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Perspective

Water Infrastructure Asset Management Is Evolving

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Abstract: Infrastructure Asset Management (IAM) is the process by which decisions are made and resources allocated to ensure organisational or societal assets continue to deliver, as required. IAM is an evolving field. We discuss this evolution and present our perspectives on the future direction of IAM. IAM was born as a response to the poor state of maintenance of infrastructure, largely due to lack of resources, and emphasizes the need to prioritize maintenance and renewal using risk-based approaches. The demands on IAM have also continued to evolve as asset systems have become more complex, with multifunctionality, adaptative capacity and nature-based infrastructure, all issues that IAM must now consider. These challenges underpin the changing context of Water Infrastructure Asset Management (WIAM) and the opportunity for WIAM to harness new technical developments from other IAM domains. WIAM will need to continue to evolve, responding to these challenges and take advantage of these opportunities through research and application in collaboration with a relevant education and capacity development agenda.

Keywords: infrastructure asset management; water management; maintenance; flood infrastructure; nature-based solutions

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1. Introduction

We are pleased to introduce the Special Issue on Water Infrastructure Asset Management (WIAM), showcasing some of the current innovations in the field of Infrastructure Asset Management (IAM) related to the water sector. This issue includes seven papers covering different aspects of water asset management, ranging from condition assessment and modelling of sewer and drainage systems [1–3]; large scale flood management infrastructure [4,5], asset management maturity analysis of institutions [6]; adopting asset management principles for complex, highly unpredictable situations [7]. In this perspective article, we reflect upon these papers and the ongoing evolution of IAM. We explore issues, such as why an IAM perspective is needed; how IAM can be delivered to best support Water Infrastructure Asset Management; and, what needs to change to better address future challenges.

The need to evolve asset management within water infrastructure is driven by the changing context within which it is delivered, including: (i) changing loads, in response to, for example, climate change (e.g., sea-level rise, increasing extreme weather events) and the changing strength of an ageing asset base; (ii) changing societal demands for efficient and robust investments delivering multi-functional assets; and (iii) professional trends, including the use of innovative solutions and a better understanding of assets performance with improvements in science, data and analysis capabilities.

In response, the focus in recent years has been (and continues to be) on finding a cost, risk, and performance balance for an asset system rather than a simple individual asset least-cost optimization [8,9]. This requirement is increasingly moving the IAM focus towards functionality and performance at network and system scales, rather than the level of a single asset [6].

The evolving approaches within WIAM are at vanguard of many of the developments within IAM more broadly. This is because WIAM is an example *par excellence* of the need for multiple functional asset systems across catchments, cities, networks, or coastal-cell scales. Interdependence between water infrastructure assets is central to many of the choices and complexities [10]. Research in WIAM should, therefore, not only respond to the well-understood demands of asset management in general (quality, cost, programme) but also emerging requirements for whole-life and systems-based asset management. This includes challenging existing practices and the assumptions to embrace emerging science (including those around data science, artificial intelligence, social sciences, etc.) as well as engineering (e.g., around blending built and nature-based infrastructure [11]). Delivering innovation also relies on education and professional capacities. Education, particularly at the post-graduate level, should also be informed by research and innovations in the field and vice versa.

Following this introduction, we discuss a brief history of the development of infrastructure asset management and current direction of travel. The priority research gaps we see in this continued evolution of the water infrastructure asset management are also set out together with the innovations in education and training that may be needed.

2. Development of Water Infrastructure Asset Management

Until the 1970s, engineering focused on the attributes of growth (power, scale and speed) over those of stewardship (sustainability)—Figure 1 [12]. So, in the contemporary sense, engineering did not have issues of sustainability explicitly embedded in its discourse [13,14]. Through the 1980s and 1990s, engineers and infrastructure managers had to reconsider established practice: for example, there was limited cost pressure on operation and maintenance practices during the expansion of the oil and gas industry in the 1970s. However, following the oil price crash, maintenance issues were often silently ignored or only actions implemented on a rather ad hoc basis, leading to disasters, such as the Piper Alpha oil platform explosion in the United Kingdom [15]. Risk-based decision making, which was not critical before, became central when "fixing everything" simply became untenable. Risk-based decision making continues to be at the heart of the modern IAM. The findings from the landmark report "Fragile Foundations: A Report on America's Public Works" [16] on infrastructure in the United States of America (USA), and similar reports on the poor status of water infrastructure in Australia and New Zealand in the early 1990s (among others) all indicated a common shortcoming. It was clear that operation and management (O&M) practices, developed during times of relatively good sector performance, did not deliver good outcomes when financial resources are limited and there is more to do than can be afforded. IAM was born out of necessity to guide organizations to spend limited funds to maintain acceptable performance and minimize the chance of failing to deliver the required service level (SL). This new context is enshrined in the International Organization for Standardization (ISO) 55000 standard definition of Asset Management (AM), describing it as "making intelligent choices to maintain the SL of infrastructure with limited resources and to respond to the unviable way of financing the O&M practices of the past in a resource-restricted environment" [7]. IAM can, therefore, be seen as the process by which decisions are made and resources allocated to ensure an organisation's assets continue to deliver as required.

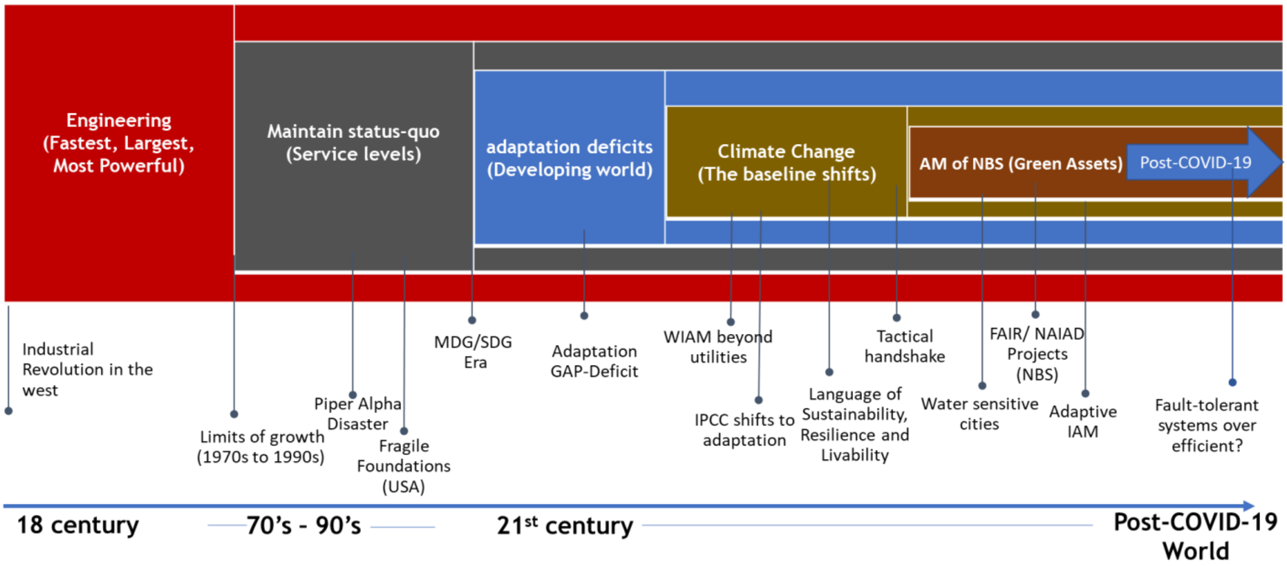

Figure 1. A timeline of the development of Water Infrastructure Asset Management.

Since the late 1990s, IAM has evolved to incorporate environmental outcomes as a priority along with economic and service-level goals [17]. The late 1990s saw the advent of adaptive planning [18] which developed into a rich research area, leading to the development of new planning frameworks based on adaptation framing. For example, Shoreline Management Plans were introduced in the UK with the explicit inclusion of Management Realignment [19,20] and leading experiments, such as the Dutch adaptive delta management plan [21] and Thames Estuary 2100 plan [22,23], which started to translate 'adaptation' into actionable asset management decisions. Around the same period, the concept of multiple (co-)benefits developed together with that of Nature-Based Solutions, NBS [24,25]. These concepts highlighted that even local IAM choices can have ecosystem service benefits, for example a rain garden system to manage stormwater can contribute to local pollinators and urban heat mitigation [26]. Delivering IAM in this context, however, is challenging for several reasons [27], including: (1) lack of data—for example, we often do not have good data or even good theories on ageing of NBS; (2) our ability to understand a life cycle analysis of adaptive infrastructure remains limited; and (3) 'failure risk' within a multi-beneficial context has many complex meanings that are yet to be fully understood (failure of one service or more, and which ones?). The public water infrastructure systems are, in many cases, multifunctional, and so multi-financed and multi-managed that this adds to the IAM challenge [28]. In combination, these challenges increase the awareness of the importance of both organisational and technical capabilities within WIAM if these challenges are to be properly addressed [5,29].

The focus on growth in the 1970s evolved to include a focus on stewardship towards the end of the 1990s and today to include adaptive asset management and issues of resilience; a focus that will be central in the coming decades [30]. Research will be central to supporting IAM in delivering on the goal of resilience; some of the most important current knowledge gaps and opportunities that are likely to influence the development of WIAM are discussed below.

3. Where Next for WIAM?

There is a disconnect between day-to-day operational processes and strategic decision making (a lesson from Flood management organizations in the North Sea region, [5]). A 'tactical handshake' (aligning strategic interests with operational interventions, i.e., breaking free from the individual organisational silos, aiming for the two domains complementing instead of contradicting each other [5]) is needed to bridge that gap, translating the strategy to concrete activities by sound prioritization and planning, based on the complete asset portfolio. This must be reinforced in the context of organizations managing water infrastructure.

IAM should not only maintain and improve performance (to address the adaptation deficit) but also prepare the way for change (for future adaptation) [31]. These two domains (current performance needs—adaptation deficits and future need for change—adaptation gaps) have quite different levels of urgency, uncertainty, and political will while competing for the same resource base. What is the optimal allocation of resources between the two domains? What are the synergies and transitions (from initially addressing deficits to later addressing gaps) that can be found?

The financing of WIAM has become an interesting and complex topic. In many developing countries, often CAPEX (Capital expenditures) and OPEX (Operating expenses) financing are separated, making it hard to encourage lifecycle-based investment assessment. The former is often covered by capital from external sources of International Financial Institutions (IFIs) such as the World Bank, while the latter is covered by (inadequate) revenues supplemented by government stop-gap grants. This is not a sustainable solution, but the full-cost recovery of infrastructure services is a politically sensitive topic. Addressing the financial challenges using mechanisms such as Public–Private-Partnerships, cross-sector subsidies, etc., is an interesting research topic. Some operational models have worked well in bringing the cost of services down over the long haul (e.g., Dutch water supply sector [32]). Lessons can be learned from these but need to be carefully contextualized for different situations, such as those of developing countries [33].

Another area that addresses not only potential financial savings, but also provides increasing self-sufficiency and environmental sustainability, is the improvement of energy use in infrastructure assets. Energy-saving and recovery [34], optimizing energy use [35] and use of sustainable alternative energy sources [36] contribute to making infrastructure more sustainable.

An increasingly relevant context for WIAM is that associated with extremely rapid and largely unpredictable change. Population (and hence the service demand) change, particularly in lower income or fragile states that may experience significant and rapid growth in demand, for example, in response to a refugee crisis, presents traditional asset management with a real challenge [7]. Extreme weather events and other disasters damage assets, causing sudden service interruptions, putting an extra burden on remaining asset systems. These are opportunities to further develop the scope of WIAM and make it much more relevant to the world's problems.

Climate change has potential impacts on infrastructure systems that could lead to significant negative impacts on service delivery [37]. Furthermore, infrastructure systems are interconnected and interdependent, causing climate impact on one system to have cascading effects [38]. For example, climate risk on a large-scale flood management system may have consequences for urban drainage, power supply and communication systems due to potential flood damages. Climate adaptation is an integral part of (strategic) WIAM and supplementing the language of WIAM with climate adaptation concepts and practices is now important to help mainstream the adaptation into IAM [39].

Natural infrastructure forming our catchments and coasts has always contributed to management of the water environment, providing benefits to nature and people [8]. Until recently, such infrastructure has been outside of the standard built infrastructure focus underpinning IAM. Although changing, water infrastructure asset managers do not have great experience with O&M of natural features [23]. Future observational and modelling studies will be needed understand the performance of natural infrastructure and built assets that attempt to mimic natural functions over time. As lessons are learnt, conventional IAM frameworks may need to be adjusted to fully embrace natural assets.

The 'benefits' of WIAM are broader than economic: sustainability, resilience and livability concepts [40] are increasingly connected to WIAM ('Water sensitive' IAM [41]). With the prevalence of the view of asset systems as multi-beneficial entities, and having impacts on many different systems and sectors, the concepts of 'risk' and (financial) 'benefit' in WIAM needs broadening. Concepts narrowly focused on (direct) financial risks, costs and benefit are of little use for evaluating modern, complex systems combining built and natural infrastructure. Accounting in asset management has to encompass societal and environmental costs, benefits and risks, in addition to those of a direct or financial nature. The acknowledgement of these has already happened, but a lot more work must be done on quantification.

Lack of adequate data is a perpetual issue in WIAM (particularly in the domain of condition assessment and early detection of failure possibilities, but also in areas such as asset performance and service delivery) [42]. The developments in citizen science and crowdsourcing provide great opportunities to fill the data gaps. Services such as Kobo-toolbox [43] have made citizen-driven data collection, geolocation and mapping easy. Another important potential research area that is connected to this is the use of distributed sensors. Ranging from low-cost LoRaWAN (Long Range Wide Area Network, i.e., Internet of Things) devices to smart meters; these also can contribute to addressing the issues of a lack of data. These include mobile-phone-based technologies/sensors and add-ons such as Akvo Caddisfly [44].

There are significant developments in Artificial Intelligence (AI) and related technologies. These open research opportunities such as condition assessment of buried assets —pipes, early discovery of weaknesses in flood protection infrastructure, etc. [45]. Combined with modern sensors and data gathering methods (above), AI applications provide a powerful platform for innovation in IAM.

In the past, infrastructure has been viewed as merely 'servicing' the society. However, particularly with WIAM, it has become clear that society is transforming from a passive beneficiary to an essential partner in ensuring the sustainability of assets. Often, the sustainable management of NBS critically depends on the collaboration of society. During water scarcity situations, water system beneficiaries need to be directly involved in equitable water distribution decision making [46]. The active roles of the society in IAM are, therefore, an important area of research. A related concern is how IAM can better serve disadvantaged communities and contribute to sustainable development goals. A broad-based evaluation of IAM services that goes beyond financial outcomes and overall service levels is needed. For example, a flood management system's performance should also be evaluated on its contribution to vulnerability reduction in the number of disadvantaged communities (e.g., informal settlers who often live in flood-prone areas), in addition to overall risk reduction.

Today we are at another time of reckoning as we pass through the COVID-19 era. As with many important concepts, WIAM should also take stock and learn lessons from this period. It is too early to say what we will learn in the context of WIAM; however, some contenders are:

1. COVID-19 confirmed the long-known, but underappreciated, principle that classically optimized systems (e.g., large-scale economics instead of distributed; just-in-time instead of just-in-case, etc.) are generally vulnerable to unpredictable events. For the best outcome in the long term, robustness is equally as important as cost minimization. Proven approaches such as robust optimization [47], can be retooled in the context of high-impact, rare and hard or impossible to predict events (deep uncertainties).
2. WIAM's risk-based approach was largely limited to predictable uncertainties (e.g., Background ageing-driven failure). Risk-based WIAM should be expanded to prepare for unknown uncertainties alongside the known.
3. The resilience of infrastructure systems is often limited by the most vulnerable component. A failure event chain can originate not only from the asset system (component failure) but from events in the far-field [48]. Classical risk propagation methods such as Bow-Tie analysis [49], focused mostly on the asset components and the system boundaries. New theoretical developments are useful on how to address risks arising from far-field events that are hard to predict and hard to detect.

None of these concepts are completely new. However, again, WIAM will likely transform as a result of researchers paying attention to such new areas, breaking new ground, particularly in disciplinary interfaces [50].

4. The Need for Education and Training

In the higher education sector, WIAM is generally included as a post-graduate level subject [7]. As the importance of the subject further evolves, it may be beneficial to consider introducing principles and elements of WIAM in the undergraduate engineering curricula. This is a useful way to encourage budding engineers and managers to see beyond the implementation phase of infrastructure and embrace the lifecycle-based approach for water infrastructure development. This will help to shift excessive focus on the implementation phase at the expense of that on the operational phase of water assets, towards a more balanced one. WIAM emphasizes the importance of infrastructure sustainability achieved by best practices of operation, maintenance, and renewal (O&MR). One of the approaches to achieve this shift in paradigm is to emphasize the financial aspects of the asset life cycle.

We envision WIAM curricula to address three distinct areas. First, the principles of asset management including the rationale for asset management (topics mentioned in Section 2) and the principles (e.g., risk-based decision making). The second should cover asset management techniques. These are very much domain-specific; for example, ageing models for buried pipes, hydraulic model-based failure consequence analysis, condition assessment methods, etc. Such techniques have been widely used in IAM practice and students should be familiar with them. The third area should be new trends and developments in asset management. Research conducted in addressing the gaps identified in Section 3 should contribute to these. Frontier knowledge on topics such as managing climate change risks, new methods in data collection, asset management of nature-based solutions, application of machine learning and artificial intelligence, etc., should be introduced here. Naturally, this final component of a WIAM educational package will be the most dynamic. It would be beneficial to subject this to frequent (if possible, annual) review and updates as the knowledge base continually grows and changes.

Many of the senior engineers and managers today have not had the opportunity to learn WIAM during their post-secondary education. Due to the urgent relevance of WIAM to address the sustainability of our investments today, exposing this demography to the principles and practice of WIAM is important. Further, successful organizational embracing of many of the best practices of IAM requires policymakers to be aware of the benefits of asset management. This is where capacity development and training can be helpful. Organizing high-level meetings, seminars, and workshops with the participation of the policymakers, politicians and donors, attempts can be made to bring this message to those higher-level stakeholders.

5. Conclusions

This paper is not meant to be a systematic review, such as that by Malek et al. [1], in this Special Issue (covering sewer pipe condition prediction models) and others encountered in the current literature (e.g., [51–53]). It is a perspective that builds upon the authors' experience from practice and research to provide a reflective insight into driving forces for change in and future direction of WIAM (and IAM in general) with the support of selected literature.

Infrastructure asset management (IAM) can be seen as a response to the historical developments, re-balancing stewardship and growth, and combining both life cycle management and adaptivity. Introduced as a response to the lack of optimal maintenance and upkeep in public infrastructure industries, such as oil and gas, during the 1990s, IAM has continually evolved to become what it is today. Water Infrastructure asset management (WIAM), initially focused on utilities, has encompassed diverse water-related infrastructure systems, including large-scale flood defences and coastal infrastructure. Today, we also view WIAM as a largely evolving and expanding field, responding to the autonomous, societal and professional trends around water infrastructure. These include climate adaption, multi-benefits, nature-based solutions, and adaptive planning. At the same time, WIAM should benefit from development in domains such as artificial intelligence, innovations in data management and citizen science. WIAM research should embrace the relevant trends as driving forces and innovations as resources, leading to WIAM transforming towards a trans-disciplinary umbrella instead of a tightly defined, traditional, academic discipline. This makes WIAM both challenging and a fascinating field to innovate in. It is important to bring the subject to the fields of education and capacity development, not only as a response to a crisis in infrastructure performance but also as an exciting trans-disciplinary field of study that is continuously being shaped by the needs of the water sector and the exciting innovations that are happening today.

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