities.

The authors have been a part of this development over the last 40 years. The article is based on personal observations supplemented by key literature.

Urban water infrastructure as water supply and wastewater collection provides essential services to the society but also represent high costs for maintenance and rehabilitation, since they are exposed to a changing environment and deterioration of the assets.

Thus, the management of the urban water systems, and of the water cycle in general, has been and is challenged by the evolution of requirements put by the external context, which has progressed towards an increased complexity.

In the past 50 years, infrastructure asset management (IAM) has become more strategic.

However, IAM has existed for more than 100 years, when the first standardisation of materials for water and wastewater took place. Later, several standards appeared with requirements for the manufacturing of pipes, strength of pipe materials and construction methods, as well as technologies for testing of pipelines [1].

Systematic IAM dates back to the 1970s, when methods for rehabilitation planning were introduced as a measure to understand the impact of wastewater systems to the increasing pollution of water bodies [2]. The objective was to find an efficient way to rank projects for upgrading wastewater networks and treatment systems to reach the goal of water quality improvement. The methodology of rehabilitation planning was stepwise improved in the following decenniums until the early 2000s.

In this period, IAM focused first on collecting asset data from which they could gather information to support rehabilitation decisions and answer questions such as: What do we have? Where is it? What condition is it in? How does it perform? In the mid 1980s, the development of computerized information systems started in many countries and enabled water utilities to systemize information of water and wastewater networks in a far more systematic way than before when paper-based systems were applied.

Deterministic, regression, and statistical models to convert data into valuable information populate the literature of this period [3]. The models, by providing information about the system performance and changing structural conditions, aimed to guide and modify responses, routines activities, procedures, and capital investments to prevent and predict the occurrence of problems. However, in the process of testing and validating those models in practice, it became clear that most water and wastewater utilities lacked accurate data and, whenever available, the range of data to support this level of information was stored in many forms, which is difficult to recover [4–7]. Applying reliability analysis or performance analysis of the system without comprehensive asset databases gave misleading results as models were run with highly approximated input.

Motivated by the need for upgrading the water distribution infrastructure in Europe, CARE-W (Computer Aided Rehabilitation of Water Networks) was started in 2001 [8] with the aim of integrating the available knowledge, modeling approaches, and overcoming existing data limitations.

Still, besides the uncertainties of the results, due to incomplete datasets, condition assessment and reliability studies' results clearly showed that basing decisions on the expected probability of pipes to fail was not feasible, due to the computed higher investments required than the available resources (money and human) could handle. Therefore, the concept of risk came to the scene to combine the computed probability of failure with a ranking factor, i.e., the eventual impact created by the failure, and therefore leading to prioritizing interventions based on computed risk levels. So, approximatively between 2005 and 2010, IAM transitioned to focus on the risk of asset failure and making capital investments to mitigate the risks and optimizing operations and maintenance activities. In a risk management process, specifically at the step of risk analysis, the likelihood of a failure and the consequences produced, if happening, have to be assessed. While the failures relate to technical aspects for which analysis water engineers can feel confident about (e.g., pipes' collapses, breaks, blockages), the assessment of the consequences might relate to a variety of dimensions and connected competences, e.g., social, economic, financial, environmental, etc.

The practice of performing risk assessment highlighted the need for multidisciplinary collaboration within the water organization, but also with external organizations or entities.

In this period, there is a transition to a more explicit attention to the service provided. In December 2007, the ISO/TC 224 published the following standards [9–11]:

- ISO 24510, "Activities relating to drinking water and wastewater services—Guidelines for the assessment and for the improvement of the service to users".
- ISO 24511, "Activities relating to drinking water and wastewater services—Guidelines for the management of wastewater utilities and for the assessment of wastewater services".
- ISO 24512, "Activities relating to drinking water and wastewater services—Guidelines for the management of drinking water utilities and for the assessment of drinking water services".

The objective was to provide the relevant stakeholders with guidelines for assessing and improving the service to users, and with guidance for managing the systems, consistent with the overarching goals set by the relevant authorities. The standards were intended to facilitate dialogue between the stakeholders, enabling them to develop a mutual understanding of the functions and tasks that fall into the scope of water utilities.

Meantime, also the challenges to be handled in a decision process to produce master and rehabilitation plans increased with the rise of technical challenges (e.g., related to climate change impact, urban development, and ageing of infrastructure), social challenges (e.g., higher customers service demands and new requirements for greener cities), environmental challenges (e.g., more pressing directives), and tighter legislation and societal pressure to reduce energy consumption and CO_2 emission. So, while the deterioration of the pipeline assets is still the obvious 'frontline' reason to adopt IAM practices, a more overarching driver is now the need to gravitate towards sustainable development and set short-term and long-term objectives encompassing economic, social, and environmental goals.

These change drivers put pressure for a transition, or paradigm shift, in the traditional management of the water sector, which, however, is conservative, complex, and fragmented. In fact, although it became clear that IAM is not just about infrastructure assets, but also about people, still major barriers exist to break through the silos of information and expertise inside and outside the water utilities towards a crucial multi-stakeholder collaboration being required.

The awareness and the identification of those barriers brought light to the idea that successful and sustainable asset management requires active leadership, organizational alignment, and coordination throughout all disciplines involved. This admission opened the current IAM generation, which can be called total integration and which focuses on new governance models able to support coordinated strategy; decision levels alignment; and, thanks to the digital transformation, IT integration among sectors.

The evolution of modern IAM over time has therefore seen three major stages:

- A 1st Generation IAM focused on asset information (late 90s to approximately 2005).
- A 2nd Generation IAM focused on asset strategies through risk (approximately 2005–2010).
- A 3rd Generation IAM focus on total integration with emphasis on governance and stakeholders' involvement (2010–2021).

The three phases have to be seen as consecutive and as feeding each other in a process of methodological development, while none of them has phased out, but together characterize what IAM is today. The timeline adopted here is necessarily an approximation between the time of research advancement and the time at which transitions are perceived in practice. It is also worth saying that not all water utilities adopted IAM practices at the same speed and therefore they might not recognize their evolution with the timeline proposed here.

Educational programs thus should have mirrored the IAM evolution, adding more and more complexity (in terms of multidimensional coverage) to cover the knowledge needs. In practice, the educational programs' requirements for students of urban water systems have to move from purely technical to a multi-disciplinary curriculum supporting the new generation of water experts in managing urban water as system where technology, economy, environment, and society are connected. Unfortunately, it appears that many education programs are still lagging and have the technical aspects as a core dimension. Furthermore, also limiting the attention to the technical aspects, it seems the teaching program of the new generation of engineers mainly focuses on providing the knowledge for the creation of new water systems, rather than for the management of existing ones, therefore lacking fundamental competences required as water professionals after the studying period, such as reliability, condition-based maintenance, risk management, and sustainability assessment.

In the following sections, each generation of IAM is described in terms of focus areas and adopted approaches, so to provide the background for the list of corresponding educational needs introduced; an IAM curriculum should reflect all the competencies merged with time in order to include the management thinking and the technical solutions that have resulted in the water and wastewater systems we currently deal with and to understand their performance.

2. The 1st Generation of IAM and the Knowledge Requirements

The 1st Generation IAM focused on collecting asset information and data and, after some system developments, applying them into computerized maintenance management systems.

The history of water networks rehabilitation leans on the so called re-active approach: First the failure occurs, then the intervention comes. For decades, the systems have been functioning with no routine maintenance at all. They are out of sight and only in the case of evidence, the operator investigated the problem and carried out the necessary repair.

The traditional IAM strategies for intervention can be listed as:

- Operative—reactive
- Proactive—preventive
- Predictive—advanced

The list is given following the evolution in time of scientific knowledge on IAM practice. Although in the first generation of IAM there was the belief that water utilities should move from the reactive approach to the predictive approach, it is now clear that none of the approaches are better or worse than the others, but each approach has its role in the decision process in relation to the concept of related risk (second generation of IAM). Also, proactive and preventive repair strategy for urban drainage systems is ideally more cost-effective than the traditional approach of reactive maintenance, however, this depends on an accurate understanding of the pipe condition to avoid premature rehabilitation: If the asset is replaced too early, there is an economic loss, since the service life of the asset has not expired. If the replacement of the asset is left too long, there is an economic loss when additional externalities for emergency repairs occur.

The proactive and preventive approach utilizes reliability and condition-based approaches to assess the pipes most prone to failure. Some more advanced decision support systems at the time also combined cost assessment to define the list of pipes to be prioritize annually balancing costs and performances. However, applying those tools called for investments in 'knowing the system', before attempting to decipher the via media.

Literature on rehabilitation planning for water distribution systems offers interesting approaches presented in the past by several researchers. Shamir et al. [12], developed an analytical approach to solve the pipe replacement problem. They expressed the pipe break growth rate and hence the expected pipe break repair cost as an exponential function. The replacement age of the pipe is that at which pipe replacement would minimize the present value of the total cost (sum of the present values of replacement costs and repair costs), which was obtained analytically.

Kleiner et al. [13–15] proposed an approach in which the network economics and hydraulic capacity are analysed simultaneously over a pre-defined analysis period, while explicitly considering the deterioration over time of both the structural integrity and the hydraulic capacity of every pipe in the system.

The optimal age at which a pipe needs to be replaced is obtained on the basis of the structural costs. The evaluation and selection of the rehabilitation alternatives are done on the basis of structural and hydraulic conditions at different stages. The algorithm is a heuristic technique based on partial enumeration and hence may not be able to easily handle large networks.

Sægrov et al. [16] used statistical methods for estimating the current and future rehabilitation needs and the use of software tools for prioritising rehabilitation actions in water systems. The need for a proactive approach for rehabilitation planning is presented in comparison to the reactive one. A framework for exploring the rehabilitation needs and strategies is suggested. About 20 years ago, these authors brought, among others, decision support systems on to the scene of water management in Europe. Two EU projects of the V Framework Programme dealing with decision support systems (DSS) for water and wastewater managers, CARE-W and CARE-S [8] and [17], paved the way for IAM in the European water sector. To support the application of a proactive approach, researchers focused their attention on the identification of parameters to decide "what", "where", and "how" to plan activities to improve the system's performance. The software allows to select and schedule the rehabilitation alternatives considering deterioration, hydraulic capacity, and reliability of the network, but risk factors are not included.

Still, it has to be admitted that the debut of the DSSs in the European water agencies was only a partial success.

The experience demonstrated that the availability of data was the first problem to be addressed and the application of advanced management approaches was unfeasible because of the lack of a long-term monitoring strategy. Applying reliability analysis or performance analysis of the system without comprehensive asset databases gave misleading results as models were run with highly approximated input. Results tended to disappoint the expectations of water municipalities on the benefits of applying those data-intense software [6,7].

It took some time before understanding that it was pointless to run complex approaches without spending the right time on data screening and collection, or that not all the available software could be applied by all users according to the availability of data. Two different solutions were performed in two different case studies: In one case we directly drove the necessary data collection, cleaning the data and also collecting data on the field when the municipality could not provide resources to do it; in the other case, we evaluated the actual availability of data and according to the dataset provided by the utility, such as failure data and hydraulic model results, a simple and practical methodology was developed using only the tools that could provide a feasible analysis of the network vulnerability [6,7]. In the first case, the data collection itself took 2 of the 3 years of the project, in the second case, very few aspects of asset performance could be analysed, but in both cases the results finally could be assumed as reliable and increased the interest of the utility for further collaboration in adopting DSSs.

The one described is only an example referred to as a specific experience, but average situations encountered by testing the DSS in other European case studies did not perform any better.

Most water and wastewater utilities lacked accurate information not only on the assets, but also on the characterization of cost, and whenever available, the range of data to support this level of information was stored in many forms, which is difficult to recover [7].

The collection of data has an economic dimension. In [18], the authors proposed a methodology for assessing the cost–benefit relationship between data collection and data utilisation for IAM tools. In this methodology, the costs were expressed as the work hours invested in collecting the data, while the benefits were expressed as informational outcomes.

DSSs, when data are available, provide the utilities with a rational framework to plan future investments, taking into consideration the condition assessment, performance targets, and investment impact of alternative solutions/strategies.

Lessons learnt from the 1st generation of IAM to enrich educational programs:

The development of the first generation IAM revealed that competences are needed for a number of topics that therefore should be incorporated in educational programs of IAM, including:

- Hydraulic models of water and wastewater networks that can be used for the analysis of system reliability.
- Methods for monitoring the network's performance and pipe condition, including: leak detection (water), CCTV inspection (wastewater), flow measurements, pipe samples, registration of failures from repairs, and previous rehabilitation projects.
- Statistical tools to analyse the information reveal large-scale trends and predict future conditions and rehabilitation needs.

- Data analysis techniques to balance between data quality and quantity. Often, as described above, data available might not be sufficient to perform reliable analysis, therefore, it is necessary to define a trade-off between data availability and tools data requirements and eventually select different analysis techniques based on the data at hand.

3. The 2nd Generation of IAM and the Knowledge Requirements Incorporating the Risk Dimension

The 2nd generation of IAM focused on asset strategies through the introduction of risk. At this stage, risk-based DSSs come into the scene. A natural follow up to the CARE-W and CARE-S DSSs, is the innovative project AWARE-P, an open-source, professional-grade computer application, offering decision support tools at the three decision levels of strategic, tactical, and operational, which incorporates risk as a metric to be balanced with performance and costs to drive rehabilitation decisions [19].

A reference standard to develop these approaches was the Risk Management Process-ISO 31000:2009 [20]. The risk management process includes the steps of "establishing the context", "risk identification", "risk analysis", "risk evaluation", and "risk treatment". Aligned with this standard, risk assessment includes the steps of risk event identification, analysis, and evaluation. Once the risk events are identified, in the risk analysis both likelihood and impacts of the events are evaluated.

The assessment of the likelihood and consequences for each event, and the following estimation of the level of risk for each event, help to compare events and to prioritize those at higher risk.

To screen priority risks, simpler methods (e.g., likelihood-consequence matrix) are often used, and further on, for priority problems, more detailed methods (e.g., quantitative risk analysis) could be applied. In the risk-based decision support systems for IAM, the aim is to combine the probability of the failure of technical functions of an asset with the derived consequence. The consequence describes the outcome of an event in terms of potential impact created. Each event can have one probability happen, but it can produce consequences in multiple dimensions (e.g., economic, social, environmental, etc.).

Furthermore, selecting the most appropriate risk reduction measures (RRM), which is part of the risk treatment step, should be carried out using appropriate criteria to balance the costs and efforts of implementation against the benefits derived. Aspects to consider in the assessment of each RRM are: level of risk to be controlled; effectiveness (achievement of the desired reduction in risk); efficiency (achievement of the desired effect with least resource consumption); sustainability; cost of implementation; side effects (e.g., some RRM may create secondary risks); legal and regulatory viability; acceptability by stakeholders and by the public; and protection of the environment. After comparison, RRM alternatives must be prioritised using the selected criteria and a decision must be made on which RRM to implement. The step of risk treatment is supported by the use of cost–benefit analysis or multi-criteria-decision-analysis [21].

Assessing consequences for multiple dimensions in the step of risk analysis and selecting RRMs in the step of risk treatment, called for the need of new competences, not limited to technical ones anymore, and of multi-disciplinary collaboration (e.g., economy, social and environmental science).

It is in the period of the second generation of IAM that a comprehensive preventive risk management approach for ensuring drinking-water quality is made available to water operators in the form of guidelines: the Water Safety Plan [22]. The IAM risk-based DSS developed in this period are also inspired by the need to support the implementation of the Water Safety Plan, as the EU project TECHNEAU [23,24]. Afterwards, the authors in [25] present the challenges faced by the water utilities to provide safe, secure, and reliable service to meet also the Water Framework Directives 2000/60/EC, in addition to the water safety plan. The analysis approach presented follows standard methodology for risk and vulnerability. In order to structure the analysis, the system is split into the various water cycle components. For each of these components, hazards and threats are identified; probability and consequences assessed; and finally, the total risk picture presented.

Factors influencing the rehabilitation decision during and after the second generation are:

- Assets structural condition
- Network reliability
- Impact assessment
- Risk assessment

Lessons learnt from the 2nd generation of IAM to enrich educational programs:

The development of the second generation of IAM revealed that, in addition to the competences introduced by the first generation, educational programs of IAM should include risk-related competence covering:

- Qualitative and quantitative methods for risk analysis, like preliminary hazard analysis, HAZOP, fault tree analysis, and event tree analysis.
- Consequence analysis.
- Data sources and uncertainties.
- Knowledge about standards, and guidelines.
- Cost/benefit and MCD analysis.

Furthermore, the programs have to provide the ability to analyze the system as a complex one, not limited to the pipelines hydraulic and structural performances, but also looking at multiple dimensions of impacts and assessment criteria.

4. The 3rd Generation of IAM and the Knowledge Requirements for the Transition towards a Sustainable Urban Water System

With the start of the 3rd generation, it is clear that behind the definition of what IAM is, there is the need for a global set of systematic, aligned, and coordinated strategies to identify and optimally manage the physical assets to meet more stringent and global requirements at the system and even city serviceability level. To make the adoption of IAM practice successful IAM, there is the requirement of an organisational plan that involves the whole company at the tactical-operational and strategic level and that needs to be set up from both the bottom-up and top-down level [26,27].

This sums up to the principles of establishing good governance within an organization. The governance includes the organisation's human resources and their training, to enable the use of information systems and engineering principles. Good governance was at the core of the EU program TRUST (TRansformation to sustainable Urban water Systems of To-morrow) [28] and is subject to a thorough discussion in several papers conducted by Katko and Hukka, et al. [29–32].

The transition to more sustainable urban water services requires a couple of elements. First, it requires a clear understanding of how sustainability of urban water services can be defined and assessed. Second, it requires detailed strategic planning involving several steps, such as diagnosis (where are we now?), vision (where do we want to go?), analysis (what is needed to get there?), technology & management options (what can be done?), prediction (what happens if?), decision-support (which option is the best one?), and finally the acceptance by decision-makers and stakeholders. TRUST developed a portfolio of solutions, tools, guidelines, software, and training material for all of these steps and demonstrated their feasibility and usability in 10 participating city utilities across Europe [28].

As sustainable development came into the core of the IAM around 2010, governance responsibilities of the operation and development of urban water systems were introduced besides the environmental, social, economic, and technical dimensions, which are already covered by risk assessment studies. As one of the first steps, a definition and a comprehensive assessment framework for sustainability assessment of urban water services were developed, including the above-mentioned five main dimensions of sustainability and subsequent criteria and measurement options for sustainability [33].

Currently, the impact of climate change presents a major challenge to urban water systems; IAM supporting tools, analysis, and approaches have been tuned to address climate change impact and adaptation as major drivers. The topic has been extensively handled in several large-scale European projects lately, e.g., PREPARED (2010–2014, [28]) and BINGO (2015–2019, [34]). We now have access to knowledge and a set of tools (climate prognosis, risk assessment, and planning) tailored to climate change adaptation as an integrated part of IAM.

Lately, the digital revolution has revealed new opportunities when it comes to smart (optimized) operation of urban water systems and improved understanding of performance (through machine learning tools, artificial intelligence solutions, augmented and virtual reality, and digital twins). The digital transformation has somehow just started, but more and more water utilities are applying data science and augmented intelligence techniques to business problems; the virtual representation (Digital Twins) of the water system will enable situational awareness and near-real-time monitoring, which has great potential to solve many of the challenges faced by the industry, towards a smarter use of water resources grounded on the concepts of circular economy. Guiding water utilities at developing strategic agendas to meet the vision of a water-smart society is the aim of recent H2020 projects, which is financed through the Horizon 2020 call "Building a water-smart economy and society" and was started in 2020:

- ULTIMATE—indUstry water-utiLiTy symbIosis for a sMarter wATer society.
- B-WaterSmart—Accelerating Water Smartness in Coastal Europe.
- WIDER UPTAKE—Achieving wider uptake of water-smart solutions.
- WATER-MINING—Next generation water-smart management systems: large scale demonstrations for a circular economy and society.
- REWAISE- REsilient WAter Innovation for Smart Economy.

It is expected that further educational needs and educational content will be provided by the research performed by these projects in the years to come.

However, the process of digitalization calls for the creation of new digital skills that integrate at once the water sector traditional knowledge on the physical assets with the ICT expertise. Furthermore, the digital transformation also leads to a more vulnerable system, and reinforced protection of the water and wastewater services is required. This has been handled in an extensive EU project STOP-IT (2017–2021), where a number of measures for water critical infrastructure protection against cyber and physical threats is demonstrated [35].

As for today, research and development in the scientific community is making progress with maturing secure digital twins in cyber-physical systems (e.g., by the H2020 projects Digital Water City and Aqua3S). This leads to interdisciplinary cooperation and new business models.

Lessons learnt from the 3rd generation of IAM to enrich educational programs:

In the third generation of IAM, water utilities are incorporating sustainability, resource efficiency, resilience, circular economy, and continual improvement principles into their practices, and at the same time, are entering the path of digital transformation.

New competences are required within digital solutions and the social, economic, environmental, asset, and governance domains, and their interaction within holistic thinking of sustainability and circular economy. In addition, the vulnerability introduced by new digital solutions needs to be understood and skills to counteract cyberattacks need to be enhanced. Furthermore, soft skills for effective communication and collaboration are requested, as well as the ability to simultaneously hold a concrete technical and operational mindset. EU projects like TRUST, BINGO, and STOP-IT, to name a few, have provided a number of tools and methods for sustainable transformation of the water systems as well as participation of stakeholders. An assembly of those tools should be included in a training curriculum.

5. Discussion

The legal requirements have increased significantly during the IAM history, introducing more strict objectives of public health and environmental impact as well as concepts like sustainability and circular economy. To cope with a steadily more demanding environment, the IAM has become more complex, adding a magnitude of new tools developed in the research community to obtain good governance and good management.

As a general picture, the tools until now have only to a small degree been implemented for urban water systems. Thus, information and training of water utility staff members should be a high priority worldwide in the years to come, starting from enriched educational modules within the universities' curricula.

The development in the urban water sector is not unique but has parallels in other building and infrastructure sectors. Similar competencies are needed for other infrastructures, like buildings, roads and railroads, and cyber systems.

Until now, IAM and the underlying approaches have not been a part of civil engineering education. There is an urgent need to introduce principles as risk, sustainability, circular economy, and digitalization, as well as principles and tools for integrated asset management in civil engineering education programs.

6. Conclusions

The authors have made a journey in time to describe the evolution of IAM and matching those steps with educational needs. Each development step of IAM has brought new approaches and methods leading to the need for new competences to be presented to the decision makers of tomorrow. Each IAM phase feeds the next, therefore contributing to the overall opportunities that IAM, as a methodological, analysis, and organizational process, provides today. None of the phases have to be considered as having ended, but as part of the incremental approach, and as such, each phase brings its contribution to the list of competences required.

IAM is generally spoken of as a systematic way of assessing the urban water systems in light of legal requirements with the aim to identify weak spots that need upgrading.

We are now on the threshold of the common use of advanced planning and decision-making tools for integrated asset management. To ensure the process, a comprehensive review of the education programs of the practitioners and the civil engineers of tomorrow is urgent.

Knowledge has been the core of IAM since the first standard in 1913. Learning over 100 years has brought the IAM forward to the advanced practice of today at the forefront water utilities. In future, we should expect this practice to spread and reach general acknowledgement. This may safeguard the water and wastewater services and contribute to a better environment achieved at a lower cost.

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