Water infrastructure asset management: state of the art and emerging research themes

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Abstract

The long-term maintenance of infrastructure requires asset management. This latter is defined as a series of actions aimed at the long-term maintenance of the capacity of an infrastructure to provide an efficient service for users, at costs and with impacts that are tolerable for society and the environment. The actions implemented concern notably the inventory of infrastructures, their monitoring, inspection and maintenance, the analysis of their state and performance, their reinforcement, renovation, and the definition of long-term technical-financial policies. This paper is structured around four themes based on the authors' experience faced with an analysis of the perspectives set out in recent articles. For each theme, a state of the art largely based on the literature in the field, as well as emerging and nevertheless pressing needs in terms of knowledge production and tools to support reflection and decision-making are presented: temporal and spatial dimensions of Water Infrastructure Asset Management and their consistency; multi-infrastructure management seen from the perspective of physical interdependences and decision-aids; governance, organisations and territories; digital representation of the socio-technical infrastructural system. The analysis is carried out following several disciplines from the engineering and, the human and social sciences. Infrastructure linked to water are studied.

Keywords

Infrastructure asset management, water and drainage networks, hydraulic works, interdisciplinary approach, socio-technical system, governance, multi-infrastructure management

1. Introduction

Infrastructure represent major economic, health, social and environmental challenges. Their long-term maintenance therefore requires adapted techno-economic management rules to offset the negative effects of their ageing and their possible obsolescence, by ensuring their gradual adaptation to changes in service requirements. Infrastructure asset management (IAM) is defined here as a series of actions aimed at the long-term maintenance of the capacity of an infrastructure to provide an efficient service for users, at costs and with impacts that are tolerable for society and the environment (Amaral et al., 2017; Le Gat et al., 2016; Ugarelli & Saegrov, 2022). In this context, the system concerned by IAM includes infrastructure, the service with its employees, and the individuals, users or beneficiaries of the services rendered (Rozan et al., 2017; Serag et al., 2020). The natural environment (resource, ecosystem) is an external component in interaction with this system; it will not be dealt with as such in this article, since it has been chosen to focus more specifically on the human environment.

The actions implemented concern in particular the inventory of infrastructures, their monitoring, inspection and maintenance, the analysis of their state and performance, their reinforcement, renovation, and the definition of long-term technical-financial policies. The term ‘Infrastructure Asset Management’ links this research subject to the disciplines of engineering sciences relating to the technical and physical dimension of ‘infrastructure’, and to those of management science/public management, economics and sociology regarding the ‘asset’ dimension (i.e. management, use, transmission, perception, value, etc.). This therefore calls for an interdisciplinary construction in view to aiding decision-making (Le Gat et al., 2016).

The establishment of principles and regulations by the public authorities regarding the IAM of structures considered critical, such as large dams and road bridges, has been driven in western countries by the occurrence of disasters such as the rupture of the Malpasset dam (France) on 2 December 1959, the collapse of Silver Bridge in Ohio (USA) on 15 December 1967, and that of Wilson bridge in Tours (France) on 9 April 1978 (Cavalline et al., 2015; Le Gat et al., 2016). This interest for IAM seems to have been increasing constantly since the 2000s, as much regarding the owners, operators and the socioeconomic actors involved in infrastructure management and the contracts linked to their construction, maintenance and renovation, as for the persons responsible for public policies and users’ associations (Alegre et al., 2012).

Besides issues of safety and convenience, this interest is often explicitly motivated by the importance of the infrastructure and the public services that they provide to ensure competitiveness and economic dynamism. For some, infrastructure are considered critical, i.e. essential for maintaining the vital functions of society, health, safety, security and the economic and social well-being of the population (European Union, 2008).

This interest in IAM is also associated with the fear frequently expressed by many decision-makers regarding the insufficiency of the resources devoted by the public authorities to maintaining and renovating ageing assets with finite lifetimes. Very recently, in 2021, the Biden Build Back Better Framework in the USA proposed public financing amounting to US$1,200 billion for the renovation and construction of infrastructure among which those linked to water took up a considerable share. The current French recovery plan proposes €300 million for drinking water and drainage infrastructure. The interest for Water Infrastructure Asset Management (WIAM) can also be seen in the recent evolution of the regulations, standards and institutional framework (for instance, at the

European level, the Water Framework Directive, Flood Directive) which gives new directions regarding many types of infrastructure (in particular, water network, drainage, flood protection systems), but which also affects investment choices.

Relatively early, needs for research emerged to understand and model infrastructure deterioration processes (Jiang & Sinha, 1989), and to know the costs of maintaining and renovating structures (Cavalline et al., 2015; Saegrov, 2005, 2006). The responsibility taken by institutions and research for managing the risk pertaining to different critical structures spread at the end of the 1980s to all collective infrastructure rendering essential services to society, especially those relating to transport, energy and water (protection and network structures). Since the beginning of the 1990s, INRAE (French National Research Institute for Agriculture, Food and Environment) carried out research works aimed at improving the techno-economic management of infrastructure linked to water as a resource – raw water, drinking water, wastewater, irrigation water, water stored in reservoirs – or as a source of risks for human populations – floods, torrential phenomena in mountain areas (Le Gat et al., 2016). In the middle of the 2010s, in order to consider these highly interdependent socio-technical systems as a whole, the issue of linking the engineering sciences and the human and social sciences emerged, as did the development of synergies between approaches and the work carried out by teams studying heterogeneous objects: drinking water and drainage networks, dams, flood protection systems, and protection against avalanches and debris flows.

Starting from these interdisciplinary reflections and the diversity of the infrastructure studied and, largely supported by an analysis of the literature, four emerging themes have been identified for which the need to produce knowledge and tools for reflection and aiding decision-making appear to us to be the most pressing. These research themes are broken down into orientations then proposals. This paper is not a systematic review as others encountered in the current literature and used in the following (Bradley et al., 2016; Bruaset et al., 2018; L. Chen & Bai, 2019; Daulat et al., 2022; Hawari et al., 2020; Langeveld et al., 2022; Matejko, 1983; McDonald, 2019; Mohammadi et al., 2019; Mohammadi et al., 2020; Nkwunonwo et al., 2023; Sadeghikhah et al., 2022). It highlights research proposals based on the authors' experience faced with an analysis of the perspectives set out in recent articles (2018-2022), and supported by a state of the art largely based on the literature in the field. The methodology used to define the research themes, orientations and proposals is presented in Section 2. The rest of this article deals with the four emerging themes, successively:

- the temporal and spatial dimensions of WIAM and their consistency (Section 3);
- multi-infrastructure management seen from the perspective of physical interdependences and decision-aids (Section 4);
- governance, organisations and territories (Section 5);
- the importance of the digital representation of the socio-technical infrastructural system (Section 6).

2. Methodology

Figure 1 presents the methodology. It comprises three main steps (S1, S2, S3) and strongly relies on the literature and authors' experience built in various past projects. The authors group is composed of one researcher in applied mathematics, two in decision-support and civil engineering, one in management sciences, one in economics and one in sociology. The authors shared their knowledge and experience to identify and describe emerging themes concerning WIAM.

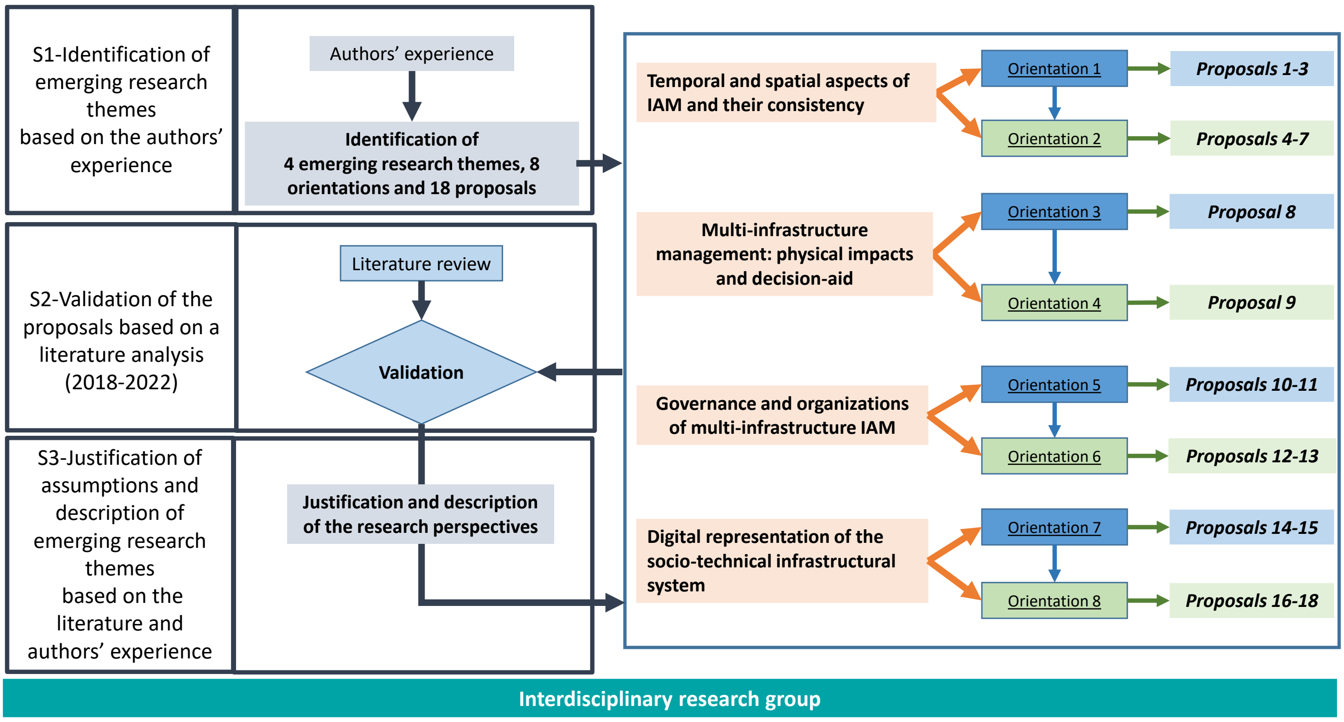

Figure 1. Methodology steps.

S1 concerns the identification of the research themes, orientations and proposals from projects the authors were involved in. This step leads to identify 4 research themes, 8 orientations (2 per research theme) and 18 proposals for the 8 orientations (from 1 proposal for orientations 3 and 4, to 4 proposals for orientation 2 - the orientations and proposals will be explained in the following sections).

To validate this list (S2), an analysis was carried out of the Web of Science (https://www.webofknowledge.com) and the SCOPUS databases (https://www.elsevier.com/solutions/scopus). Two requests were performed:

- search for review articles using as keywords: (asset management and water infrastructure) or (water supply or sewer or levee or dike or dam or drinking water or urban water);
- search for review or scientific articles using as keywords: [(asset management and water infrastructure) or (water supply or sewer or levee or dike or dam or drinking water or urban water)] and (trend or perspective or future work or further work or emerging or research need or challenge) ;

Years considered were 2018-2023. The analysis was limited to the five last years as it aims to search future directions. Duplicates were removed leading to 84 articles, after which finer analyses were performed. This operation led to keeping 31 references (Tables 1-4): articles dedicated to case-studies, or concerning a specific method (e.g. Multi-Criteria Decision Aid), or orientated towards technological developments of sensors for instance, etc. were removed from the original corpus.

Additionally, a more specific search was carried out for four proposals that were orphaned by previous searches: Probabilistic simulation MCDA ("Temporal and spatial aspects of IAM and their consistency"); Extension of BIM to infrastructures other than buildings, Extension of BIM to the whole lifecycle of an infrastructure and Integrated management (several infrastructures; several managers) ("The digital representation of the infrastructural socio-technological system and its importance). With this search, 8 articles were added to the first set of 31 references.

The 39 articles are distributed as follows: 5 in 2018, 10 in 2019, 7 in 2020, 5 in 2021, 10 in 2022 and 2 in 2023. The themes of the journals in which the articles were published fall into three broad categories: water and water infrastructure (e.g. Journal of Pipeline Systems Engineering and Pratice, Urban Water Journal, Water, Water Science and Technology, Water Supply), infrastructure (e.g. Infrastructures, Structure and Infrastructure Engineering), others (e.g. Automation in Construction, Sustainability).

At the end of S2, all the proposals were retained as at least one article was found in the literature to confirm the relevance of the whole set of proposals. The results are presented as a table for each research theme in the following sections (Tables 1-4).

For each emerging theme, S3 consists in a justification of the assumptions, which corresponds to explaining why the theme is relevant, thus leading to the orientations and proposals. Each of them is then described. This step is performed with the support of selected, relevant articles, stemming from states of the art we carried out in our previous projects.

3. The temporal and spatial dimensions of WIAM and their consistency

3.1 WIAM activities and temporal dimension

WIAM activities are by nature operational, decisional and informational; they are linked around four temporal aspects (Alegre et al., 2012):

- the real time is that of monitoring the operation of the infrastructure, the implementation of inspection, corrective and preventive maintenance and renovation operations (renovation, replacement, or simple shutdown) of components of the infrastructure, the reporting of these actions within the information system of the management service;
- the short-term, yearly or two-yearly, is that of establishing programs of equipment, inspection and renovation, in particular requiring the prioritisation of the infrastructure components concerned, besides the choice of technologies and suppliers;
- the medium-term, typically ten years, concerns the budgetary planning of annual and biennial programs of equipment resulting from multi-annual investment plans, inspection and renovation, and the consistency of their funding (subsidy, loan, or pricing access to the service), and possibly the type of organisation of the management service (*e.g.,* public corporation vs. delegation);
- the long-term (several decades) is that of defining the strategic objectives of WIAM, aimed at transmitting to future generations assets whose state will ensure a quality service in return for tolerable maintenance and investment costs.

A central question in WIAM is whether or not the investment budget is sufficient to fund the (long-term) strategic objectives on the one hand, and the constraints of implementing the annual program of renovation works on the other. Logically, this question of consistency between timeframes must be included when considering the fate of assets. It therefore entails remedying situations that are rather caricatural though nevertheless encountered in practice (Large et al., 2014), such as that in which the annual programming of renovating the piping of a large drinking water network begins with ranking sections according to the risk due to their deterioration and their context of operation (using the multicriteria method: rate of failure and hydraulic and socioeconomic impacts, coordination with roadworks, increasing diameter, etc. - cf. Le Gauffre et al. (2007)), whereas renovation budgets are planned over periods of ten years with the sole aim of limiting the average age of the pipe sections.

This quest for temporal consistency leads to proposing two complementary directions. Orientation 1 is aimed at linking the short-term management of defined objects (management of a specific structure) and that of the medium-term management of the same objects considered as statistical items ('pool management'). Orientation 2 dedicated to ensuring the cohesion of the operational and tactical decisions of budget planning (**Figure 2**). The research proposals from 1 to 7 linked to these directions are detailed in the following sections.

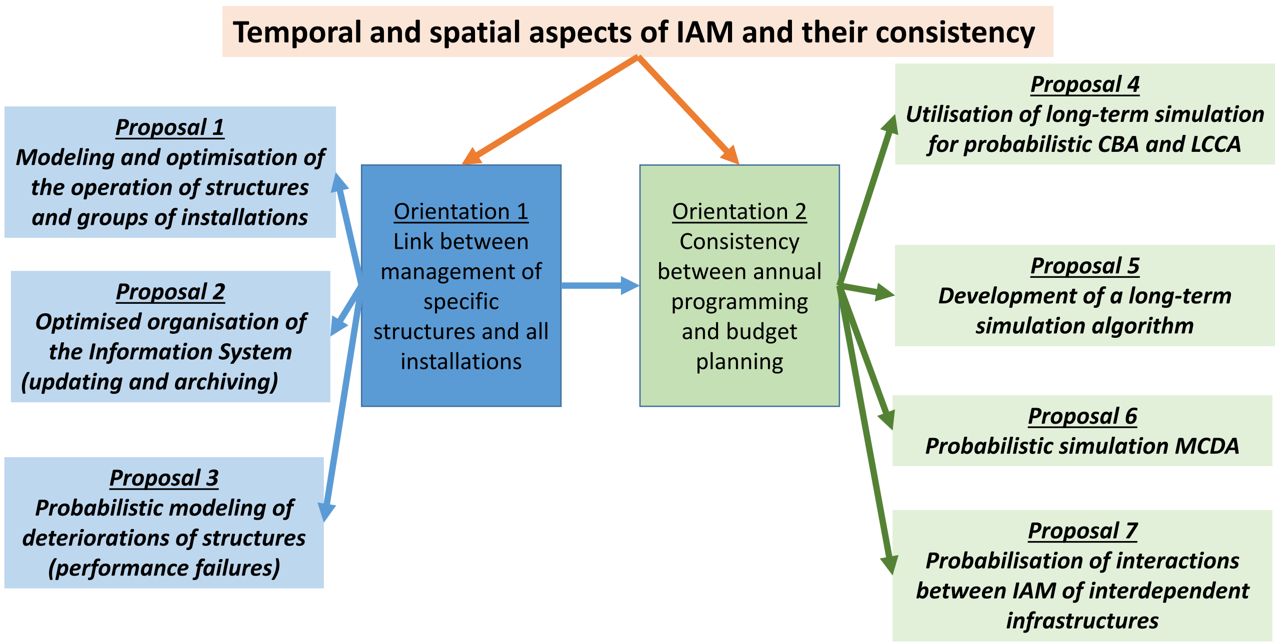

Figure 2. Research directions and proposals in terms of the temporal dimensions of WIAM (MCDA: Multi-Criteria Decision Analysis – CBA: Cost-Benefit Analysis – LCCA: Life-Cycle Cost Analysis).

Erreur ! Source du renvoi introuvable. is the result of step S2 concerning the “Temporal and spatial dimensions of WIAM and their consistency”: the preliminary research proposals, identified based on the authors' previous work and experience, are cited by various authors. In that sense, the authors considered that the research proposals were relevant. For the whole set of proposals, several references are available (at least 2). The proposals "Optimised organisation of the Information System (updating and archiving)" and "Probabilistic modeling of deteriorations of structures (performance failures)" are particularly identified as future research directions. The following sections provide the context and content of the proposals associated with the theme “Temporal and spatial dimensions of WIAM and their consistency”.

Research theme	Orientation	Proposal	References
Temporal and spatial aspects of IAM and their consistency	Link between management of specific structures and all installations	Modeling and optimisation of the operation of structures and groups of installations	(Alegre et al., 2020) (Beuken et al., 2020) (Brous et al., 2019)
		Optimised organisation of the Information System (updating and archiving)	(Beuken et al., 2020) (Carrico & Ferreira, 2021) (Daulat et al., 2022) (Makana et al., 2022) (Noshahri et al., 2021) (Okwori et al., 2021) (Tscheikner-Gratl et al., 2019) (Ugarelli & Saegrov, 2022)
		Probabilistic modeling of deteriorations of structures (performance failures)	(Daulat et al., 2022) (Hawari et al., 2020) (Jonkman et al., 2018) (Martínez García et al., 2019) (Mazumder et al., 2018) (Mohammadi et al., 2019) (Mohammadi et al., 2020) (Tscheikner-Gratl et al., 2019)
	Consistency between annual programming and budget planning	Utilisation of long-term simulation for probabilistic CBA and LCCA	(Bruaset et al., 2018) (Chang et al., 2019) (Ramalho et al., 2020) (Tscheikner-Gratl et al., 2019) (Vonk et al., 2020)
		Development of a long-term simulation algorithm	(Bruaset et al., 2018) (Bruaset & Saegrov, 2018)
		Probabilistic simulation MCDA	(Cole et al., 2022) (dos Santos Amorim et al., 2020) (Salehi et al., 2021)
		Probabilisation of interactions between IAM of interdependent infrastructures	(Daulat et al., 2022) (Mazumder et al., 2018)

Table 1. Validation, based on the literature, of the relevance of the research proposals related to the theme "Temporal and spatial dimensions of WIAM and their consistency"

3.2 Management of specific structures and installation management (spatial dimension)

Real-time and the short-term concern assets (*e.g.,* sections of the network or containment systems) or functional units (hydraulic sector of the network, dam) taken in terms of their clearly identified specificity. Considering this form of management of ‘specific structure’ may be sufficient:

- when the strong criticality of the structures (*e.g.,* certain dams and levees) requires regular inspections, and the indefinite implementation of reinforcement or renovation works as often as necessary (Curt et al., 2018);
- when the management body is responsible for only a small number of structures.

Apart from these two cases, and when the infrastructure is composed of a large number of items, the latter are considered in the medium and long-terms as static items pertaining collectively to a form of ‘pool management’. Indeed, it is impossible to precisely determine beforehand, beyond a few years, which items of the assets will deteriorate to the point of making their renovation a priority, whose configuration will become incompatible with the evolution of territorial development, or which will be subject to the opportunity of carrying out coordinated operations. On the scale of installations, the total volume of such works is however liable to be estimated in a ten-year timeframe or it may be the subject of prospective scenarios over a longer timeframe. Installation management also provides the advantages of (i) ensuring global consistency to management decisions when items function interdependently (Proposal 1) and (ii) pooling feedback between items in view to guaranteeing the quality of IS (Proposals 2) and enabling the production of probabilistic models of performance failures (Proposal 3).

It should be pointed out that the inclusion of infrastructure items in an annual renovation program depends only partially (and often at lower levels in the case of water and drainage networks) on their state of deterioration and the potential impacts of their failure; certain items are concerned by territorial development operations, requiring their reorganisation or relocation independently of their condition; other items are concerned by renovation works on other types of infrastructure (very often roadworks) and it may be pertinent to grasp the opportunity to carry out joint coordinated operations, by carrying out their early renovation in view to minimizing costs and the nuisance of works to the residents and users of the roads concerned (Large et al., 2014). It is therefore necessary to distinguish 'targeted' renovation works for items whose deterioration jeopardizes the performance of the service rendered to the user, obligatory works, and renovations performed through 'opportunity'.

The distinction between managing a specific structure and managing several installations can be expressed methodologically:

- the conjunction of multiple strategic objectives and various practical constraints justifies that operational programming resorts to Multi-Criteria Decision Aids – (Saegrov, 2005, 2006);
- budget planning (ASTEE-AITF-ONEMA-FNCCR, 2014) sometimes uses Cost-Benefit Analysis – CBA or Life Cycle Cost Analysis (LCCA) on the lifecycle of infrastructure items (Proposal 4).

3.3 Ensuring consistency between short-term operational planning and medium-term budget planning: the interest of long-term simulations

The complexity of operational management and the need for consistency between timeframes justifies the continuation of research following the works of (Large et al., 2014) (drinking water distribution networks) and Taillandier et al. (2020) (wastewater collection networks), in view to developing long-term simulation tools aimed at assisting the management organisation (Proposal 5) regarding:

- the magnitude of the long-term budget effort for asset renovation;
- the choice of annual works planning rules.

This type of simulation tool must take into account the impossibility seen above of precisely determining, beyond a timeframe of a few years, the infrastructure items liable to be concerned by targeted, obligatory or opportunity renovation. One possible path is to adopt a theoretical probabilistic framework (there are however other possible approaches belonging to fuzzy logic or the theory of possibilities, presented by Talon et al. (2014)).

Long-term simulation must also link different models to each other:

- probabilistic models regarding deterioration, the probability of exposure to operations on third infrastructure or territorial development (especially regarding roads, by taking into account annual rates of renovation and new constructions);
- more deterministic models for repair or costs for reinforcement, decommissioning, replacement or construction;
- once again, rather probabilistic models regarding the social and environment costs due to the impacts of possible failures.

Figure 3 depicts how a long-term simulation algorithm can be proposed to explore, for each element, and by iteration by annual time step between an initial year and a simulation timeframe, the possible trajectories assigned with their probabilities. This algorithm avoids combinatorial explosion by grouping concurrent trajectories passing via the renovation of an item the same year (this grouping of trajectories is shown in Figure 3 by upwards arrows for a given year). Taking into account the different costs of maintenance, renovation, instrumentation, operation, and replacement according to the trajectories simulated allows reviewing the comparison of WIAM strategies by CBA or LCCA in a probabilistic direction, where in particular the length of service of the assets is not determined beforehand but the result of the application iterated year after year of the management rules to be compared (Proposal 6). One point to be emphasised is the possible utilisation of deterioration models endowed with a memory, similar to the LEYP model proposed by (Le Gat, 2014) for water pipes under pressure. This type of model also requires simulating the gain in information that enriches the IS at every iteration, thus modifying the simulation of operational decision-making (Taillandier et al., 2020).

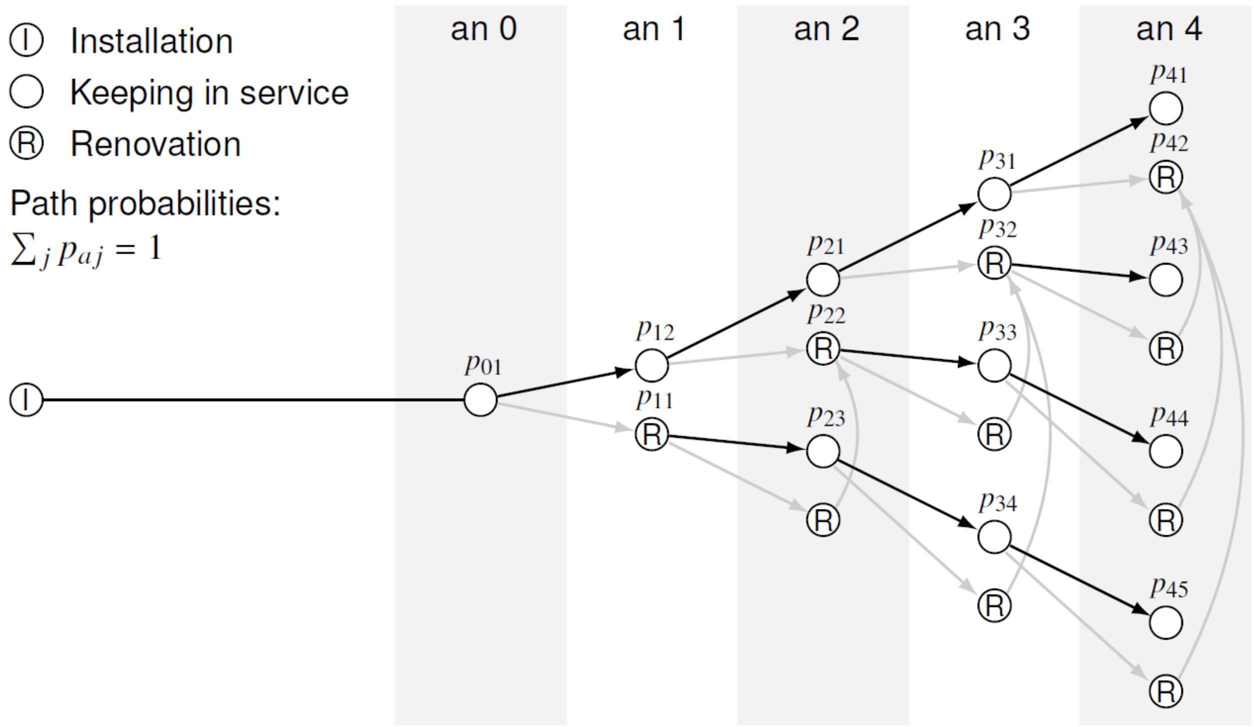

Figure 3. Long-term simulation algorithm (Rulleau et al., 2020).

Each simulation is based on:

- an initial state of the infrastructure, listing all the items assigned with their year of installation, and their technical characteristics (which raises the question of uncertainties on the dates of installation);
- a set of management hypotheses, bearing on the global budget for monitoring; inspection and maintenance, the global budget of renovations year by year; the relative portions of the budget assigned to planned renovations and those chosen by opportunity; the level of information of the management body regarding the programs concerning third infrastructure, especially roads;
- a set of contextual hypotheses, such as the intensity of the renovations of third infrastructure and territorial developments.

This requires the probabilisation of interactions between interdependent infrastructure, which represents an important field of research (Proposal 7). Furthermore, the probabilistic simulation of multicriterial choices, in a context of iterated increases of information and probabilised interactions with third infrastructure, represents an open field of research as yet relatively unexplored (Proposition 5).

How to mathematically formalise management rules in accordance with broadly contextual prospective scenarios (related to demography, climate, governance or policy changes) represents a crucial difficulty in implementing simulations; on this depends the level of compatibility of the simulated final state with a given scenario (Rulleau et al., 2020). This treatment comprises a margin of interpretation, and the same prospective scenario is therefore susceptible to be interpreted by an array of long-term simulations.

4. Multi-infrastructure management: physical interdependencies and decision aids

4.1 Infrastructure in interaction in urbanised territories

The density of different types of infrastructure is greater in urbanised territories, with different types of interactions. These interactions can be spatial (water network, drainage and energy located along roads and pavements, roads located on levees, etc.) or functional (dependence of water and drainage networks on the electricity grid, etc.). Furthermore, these physical/technical structures interact with a social component (decision-makers, managers, users) to form socio-technical systems (Bhamidipati et al., 2016) that produce a service. In this section two types of reciprocal influences relating to WIAM are discussed: on the one hand, physical interdependencies between different types of infrastructure, and the other hand, their integrated management by several organisations or different services of the same organisation. To these two major orientations two research proposals are linked. They aimed at avoiding silo-type operation, classical in current practice, to go towards greater integration to generate economies of scale, pool resources, increase effectiveness and efficiency, and harmonize the requirements of the different stakeholders (**Figure 4**). In addition, to be noted is a strong link with issues of governance and organisation that will be dealt with in Section 5.

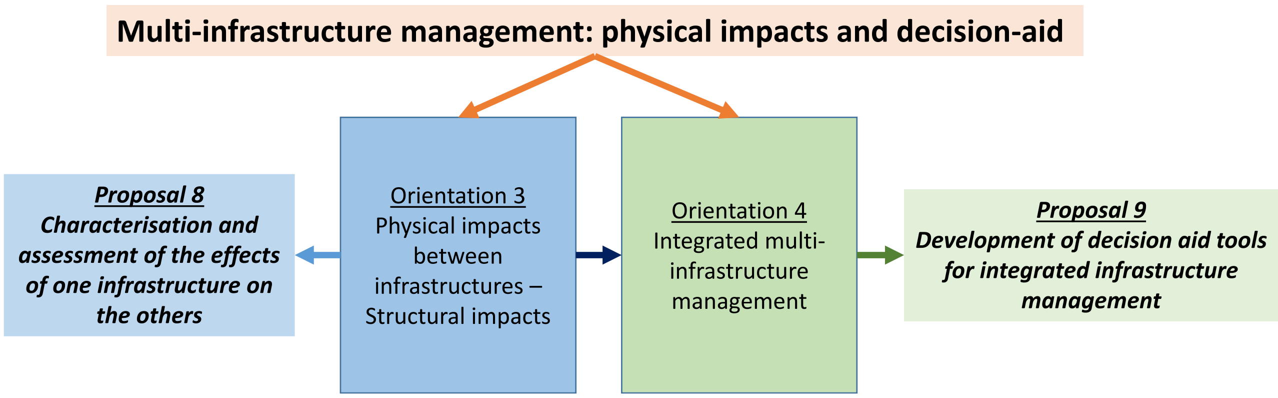

Figure 4. Research orientations and proposals in terms of multi-infrastructure management.

Table 2 is the result of step S2 concerning the “Multi-infrastructure management: physical impacts and decision-aid”: the preliminary research proposals, identified based on the authors' previous work and experience, are cited by various authors. In that sense, the authors considered that the research proposals were relevant. For the 2 proposals, 3 references are available. The following sections provide the context and content of the proposals associated with the theme “Multi-infrastructure management: physical impacts and decision-aid”.

Research theme	Orientation	Proposal	References
Multi-infrastructure management: physical impacts and decision-aid	Physical impacts between infrastructures – Structural impacts	Characterisation and assessment of the effects of one infrastructure on the others	(Daulat et al., 2022) (Imani & Hajializadeh, 2019) (Tscheikner-Gratl et al., 2019)
	Integrated multi-infrastructure management	Development of decision aid tools for integrated infrastructure management	(Daulat et al., 2022) (Tscheikner-Gratl et al., 2019) (Van Engelenburg et al., 2019)

Table 2. Validation, based on the literature, of the relevance of the research proposals related to the theme “Multi-infrastructure management: physical impacts and decision-aid”

4.2 Taking into account physical interdependencies between infrastructure

Physical interdependencies concern the potential structural impacts generated by an infrastructure on another one and which can lead to a decrease in the performance and level of service of the entire system (Curt & Tacnet, 2018; Talon et al., 2014). For instance, leaks from a drinking water or drainage pipe buried in a levee can affect the performance of this protective structure (Aguilar-López et al., 2016; Curt et al., 2018) (**Figure 5**); likewise the sliding of a section of the levee may break the water or drainage pipe.

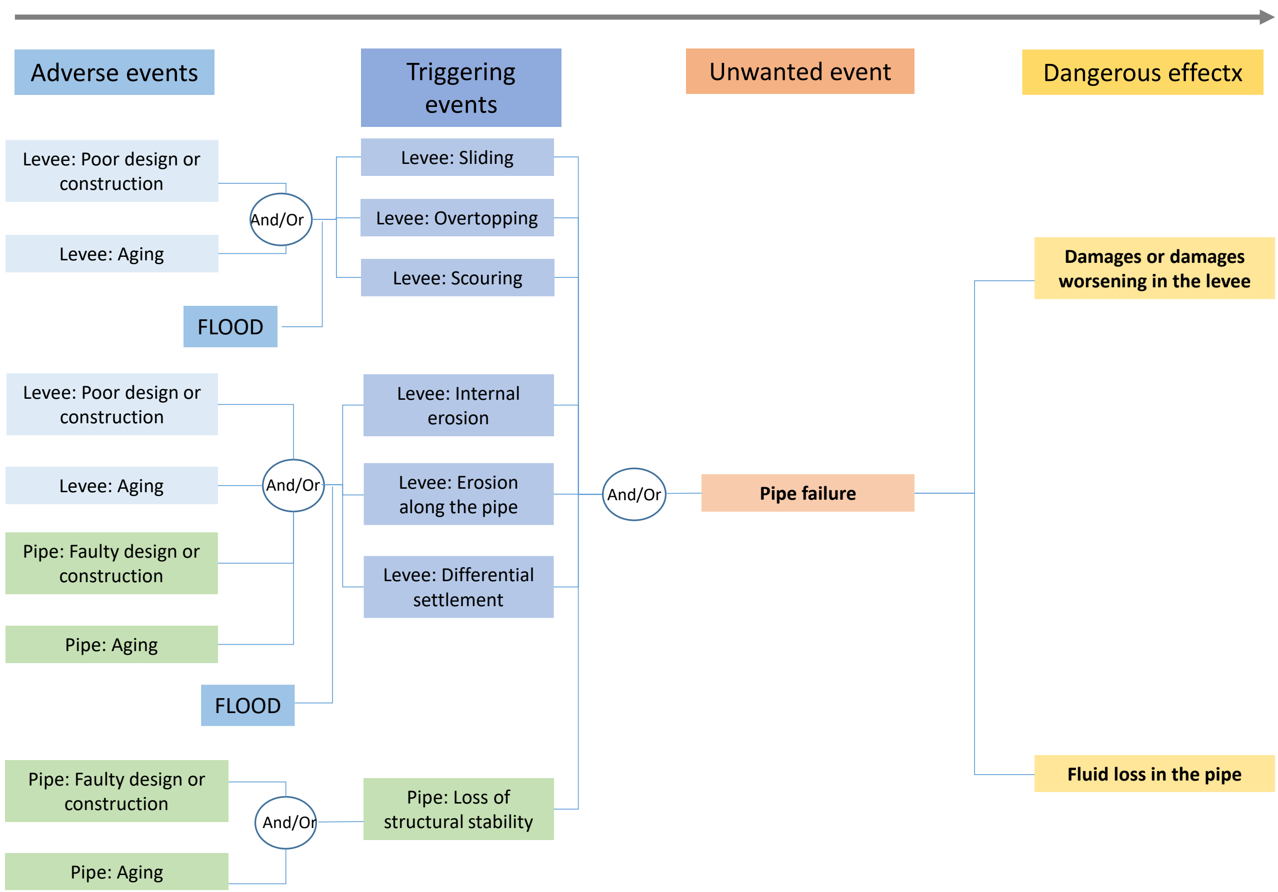

Figure 5. Levees and pipes in interaction: reciprocal effects of failures – representation according to the bowtie method.

Models have been proposed in the scientific literature to assess the performance and impacts of infrastructure (Bambara et al., 2018; Le Gat, 2016; Talon et al., 2014). At the international and national levels, reference documents dealing with a specific type of infrastructure have been published such as the 'International Levee Handbook' which devotes chapters to the inspection and maintenance of levees (CIRIA, 2013), and French manuals on the management of water and drainage networks including 7 guides published by the ASTEE (French Scientific and Technical Association for Water and the Environment) and OFB (the French Biodiversity Agency (ASTEE-AITF-AFB-FNCCR, 2017). Reflection is carried out by the Strategic Asset Management specialist group of the IWA (International Water Association), the Levees Flood Defence of the EuCOLD (European Commission on Large Dams) and the ICOLD (International Commission on Large Dams) workgroups. In addition, IAM benefits from reference manuals such as the International Infrastructure Management Manual (5th edition-2015) (International Infrastructure Management Manual, 2015) and standard ISO 55000 (ISO TC 251, 2014) that advises integrated management between technical and financial departments within organisations and coordinated governance between territories in interaction. Its international scope reveals differences in implementation between different countries although it encourages mutual learning.

Generally, each infrastructure is therefore currently managed independently, without taking into account the physical interdependences that it may have with other infrastructure. At present, the modelling of interdependences is mainly aimed at preventing catastrophic failures and minimizing risks of future ones (Lu et al., 2019). The authors think it is necessary to better characterize and quantitatively assess the effects of interdependence between infrastructure, in order to optimize maintenance, renovation and upgrading (Proposal 8). This knowledge will improve the planning of works and actions and determine critical areas, i.e., vulnerable and exposed to a hazard leading to a service dysfunction or failure, for instance, for levees, and water and drainage networks. The authors therefore encourage works that permit modelling the different interdependences between infrastructure since they form an essential and basic element for the joint management of infrastructure.

4.3 Aiding decision-making for integrated multi-infrastructure management

Standard ISO 55000 describes the general principles of IAM (ISO TC 251, 2014) but according to their size, financial resources and regulatory constraints, organisations may carry out their operations differently from each other (Cardoso et al., 2012). They operate in a regulatory framework that will necessarily undergo changes in the lifetime of the structures given their expected length of service/lifetime (more than a hundred years for water pipes and levees for instance). Thus in France, the new competence GEMAPI (French acronym for Management of Aquatic Habitats and Flood Prevention) (Loi MAPTAM, 2014) and the NOTRe Law (Loi NOTRe, 2015) have recently led to setting up new organisations or modifying existing ones, implying the management of a diverse range of hydraulic infrastructure (flood protection, water and drainage, rainwater management) (Section 5).

Most usually, WIAM is carried out individually by several organisations with different functions or statuses (public, private). Few works focus on the management of infrastructure in interaction and most are recent in the scientific literature (Abu Samra et al., 2018; Inanloo et al., 2016; Marzouk & Osama, 2017; Pericault et al., 2018; Tscheikner-Gratl et al., 2019; Tscheikner-Gratl et al., 2016). This silo-type management leads to a lack of coordination between the services managing the different systems and infrastructure. For instance, the maintenance of sustainable drainage systems – for which drainage, green spaces and waste collection are concerned – can be the responsibility of different services (Belmeziti et al., 2015; Cossais et al., 2018). Approaches aimed at integration have been proposed by local authorities on a more operational level (NRC-CNRC, 2003; Shaw et al., 2015) for the management of water, drainage and road networks in particular. Operations carried out on an infrastructure can trigger actions or have an impact on another infrastructure (Tscheikner-Gratl et al., 2016; van Riel et al., 2015). For instance, the replacement of the piping of a drainage network can be decided following inspections by camera or the age of the pipes, also according to the planning of roadworks (Parlement Wallon, 2009). Likewise for drinking water for which WIAM relies more on the occurrence of failures and detecting leaks, there is considerable interference from roadworks programs which seem to take the direction of greater cooperation due to the development of decision-aid tools (Large et al., 2015).

Although the coordinated management of infrastructure is desirable, it is faced with two barriers: (i) the privilege given *de facto* to the short-term operational programming of asset renovation works (Large et al., 2015; Tscheikner-Gratl et al., 2019) rather than to long-term strategic planning (Bhamidipati, 2015; Parlikad & Jafari, 2016), and (ii) the assessment of performance carried out differently according to the infrastructure (Chae, 2015). This does not facilitate the allocation of budgets to maintain the balanced performance of all the infrastructure. However, trends are emerging regarding, for instance, the optimisation of costs for roads and bridges, with the aim of ensuring driving comfort, structural integrity and safety (Z. Chen et al., 2019) or representation that takes into account the interactions between drainage, electricity and road networks (Bhamidipati et al., 2016). Certain water and drainage utilities now have tools that allow them to program their renewal and coordinate it with that of roadworks. Grouping organisations of a ‘sufficient’ size will also allow smaller utilities to achieve the same result (Section 5).

Thus, the authors want to bring to the forefront a direction of research, which they think, is pertinent because it focuses on the challenge of the knowhow and coordination of the actors involved in increasingly complex systems. The aim is to develop new decision aid tools for integrated management, i.e., performed jointly between infrastructure and between the stakeholders involved in WIAM (Proposal 9). This requires interoperable tools shared between the different actors, allowing modelling, editing and archiving data and above all, in the framework that interests us, combinations and comparisons of data and the prediction of behaviours for infrastructure in physical interaction and the analysis of common vulnerable territorial areas. Here, multicriteria decision-aid tools can be of great interest as they allow combining data of different formats and units to help decision-makers in WIAM (Le Gauffre et al., 2004; Tscheikner-Gratl et al., 2017). The authors consider that optimisation and predictive analysis methods are two other types of approach to explore. Works in this direction have recently been published (L. Chen & Bai, 2019; Parlikad & Jafari, 2016; Taillandier et al., 2017). These decision aid tools can be coupled with information systems (IS) for which the authors propose paths of research in section 6. Information systems refer to the interaction between persons, software, corporate processes, data and hardware technologies for processing and exchanging information (Haider & Rasid, 2002; Volker et al., 2013).

This proposal entails putting forward new modes of governance that favour this integrated management: managers must structure and coordinate their approaches to ensure the sustainable, pertinent and efficient management of their system(s) (Curt et al., 2018; Halfawy et al., 2006; Werey et al., 2018). The aim is to define the conditions of coordinated practices in terms of governance and decision-making, instead of decisions taken individually, and to adapt budgets and consider users. These works should lead to implementing strategies for improved management. Regarding these two paths, the transaction costs (costs of discussions/negotiations between the different actors, for instance) must be studied in order to ensure more efficient management. This point is developed in the following section.

5. Governance, organisations and territories

5.1 Institutional and regulatory context

In certain countries, the evolution of the institutional and regulatory framework for the different competences (drinking water, drainage, rainwater, flood protection) and the diversity of management modes question the governance and organisation of utilities. This is still done for the most part in silos, whether in the internal organisation of the same infrastructure or in multi-infrastructure relations. The dissociation that sometimes exists between the contracting owner and the operator must also be taken into account and formalised. Coordination between urban planning, development, consultancy, project management assistance, government services and the integration of users is undergoing change and varies according to the urban and landscape operations. Urban renovation can be a source of integration between the different water infrastructure and the habitat, in particular in ‘eco-districts’ or regarding the regulations.

Governance is defined as ‘a process of coordination of actors, social groups and institutions in order to achieve objectives defined and discussed collectively’ (Le Galès, 1995). It can be studied at different scales: local, meso (e.g., departmental level (Barbier et al., 2015)), hydrographic basin via the 6 French water agencies or the 26 *Waterschappen* in the Netherlands (Reimink, 2015), or national through the Ministries of the Environment. The analysis of the local scale makes it possible to clarify the decisions made and their application at the utility scale; the meso scale is pertinent for building coordination and regulation processes between the different stakeholders; the national scale permits understanding the inclusion on the legislative agenda of infrastructure assets and multi-infrastructure management.

At the European level, inter-local authority governance has developed differently and has sometimes been imposed for drinking water and drainage: e.g., the Galli law of 1994 in Italy that positions water and drainage services on the inter-local authority scale in the *ATO (ambiti territoriali ottimali*) (Lippi et al., 2008); the German institutional reform of the *Kreize* carried out in two steps, the former West then the former East (Wollmann, 1997) where competences for water are often still municipal, or on a ‘water management’ territory or hydro-territories in a *Bund*; institutional reform in Portugal (Amaral et al., 2017) which has led to the establishment of fifteen different inter-local authority groups for drinking water and drainage.

In France, competences for drinking water and drainage have changed from the municipal level to the inter-local authority level with the Public Establishment for Intercommunal Co-operation (PEIC – City, inter-local authority, inter-urban authority, group of municipalities) with their own taxation, oriented more on areas of population and labour catchment areas (Loi NOTRe, 2015). This reform has nonetheless met with resistance from large inter-local authority federations responsible for drinking water and drainage, which in particular vaunt the pertinence of their hydraulic knowhow over that of population and labour catchment areas (Groupe NOTReau et al., 2019). For flood protection, which concerns in particular levees and their management, setting up the Management of Aquatic Habitats and Flood Prevention (in French *GEMAPI)* consists in taking responsibility for infrastructure and their maintenance by the inter-local authorities (Vigier et al., 2019). Here again, this responsibility belonged to local authority *syndicates* covering river watersheds, sometimes astride the territory of the PEIC, and which attempt to hold on to their prerogatives. Sharing competences is more difficult in large conurbations such as cities and remains a process in progress in many rural areas: competences are therefore grouped in PEIC with their own taxation, or driven by different structures with sometimes overlapping perimeters.

However, often, the links between the management of the small and large water cycles, which distinguishes the competences of drinking water supply and drainage from rainwater management, have not yet been stabilised or integrated. Protection against floods and runoff are other points that have not been consolidated and require construction in view to ensuring multi-infrastructure asset management. This is especially the case since the structures of these regions in which water is present are sometimes different from those of inter-local authority structures.

Regarding IAM, the analysis of organisations/governance/territories shows that institutional or voluntary reforms sometimes jeopardise knowhow at a pertinent scale regarding the direction of water flow; however, they also provide at present and in the future innovative solutions such as new institutional 'water utility' structures, covering a wider scope with greater efficiency (Groupe NOTReau et al., 2019) or more integrated (drinking water and drainage), and will require the reorganisation of knowhow. To go towards a more integrated vision of water in the city, strengthening the links between the water management and urban planning services of local municipal authorities would make it possible to design urban projects (urban renovation and upgrading, building eco-districts, etc.) that take into account the challenges of asset management linked at minimum to infrastructure and the built habitat.

Two orientations are presented in this section: the coordinated governance of several infrastructure involving several actors (users, decision-makers, etc.), possibly several territories, and organisation in transversal management. These orientations are defined in four proposals for research, as detailed in **Figure 6**.

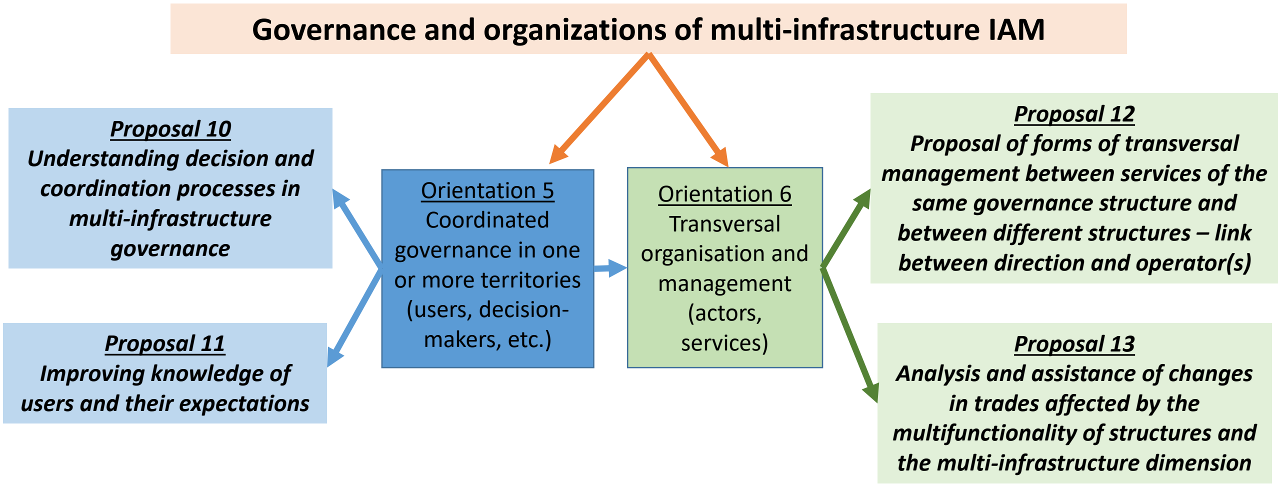

Figure 6. Research orientations and proposals in terms of governance, organisation, management tools.

Table 3 is the result of step S2 concerning the "Governance and organizations of multi-infrastructure IAM": the preliminary research proposals, identified based on the authors' previous work and experience, are cited by various authors. In that sense, the authors considered that the research proposals were relevant. For the whole set of proposals, at least one reference is available. The following sections provide the context and content of the proposals associated with the theme "Governance and organizations of multi-infrastructure IAM".

Research theme	Orientation	Proposal	References
Governance and organizations of multi-infrastructure IAM	Coordinated governance in one or more territories (users, decision-makers, etc.)	Understanding decision and coordination processes in multi-infrastructure governance	(Daulat et al., 2022) (Tscheikner-Gratl et al., 2019)
		Improving knowledge of users and their expectations	(Tscheikner-Gratl et al., 2019)
	Transversal organisation and management (actors, services)	Proposal of forms of transversal management between services of the same governance structure and between different structures – link between direction and operator(s)	(Kang, 2019) (Michalec et al., 2022) (Ugarelli & Saegrov, 2022)
		Analysis and assistance of changes in trades affected by the multifunctionality of structures and the multi-infrastructure dimension	(Daulat et al., 2022)

Table 3. Validation, based on the literature, of the relevance of the research proposals related to the theme "Governance and organizations of multi-infrastructure IAM"

5.2 For an integrative approach: understanding the decision-making and coordination processes in multi-infrastructure governance

Multi-infrastructure IAM necessarily involves an expanded system of governance, given its inter-sectoral dimension (Monstadt, 2009). This system mobilises a wide range of different stakeholders: local officials and managers of services as representatives of the local authorities, public utilities and operators, domestics and non-domestics users of the services and infrastructure, deconcentrated state services as representatives of the national regulator. The perimeter of coordination results – in part – from the territorial scale (municipality or groups of municipalities, watershed, etc.) and socio-technical (overlapping of infrastructure, interconnections, interdependences, etc.) and environmental challenges concerned by multi-infrastructure management (Monstadt & Schmidt, 2019; Smith et al., 2007) . According to the situation and the different actors, this scope evolves from the perimeter of infrastructure previously managed in silo, to a larger and more integrative scale (e.g., watershed).

Many concepts and approaches have been proposed over the last fifty years to grasp the different modes of governance and their changes, from a perspective as much local as multi-level. A recent review (Poupeau, 2017) shed light on the complexity of this field of research, with respect to the diversity of dimensions inherent to governance (political systems; institutions and organisations; political economies; modes of regulation; resources of power and leadership; etc.). Whatever the case, the authors esteem that three additional inputs are of interest for understanding the decision and coordination processes involved in the governance of infrastructure assets: the social and political construction of the (multi-)infrastructural management problem; trajectories of formulation, implementation and reorganization of the public policies pertaining to WIAM; the influence of the local context on WIAM. These inputs therefore reveal the socio-political dimension involved at different scales (spatial and temporal) in the technical management of infrastructure (Proposal 10).

Firstly, the aim is to understand how infrastructural stakes are built as 'public problems' and converted into public policies (Neveu, 2015), as much as on the scale of the utility or utilities as on the national scale and beyond (e.g., European scale). This approach reveals the interplay between the actors, in particular the status of and the work done by the stakeholders (Gusfield, 1981), who endeavour with the public authorities to define and regulate the 'good practices' that will be employed to manage the infrastructure, and the good state of the assets (e.g., renewal of infrastructure over a constant period, encouraging a multi-infrastructure approach, etc.). In addition, this approach identifies the constitution of a 'network of actors' (Le Galès & Thatcher, 1995) and 'coalitions' (Sabatier & Weible, 2007), or 'management communities' (Mermet & Treyer, 2001), i.e. more or less formal groups that work to formulate a common 'framework of action' (Jobert & Muller, 1987) for the WIAM. For instance, in the case of France, during the 20^{th} century, coalitions composed of deconcentrated state services and water agencies, or departmental councils, intervened to guarantee public water services. These actors therefore promoted the generalisation of interconnections between services, the implementation of concrete policies to renew networks and the 'rationalisation' (i.e. reduction) of the number of resources used and competent utilities in order to favour economies of scale, invest in a water and infrastructure management approach, and further regulate the activity of service operators (Barbier & Roussary, 2016). However, other actors support more or less different positions. This is the case, for instance, of *Canalisateurs de France* and the French Professional Federation of Water Companies, which attempt to normalise the notion of service life for pipes to the detriment of that of 'keeping in operation' (Renaud et al., 2014), and which transfer to the public authorities the expense (political and economic) of the performance and cost of water services and networks in France (Canalisateurs de France, 2011; FP2E, 2017).

Secondly, the aim is to track the trajectories of changes occurring in asset management up to a multi-infrastructure approach, in order to identify the different stakes, levers and barriers linked to this management. These processes are partly influenced by 'dependence effects' linked to political, economic, technical and institutional decisions that frame in the more less long-term the margin of possibilities regarding water and infrastructure management (e.g., make infrastructure profitable, set up/merge *syndicats)* (Kay, 2005). These paths also appear marked by cycles of stability and then changes, revealing the evolution of reference frameworks (Muller, 2015). (Denis & Florentin, 2022) evoked an 'asset turning point' occurring during the 2000s-2010s, notably in the cities of the northern countries. This turning point was characterised by the growing attention given to infrastructure and by the progressive departitioning of drinking water management in relation to other services and infrastructure (e.g., roads). It has resulted, year after year, in the implementation of new forms of organisation and coordination, by the adoption of new technical and management cultures, and by the deployment of dedicated tools (Monstadt & Coutard, 2019). It is on this direction that can be analysed – in part – the regionalisation of water policy in Italy initiated by the Galli law of 1994 (Lippi et al., 2008), the trend of 'decentralised' or 'alternative' techniques instead of huge infrastructure systems (the creation of independent mini-networks, the relocation of water and energy production sources, etc.) (Coutard et al., 2014) or the installation of single multi-service operators (Florentin, 2017).

Lastly, it is necessary to review the environment (socio-political, economic, technical, institutional, natural, etc.) in which the WIAM operates. This approach clarifies the relations of interdependence that form within and on the edges of the infrastructural systems, and which affect the actors and the non-human environment (e.g., natural resources and aquatic habitats, service infrastructure, management systems, etc.) (Caillaud et al., 2022; Pflieger & Rozenblat, 2010). This underlines the rationales of action and the effects of reciprocity that result from these interactions, until 'feedback loops' liable to act on the system are formed (Caillaud, 2022). This analysis encourages the actors to adopt a more inclusive approach to the management of their infrastructure, by anticipating as much as possible the reciprocal relations and effects between the infrastructure and their 'environment' (in the broad meaning). These interactions sometimes go beyond infrastructural and (inter)sectoral stakes (institutional competition between utilities, defence of working conditions, partisan political games, etc.) (Artioli et al., 2017; Brochet, 2019; Caillaud & Nougarol, 2021; Monstadt & Coutard, 2019).

5.3 Towards better knowledge of users and their expectations

The possible gap that can exist between the expectations of users in terms of service and what the supplier thinks these expectations are (Han et al., 2015) justifies Proposal 11. It proposes moving towards better knowledge of users, whether they are subscribers of the service, residents, the surrounding population or, more broadly, citizens. In the WIAM, this information can take on three dimensions.

The first, more specific to drinking water infrastructure, deals with the estimation of residential demand. It entails, by conducting empirical work, linking the quantity of water consumed to the price, and the socioeconomic characteristics of the household, in order to predict consumption (e.g., (Schleich & Hillenbrand, 2009; Worthington & Hoffman, 2008)). However, these studies, although they provide important information for the water utility, do not as yet really establish the direct link between users' expectations and WIAM. A path of research, made possible by the development of connected meters could be, for instance, to integrate more technical, environmental dimensions or collective dimensions in the functions aimed at estimating the consumption of households and identifying its determinants.

The second dimension pertains to users' preferences, and more specifically to the willingness to pay (WTP) (Coutard & Pflieger, 2002). This entails establishing a link between what users want, i.e., their preferences, and what they are prepared to pay (for instance, through their water bill, or through their local taxes) to obtain it. More broadly, the estimation of WTP permits estimating the benefits that users obtain from their drinking water or drainage service and thus the value they assign to it. These results can be coupled with an analysis of costs as considered in section 5.4, to carry out a CBA (e.g., Malm et al. (2015)), or directly integrated in MCDA (Multi-criteria Decision Analysis) (e.g., Sjöstrand et al. (2018)) thereby providing a valuable decision-aid. Paths of research regarding taking this information into account, whether in CBA or in MCDA, increase the information available to the manager (including on the evolution of user's expectations, etc.) year by year and the branching of trajectories that this increase in information brings about.

The estimation of WTP can also concern the performance of the drinking water service (e.g., Hensher et al. (2005)) and the drainage service (e.g., Munusami et al. (2014), Ndunda and Mungatana (2013)), as well as issues of securing the service against the effects of climate change on the resource (e.g., Appiah et al. (2019), Cooper et al. (2019)). Nevertheless, with the exception of the latter issue, works on the subject are relatively few or old, pointing to the need to update research on these issues. The aim is especially to situate these questions in the long-term when they give an image of a given moment barely compatible with the challenges of WIAM: taking into account the challenges of climate change, evolutions of society, modifications of users' behaviour and preferences over time, drivers of change, technological changes, etc. and the uncertainties inherent to these phenomena.

Certain studies have begun to focus on new themes such as user WTP to avoid drainage service dysfunctions (e.g., Rozan et al. (2017)) or to obtain better resilience of drinking water networks (e.g., Brozović et al. (2007), Rulleau et al. (2020)). In the context of climate change and the rarefaction of resources, others study the readiness of households to recycle wastewater and rainwater for domestic use (e.g., Hurlimann and McKay (2007)) which will undoubtedly have an effect on tap water consumption and thus, in some countries, capacities to fund services.

Lastly, a third dimension concerns the fact that estimations of WTP are based on household surveys that make use of specific economic assessment methods (Johnston et al., 2017). These surveys permit going beyond the study of respondents' preferences to know better their uses, knowledge, perceptions, motivations, etc. Thus, they make it possible to understand better who the users are. As identified by, among others, Barbier (2013), Busca et al. (2019), and contrary to what a purely technical analysis of the service might lead one to think, the user is plural and heterogeneous, and a host of factors may influence their decisions (see, for example, Johnstone and Serret (2011) and (Bontemps & Nauges, 2016) on the trade-offs between the consumption of bottled water and that of tap water). Surveys allow understanding more psychological dimensions or those linked to emotions that can then, using recent econometric developments, be introduced in WTP models to analyse with greater precision the variables influencing the preferences of respondents (for instance, hybrid models, Ben-Akiva et al. (2002)). Research works on these questions are currently being developed (Mariel & Meyerhoff, 2016). Finally, questionnaires can be a vector for disseminating information to users, and which can then, for instance, make them more aware of dysfunctions and turn them into whistle-blowers (Heitz & Ward-Perkins, 2015). Whatever the case, the aim is to better know the users in order to better integrate their expectations in public decisions, as their involvement in public policy and their readiness to accept it are key factors for its success (Nilsson et al., 2016).

5.4 Evolution of services and organisations

Coordinated governance at the level of structures is essential for integrated multi-infrastructure WIAM. It requires setting up transversal management at the level of technical and financial services, considered as organisations. Looking at the theory of organisations: an organisation is a group of people who, together, produce a result that none of them could have obtained separately(Matejko, 1983). Mintzberg (1989) defined the management of the organisation as a 'collective action' in the pursuit of achieving a common mission'. He introduced systemic analysis to describe the operation of a system, privileging the global analysis of exchanges between its parts rather than the analysis of each one of them.

The establishment of operating rules and internal decision circuits between services is an important aspect of asset management and risk management, but taking users into account is also becoming more important (Rozan et al., 2017; Rulleau, 2020). Research works could also study the influence of management modes on IAM, particularly regarding exchanges of information (asymmetry) within the organisational triptych: organising authority or contracting owner (elected representative and internal and external professional experts), operator (administration or delegated public or private management) and individual users (ASTEE-AITF-AFB-FNCCR, 2017). **Figure 7** shows the link between the notion of organisation that 'implements' (services, operators) and the governance 'that decides' (elected representatives who compose the organising authority (OA) aided by the directive part of the technical and financial services). It should be noted that the user/individual is in relation with two other groups of actors. The importance of taking users into account was presented in the previous Section.

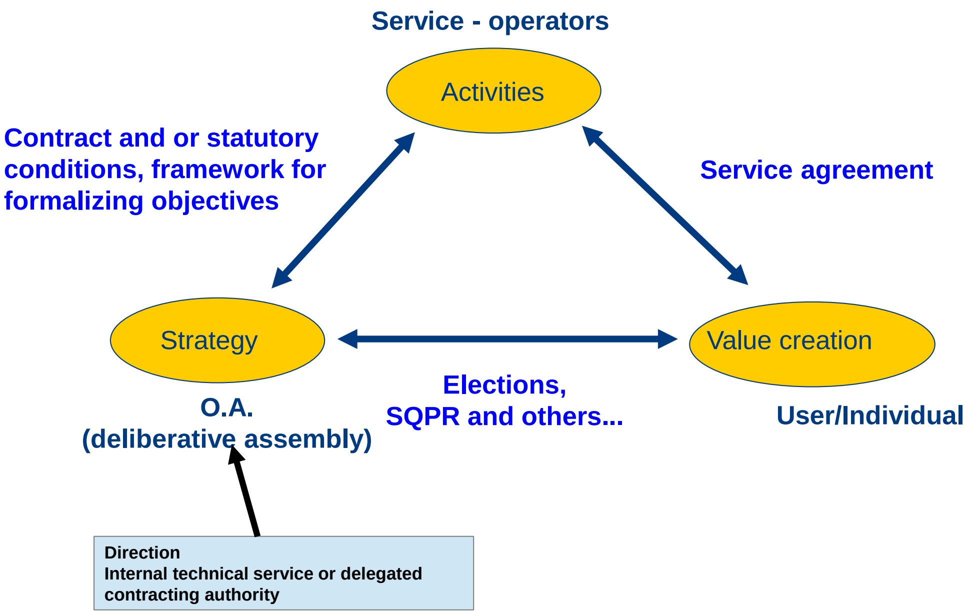

Figure 7. The links between the organising authority (OA), operator and user (ASTEE-AITF-AFB-FNCCR, 2017). SQPR: Quality/price ratio of the service.

This figure is valid in particular for drinking water and drainage utilities. Indeed, the interactions between the actors, the general management and the direction by the organising authority, the transfer of data and information can be influenced by the internal organisation of the services and the mode of management (ASTEE-AITF-AFB-FNCCR, 2017). Thus, IAM requires data from the service/contracting owner/main contractor (*e.g.,* length of levees or pipes, age, materials, investment costs, etc.); data on interventions and preventive and/or corrective maintenance (repairs, unclogging, leak detection campaigns for networks, monitoring data for dams and levees, etc.); data on investment and operating costs, etc. (this aspect will be developed in Section 6).

Relations between operators and the main contractor have evolved towards greater transparency, sometimes facilitated by a regulator (*e.g.,* Portugal, United Kingdom, etc.) or changes in the regulations (e.g., Sapin Law (1993) and Barnier Law (1994) in France on the transparency of service management). These relations lead to contracts involving more communication and reporting from the operator and, involvement and monitoring by the contracting owner. Sometimes, common specifications for the operator administrating the service and/or the private company or companies assigned to carry out the services are implemented. This is the case, for example in France for *Nantes Métropole, Métropole du Grand Lyon, Métropole de Montpellier*, etc., favoured by the Sapin Law and the Barnier Law.

Organizational evolutions impelled by multi-infrastructure asset management require research that involves local authorities: it is necessary to analyse existing organisations and those undergoing change to propose cross-disciplinarity between services to move towards integrated management. For example, this entails setting up assistance to the contracting owner for rainwater management or *GEMAPI*, developing a common collaborative tool or defining a new reference framework for trades covering the management of different infrastructure (*e.g.,* common urban project service, etc.) (Proposal 12).

Apart from decision-aid tools for long-term planning and the prioritisation of infrastructure to be upgraded (see Sections 3 and 6), management tools (Moisdon, 2005) are pertinent resources for assisting changes internally in the organisation of utilities and improving coordination and efficiency. Mention can be made of analytical accounting and the analysis of individual costs, dashboards, etc. Thus, the analysis of costs (direct and indirect expenses) provides information on financial resources and other resources in terms of the machines and human resources to be employed for maintenance, for instance. It is noteworthy that decision aids (MCDA, CBA, etc.) are also considered as management tools. The authors think that in this area, it is still necessary to implement cross-disciplinary multi-infrastructure management tools. This evolution could rely on information systems still used in silo mode, such as CAMM (Computer Assisted Maintenance Management) or the development of ERP (Enterprise Resource Planning software) dedicated to connect accounting and technical data still little used in public water utilities in France, as well as the construction of tools customised according to the size of the structure.

The organizational dimension of services is undergoing radical change, often driven by elected representatives and the services themselves, by placing to the fore the role of the organising authority (contracting owner) alongside that of the operator in terms of organisation. The integration and pooling of skills, sometimes making use of versatility, and services with integrated territorial management that bring together skills and resources (human and financial), are also undergoing change. For example, in France, changes regarding skills is in progress regarding IAM of sustainable green drainage systems (Cossais et al., 2018). This evolution is either linked to the deployment of decision aids, or to the multifunctional nature of these infrastructure managed with an array of skills for maintenance or design between services responsible for drainage, green spaces, roads and waste collection (Werey et al., 2019) (Proposal 13). This favours the implementation of management tools such as cost analysis. Still in France, a large number of local authorities are rethinking their organisation to expand the directive function of organising authority with a multi-skill vision of water, drainage, *GEMAPI*, *GEPU* (Urban Rainwater Management) and cross-disciplinary organisation with the services of other departments of a local authority. The transaction costs (but also the benefits) between the different services (drinking water, drainage, roads, for example) could be taken into account in this reorganisation.

6. The digital representation of the infrastructural socio-technological system and its importance

6.1 Data and information systems

Tactical and strategic decision-making and the implementation of efficient strategies greatly depends on the data on the infrastructure and their management (Amaral et al., 2017; Curt et al., 2018). These data fuel different types of criteria (**Figure 8**):

- technical, i.e., relating to the state and operation of the structures and installations that compose the assets: the diameter of a pipe, the material composing the structure, etc.;
- environmental regarding the natural habitat and the property and people exposed to risks due to the presence of the asset. This entails the vulnerability of the environment of the structure (pollution; number of inhabitants potentially affected by a dam breach; the location of these inhabitants; rail networks impacted by a pipe break; the impact of the rupture of a drainpipe or water mains on other buried networks, etc.). This area also includes natural hazards taken into account to calculate or diagnose structures;
- socio-economic relating to the satisfaction of users' needs and expectations (water quality, service continuity, accessibility of roads, recording of complaints, information resulting from satisfaction surveys, analyses of surveys of people affected by failures (Section 5);
- economic, financial and accounting pertaining to investment an operating costs, and to possible direct and indirect costs of impacts on the natural and human habitat (Rozan et al., 2017; Werey et al., 2019).

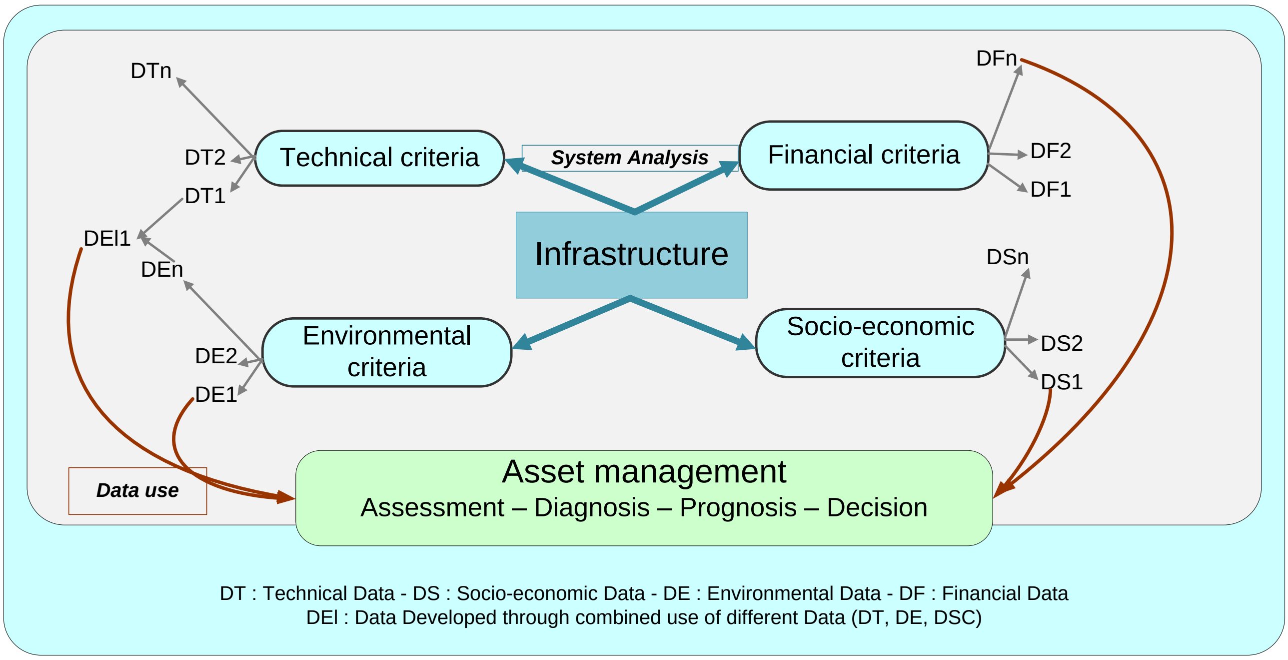

Figure 8. Data and criteria fuelling asset management.

These data must be collected then organised, processed, stored, shared and exchanged between the stakeholders (Brous et al., 2016; Esmaili & El-Diraby, 2017; Farghaly et al., 2018; Saptari et al., 2019). On the spatial level, the data can correspond to very different scales, from the material used to the asset, with in between the structure and the section. Lastly, different actors may intervene in the collection, formatting, qualification and storage of the data.

The process from collecting to sharing the data is performed through time and concerns the entire lifecycle of the infrastructure. Data can be demanded for different time steps: in the short-term during routine maintenance operations on structures, in the medium term for pluri-annual planning (prediction of failures and works, estimations of budget envelopes), and for long-term planning (trends of demand, performance indicators, etc.). The regulations impose several obligations at given frequencies (Amaral et al., 2017). For example, in France the following must be carried out: a hazard study for hydraulic structures with a time step calculated according to the class of the structure (e.g., 10 years for levees and hydraulic systems of Class A, i.e., protecting more than 30,000 people), the detailed description of transport and drinking water distribution structures with annual updating. The time series associated with a structure can be very large: some dam sounding data are collected daily (reservoir water level) or weekly (piezometry), generating long time series through the lifetime of the structure. On another level, it is in the nature of public accounting to present expenses and receipts by category and for the period assigned to the budgetary exercise. In the absence of analytical accounting, it is often difficult to reconstitute expenses on operations (repairs of breakdowns, leak detection, levee maintenance, etc.) or expenses with different time steps (major investments running over several years).

However, drinking water and drainage utilities are increasingly subject to global and punctual approaches regarding the analysis of operating costs (or analytical accounting) in internal development or relating to research (ASTEE-AITF-AFB-FNCCR, 2017; Chéritat & Werey, 2020; Werey et al., 2019). The association of technical and financial data, often resulting from different budgets, requires strong organisational will and the implementation of in-house information management tools for supervision and monitoring ERP software dedicated to increasing volumes of accounting and technical data; CAMM, etc.).

ISs are utilised to perform these different tasks from the organization of data to sharing them between the actors involved. Their purpose is to provide an integrated view of information on lifecycles in order to ensure the efficient operation of infrastructure and make informed choices on their management. Thus, the dimension of information holds a central position in building WIAM strategies: all the descriptive data of the asset and its history, as well as the algorithms and models associated with it, form a genuine 'information capital' whose value deserves to be taken into consideration (Curt et al., 2018; Werey et al., 2018).

Works have been performed on this dimension of information, especially over the last ten years. Five research proposals appear to be particularly interesting to us to explore in the coming years: two of them are linked to data and the three others to information systems (**Figure 9**).

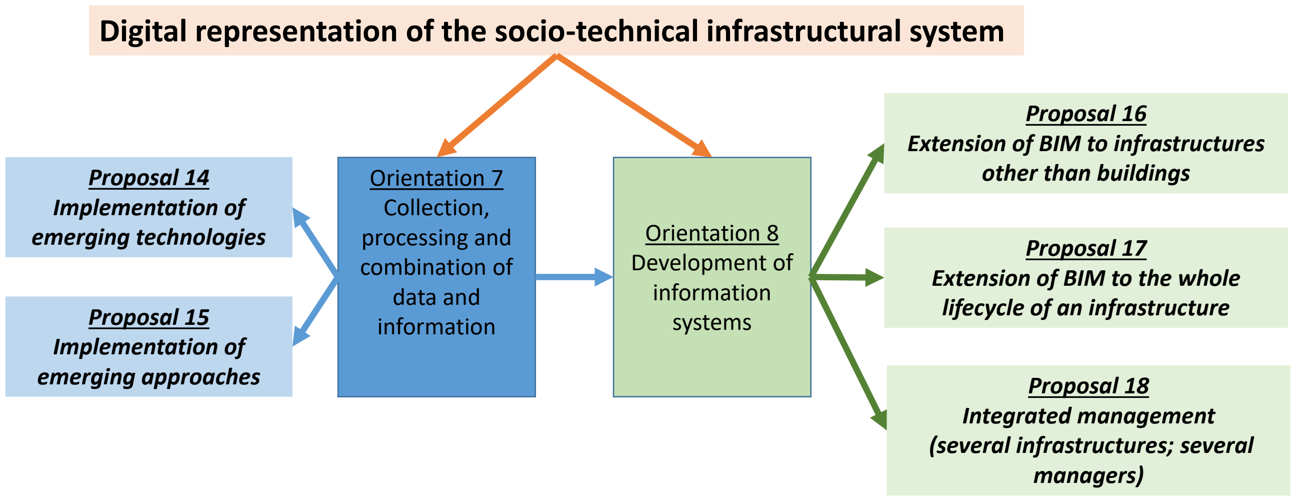

Figure 9. Research orientations and proposals relating to the digital representation of infrastructural sociotechnical systems (BIM: Building Information Management).

Table 4 is the result of step S2 concerning the "Digital representation of the socio-technical infrastructural system": the preliminary research proposals, identified based on the authors' previous work and experience, are cited by various authors. In that sense, the authors considered that the research proposals were relevant. For the whole set of proposals, several references are available. The following sections provide the context and content of the proposals associated with the theme "Digital representation of the socio-technical infrastructural system".

Research theme	Orientation	Proposal	References
Digital representation of the socio-technical infrastructural system	Collection, processing and combination of data and information	Implementation of emerging technologies	(Brous et al., 2019) (Langeveld et al., 2022) (McDonald, 2019) (Sadeghikhah et al., 2022) (Suprun et al., 2022) (Tscheikner-Gratl et al., 2019) (Wang & Yin, 2022)
		Implementation of emerging approaches	(Brous et al., 2019) (Kang, 2019) (Nkwunonwo et al., 2023) (Pathirana et al., 2018) (Tscheikner-Gratl et al., 2019) (Wang & Yin, 2022)
	Development of information systems	Extension of BIM to infrastructures other than buildings	(Suprun et al., 2022) (Szeligova et al., 2023)
		Extension of BIM to the whole lifecycle of an infrastructure	(Atencio et al., 2022) (Suprun et al., 2022)
		Integrated management (several infrastructures; several managers)	(Beck et al., 2021) (Harris-Lovett et al., 2019)

Table 4. Validation, based on the literature, of the relevance of the research proposals related to the theme "Digital representation of the socio-technical infrastructural system"

6.2 Directions of research concerning data

It is important to recall that IS (Information System) data must be available, reliable, relevant for each of the actors concerned, and updated throughout the lifecycle of the infrastructure, especially the phases of operation, maintenance and rehabilitation (Cooksey et al., 2011; Curt et al., 2018; Esmaili & El-Diraby, 2017; Gersonius et al., 2019). The efficiency of IAM strongly depends on the quality and completeness of the data on which it is based and standards play a role in improving the global performance of an infrastructure (Parlikad & Jafari, 2016). Tools such as data dictionaries (Baudrit et al., 2018), the INSPIRE (Infrastructure for spatial Information in Europe) Directive

(European Parliament, 2007) and the French COVADIS standards (*Commission de validation des données pour l'information spatialisée*) make it possible to give a pertinent structure to the data, better traceability and better access to the data, better sharing between organizations or services, etc. One direction of research concerns the use of emerging technologies (LIDAR – Laser Imaging, Detecting And Ranging –, smartphones, integrated sensors, Internet of Objects) (Brous et al., 2016; Parlikad & Jafari, 2016) leading to the concept of 'smart' or 'communicating' infrastructure (Proposition 14). However, several points must be considered.

Firstly, although these technologies provide the advantage of reducing the number of physical inspections due to the automation of data in real-time and thus continue collecting data in specific situations (remote structures, difficult meteorological conditions), the security of the data must be ensured through time. The latter would benefit from being archived in an open format (e.g., ASCII – American Standard Code for Information Interchange – rather than binary), making their structure easily understandable and their utilisation and diffusion applicable at lower cost (not bridled by commercial licenses). This is particularly the case since video-monitoring leads, by recoil, to a reduction in the number of personnel dedicated to this task, and in the long term to a loss of knowledge linked to inspections, and on the other hand, the necessary reorganisation of utilities (Section 5). Account should also be taken of the intrusive nature of certain of the systems installed in residents' homes and/or the scepticism with which consumers have for them, and who hesitate to use them to their full potential (e.g., smart water meters (Sønderlund et al., 2014; Strengers, 2011)). Indeed, these new technologies also give rise to a large number of debates (e.g., the harmful effect of electromagnetic waves on biodiversity and human health, the risk of cyberattacks, social fears of generalised video-monitoring, etc.) likely to slow down their deployment.

Secondly, these data have potentially different characteristics and formats, are dynamic and contain imperfections (imprecision, uncertainties, incompleteness and conflicts between data) (Curt & Gervais, 2014). In order to exploit them, collection methods and tools, processing and possibly the combination of heterogeneous, dynamic and imperfect data must therefore be proposed. Another point to consider is the massive quantity of data that can be recovered, calling for the utilisation of methods based on artificial intelligence to extract pertinent information from this mass of data. Works have been carried out in this direction (Arsene et al., 2022; Brous et al., 2016; Wu et al., 2015) and should be extended. Another current challenge relating to data is the development of emerging approaches that take into account data produced by the users (e.g., (Villesseche et al., 2017); https://adoptadrain.sfwater.org/) (Proposal 15). Finally, it should be noted that access to budgetary and financial data is sometimes more difficult than for technical data. Cost analysis and analytical accounting type approaches calling on technical and financial data facilitate their exchange.

6.3 Directions of research concerning information systems

These data will fuel ISs of which BIM (Building Information Management) is an example. It is considered to be an efficient tool for storing and managing data during the lifecycle, initially, of buildings: it (i) provides a common environment for data for different stakeholders and thus their reutilisation, (ii) permits visualisation, especially in 3D, (iii) improves collaborations between disciplines and parties, (iv) guarantees the availability and reliability of information, (v) forms a reliable basis for decisions during the lifecycle of an installation, and (vi) permits the automation of repetitive tasks, advanced analyses and bringing together series of information (Bradley et al., 2016; Cavka et al., 2017; Farghaly et al., 2018; Kivits & Furneaux, 2013). Three paths of research appear pertinent to follow regarding information systems.

Firstly, it would be interesting to extend the utilisation of BIM to infrastructure other than buildings (Proposal 16). Several works have emerged in this direction in recent years. In particular, there is the issue of combination with GIS (Geographic Information System) (Abdelaty et al., 2018; Cooksey et al., 2011; Hijazi et al., 2018; Lee et al., 2018). Indeed, for long infrastructure and networks like levees, drinking water and drainage networks, systems coupling BIM and 3D GIS would definitely be pertinent: BIM is used to provide reference information on geometry and the characteristics of public installations and services whereas 3D GIS provides this system with information on topology, altitude and the surrounding environment. This permits integrating the data necessary for maintenance management, a common spatial reference for different infrastructure and a process for linking monitoring data, associated maintenance data and a model of visualisation. To ensure the interoperability of these two tools, new standards for data and methods for adapting existing standards have been introduced by several studies (Lee et al., 2018).

Secondly, current uses of this tool are mainly oriented to the design and construction of infrastructure and hardly concern their management, whereas BIM can make significant contributions to this task (Cavka et al., 2017). One challenge is to clarify the requirements for such a use, meaning identifying and formalising the information required and collecting the corresponding data when possible, accessing pertinent data rather than all the data, proposing a decision aid for maintenance, replacement, upgrading (Proposal 17). These tools must consider the whole lifecycle (from design to dismantling) of an infrastructure. Thus, the diagnostic of a hydraulic structure will require data on its design and construction, and those resulting from its monitoring by instruments.

Thirdly, the different types of data are stored and managed in isolated and often incompatible systems: existing systems are very fragmented, with isolated functionalities to satisfy the characteristics and specific requirements of different infrastructure systems (Bradley et al., 2016; Halfawy et al., 2006; Marzouk & Osama, 2017; Ng et al., 2018). This silo type situation is found in services of the same entity and especially between several entities managing different infrastructure (water network, drainage, roads, levees, etc.). Lastly, it reflects silo type management focused on infrastructure taken separately (Section 4). Tools such as ERP and CAMM, integrated but in silo, are also information systems that it will be necessary to adapt. This fragmentation has harmful effects on the consistency, integrity, exactitude and accessibility of data, affects communication and coordination between the different owners and operators of infrastructure systems, and leads to inefficient maintenance and planning relating to the renewal of structures (Haider & Rasid, 2002; Halfawy et al., 2006; Tafazzoli, 2017). The interoperability of different IAM systems is vital for managing infrastructure data and exchanges of information between different work processes (Haider & Rasid, 2002; Halfawy et al., 2006; Tafazzoli, 2017).

A pertinent change would be to define a common vocabulary and formats for data and procedures of depositing, exchanging and extracting pertinent data, and for interoperable platforms and information systems relating to the different infrastructure involved. The aim is to maximize the reutilisation and sharing of data, promoting collaboration between different management bodies and avoiding the duplication of data and their collection (Proposal 18). Thus, although the initial costs may be high, transaction costs could in this way be reduced. For example, a proposal using the principle of crowdsourcing has been made for depositing data and their use by several management entities (Ng et al., 2018). Such shared or interoperable information system could facilitate the integrated management of risks through the appropriate representation, consolidation, data sharing and traceability, spatial referencing, and data representation format. This obviously raises the issue of data confidentiality, and conditions for sharing must be subject to collaborative approaches between the different entities.

7. Conclusions

Based upon the authors' experience and the literature, this article constitutes a reflective analysis related to WIAM. It contributes to proposals for emerging research topics relating to the management of infrastructure assets linked to water, liable to be shared by the practitioners and researchers of the different disciplines mentioned in the different parts of the article, with the common aim of producing knowledge and to inform management decision-making. Four research themes were identified, then described as 8 orientations and 16 proposals. These results were built upon authors' experience and a literature analyses for the validation of the proposals and their description. None of these works cite all of the proposed research orientations: this contributes to make this work original. However, the authors do not claim that it is exhaustive.

Research in WIAM should rely on the following three major concepts:

- Firstly, the authors assert that the subject of research, WIAM, is above all an 'industrial' activity developed in a 'socio-technical system'; the adoption of a 'systemic' standpoint (Le

Moigne, 1994) is not aimed at simplifying the reality of the system (levee construction, drinking water supply, etc.), but rather at considering that technical objects and human actors are considered. Their interactions in time and space constitute a form of 'organised complexity' (Weaver, 1948);

- Secondly, it is necessary to make use of the notion of the 'service' (Jeantet, 2003) provided by the 'infrastructural system' to its users, since the purpose of WIAM is to ensure the best possible 'performance' (Serre et al., 2007; Talon et al., 2014) in return for a supportable cost to society; performance and cost are therefore notions relative to the actors of the system (managers (Chéritat & Werey, 2020), users (Rulleau, 2020)) and its governance and organisation, with a diversity of perceptions that participate in the complexity to represent;
- Thirdly, the notion of 'risk' intervenes, in its meaning of the hazard of failure of the infrastructure or service provided, in combination with the 'vulnerability' of the stakes involved (human, material and natural), including in its dimensions of perception and behaviour, potentially subject to the impacts of the failure.

Finally, the authors' proposals are not made within a rigid and definitive framework, but, on the contrary, are intended to evolve as a function of the progress made by research, societal interrogations and global changes.

To open reflection still further, the specific theme of green infrastructure, whether mixed or hybrid is broached. They are ambivalent in nature, managed or built (anthropisation), and belong to Nature-Based Solutions (action inspired by, relying on or copied from nature (European Commission, 2015)). They can also be sources of co-benefits (or disadvantages or overcosts) in particular environmental, social or economic (Alves et al., 2019; McVittie et al., 2018; O'Donnell et al., 2020). A recent evolution of urban development and the inclusion of the large water cycle has led to the development of infrastructure (e.g., artificial recharging of aquifers, sustainable drainage systems, floodplain expansion and riparian forests), which, in addition to their technical function, provide attractiveness and fulfil a societal function of well-being for the population, and protection for biodiversity and ecosystems, notably in the context of climate change (Cohen-Shacham et al., 2016). Regarding this, the following themes appear pertinent although they are practically neglected in the scientific and technical literature: the study of the life and performance of green infrastructure and nature-based solutions; the implementation of their management as assets (Langeveld et al., 2022); their interface with grey infrastructure in more complex systems. As with everything mentioned previously, research in this area will require interdisciplinarity.

Table of abbreviations

Acronym	Definition
AFB	French agency of Biodiversity
AITF	French Association of Territorial Engineers
ASCII	American Standard Code for Information Interchange
ASTEE	French Scientific and Technical Association for water and Environment
BIM	Building Information Management
CAMM	Computer Assisted Maintenance Management
CBA	Cost-Benefit Analysis
COVADIS	French acronym for Data validation commission for spatial information
ERP	Enterprise Resource Planning software
EuCOLD	European Commission on Large Dams
FNCCR	French association on public utilities in water and energy
FP2E	French Professional Federation of Water Companies
GEMAPI	French acronym for Management of Aquatic Habitats and Flood Prevention
GEPU	French acronym for Urban Rainwater Management
GIS	Geographic Information System
IAM	Infrastructure Asset Management
ICOLD	International Commission on Large Dams
INRAE	French National Research Institute for Agriculture, Food and Environment
INSPIRE	Infrastructure for spatial Information in Europe
IS	Information System
IWA	International Water Association
LCCA	Life Cycle Cost Analysis
LIDAR	Laser Imaging, Detecting And Ranging
NOTRe Law	Law for a new territorial organisation of the Republic (France)
NRC-CNRC	Canadian National research Council
MCDA	Multi-criteria Decision Analysis
ONEMA	French National Office for Water and Aquatic Environments
PEIC	Establishment for Intercommunal Co-operation
UICN	International Union for Nature Conservation
WIAM	Water Infrastructure Asset Management
WTP	Willingness to pay

Declaration of interest statement

The authors report there are no competing interests to declare

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