Asset management of water and sewer networks, and levees: recent approaches and current considerations

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ABSTRACT: Water and sewer networks and levees must be managed in a way that guarantees their performance over time. Maintaining their service in the long-term involves huge public health and safety, social, economic and environmental stakes. This calls for integrated asset management rules and strategies to mitigate the consequences of ageing and possible obsolescence integrating life cycle approaches. The aim of this article is to present the various approaches developed by Irstea with its partners over several years relating to these three types of infrastructure. It also proposes elements of comparison and synthesis between these approaches with respect to their objectives and implementation.

1 INTRODUCTION

Infrastructures are essential for maintaining the vital functions of a society, and the health, safety, security, and economic and social well-being of the community. Their inexorable ageing and deterioration lead to significant impacts that become ever more apparent as the demands of society for levels of service, risk management and sustainability increase. Infrastructure Asset Management (IAM) is essential for efficiently maintaining, operating and renewing infrastructures, and thus lowering risk and impacts. IAM allows infrastructures to deliver a certain level of service in a cost-effective manner in both the short and long-terms, with the service function depending on the infrastructure considered: supplying water, protecting against floods, collecting wastewater, transport and so forth. Utility managers need to structure their IAM approaches to ensure the sustainable and efficient management of their systems: environmental, economic, social and technical criteria must be considered.

This calls for integrated IAM rules and strategies to mitigate the consequences of ageing and possible obsolescence and which integrate life cycle approaches. IAM has advanced significantly since the beginning of the 1990s, with reference handbooks such as the (International Infrastructure Management Manual, 2015) and more recently ISO 55000 (ISO TC 251, 2014). The latter describes the general principles of IAM but organisations – according to their size, financial means and regulatory constraints – may proceed differently from each other (Cardoso et al., 2012); IAM is implemented by organisations that can manage one or several utilities.

The conceptualisation of water and sewer network AM started at the beginning of the 2000s. The FP5 European research projects CARE-W and CARE-S (Computer Aided Rehabilitation) for water pipes (Saegrov, 2005) and sewers (Saegrov, 2006), the works by (Alegre et al., 2012), the French National projects RERAU (Rehabilitation of Urban Sewer Networks) (Le Gauffre et al., 2005) and INDIGAU (Performance Indicators for asset management of urban sewerage networks (2007-2010)) played a major role in this process. Levees, and more generally flood defence systems, must be reliable when a hydrometeorological event (fluvial or torrential flood, sea storm) occurs. Unfortunately, many inundation events involving the failure of levees have occurred during the last two decades. This is notably due to long periods of time between loading events, leading to possible disregard for the necessary maintenance of flood defences, and sometimes even of their purpose. Consequently, the need for sound asset management for levees is now recognized internationally, and many countries have already transcribed it in their national regulations. At the international scale, the International Commission on Large Dams now incorporates a specific issue on levees (Tourment et al., 2017). Moreover, the new competences of GEMAPI

(Aquatic Environment Management and Flood Protection) and NOTRe Act (New Territorial Organization of the Republic) will lead to modifying the organisation for water infrastructures (flood protection, water and sewer networks, storm drainage) with consideration given to environmental issues.

The aim of this article is to present various approaches that Irstea has developed or has participated in developing in recent years relating to water and sewer networks and levees. It also proposes elements of comparison and synthesis.

2 LEVEE ASSET MANAGEMENT APPROACH

2.1 *Life cycle of levees*

Two different types of situations have to be distinguished during the life cycle of a flood defence system: in the absence of a threatening hydrometeorological event, or due to the occurrence of such an event. Whatever the case, in both situations, the purpose of levee IAM is to ensure that the area protected by the levee will not be flooded with respect to the intended protection level. Decisions are taken concerning:

- Necessary additional investigations / diagnosis,
- Maintenance (routine or major works),
- Modifications of the defence system,
- Emergency measures:
  - intensify observations,
  - appoint one or more expert engineers to better evaluate the situation and propose solution(s),
  - carry out levee reinforcement works,
  - inform the authorities in charge of civil safety of a possible inundation.

The life cycle of levees is described in section 2.3.3 of the International Levee Handbook (Sharp et al., 2013), which integrates the two situations (normal or event based). It considers performance objectives and indicators (Figure 1).

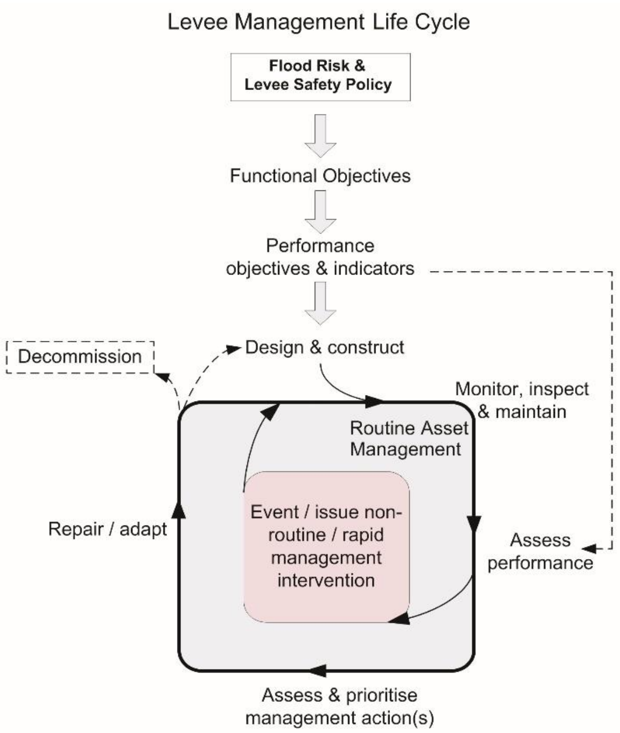

Figure 1. Life cycle of a levee or flood defence system (Sharp et al., 2013) – Chap 2.

2.2 *The cycle of inspections and assessments*

To ensure performance, optimize the maintenance of levee systems, and inform decision makers (Figure 2), it is necessary to perform regular inspections, assessments and risk analyses over their life cycle. Inspections are based on site visits and can be more or less detailed, with a frequency inversely proportional to their level of detail. Assessments rely on all available data (design, construction, inspections, monitoring, specific investigations) and conclude on the performance of the levee systems, both in hydraulic and structural terms. Risk analysis adds the analysis of the consequence of failure to the assessment results, and concludes on the residual flood risk, taking into account the natural risk and the change induced by the defence system. An O&M manual should describe these operations. Inspections, assessments and risk analyses are performed either at programmed time steps during the "normal" situation, or after the occurrence of an event with specific inspections (pre-event, during an event, after an event). In addition to previously available data, specific investigations are also necessary when it is not possible to reach a conclusion with enough certainty.

2.3 *Tools for informing decision making*

The evaluation of levee system performance can be difficult, given the old age and past history of these structures, their heterogeneity and the frequent lack of knowledge on their internal structure. Large quantities of data of different natures (topography, hydrology, hydraulics, geotechnics, morphodynamics, etc.) and from different sources are necessary. Assessments and risk analyses are based on the potential failure modes of levees and levee systems, which are quite complex to analyse; consequently, modelling the performance of the assets regarding each of these failure modes is difficult, and no simple model exists. In order to help assessment, risk analysis and then decision making on levee systems, Irstea has developed several tools for managers and consultants:

- SIRS Digues (Spatial Information-Reference System): data have a value, both in terms of their use for assessments, but also in terms of their cost of acquisition. SIRS Digues (Moins and Maurel, 2006, Tourment et al., 2012) allows storing all levee systems data in a GIS based software application, also including dating of the data;

- Functional analysis and failure mode analysis: in order to identify potential hydraulic failure scenarios and levee structural failure scenarios, Irstea has developed a method based on functional and dysfunctional (failure modes) analysis (Tourment et al., 2015). Later, the scenarios identified, some of which may be complex, can be subjected to probabilistic analysis;

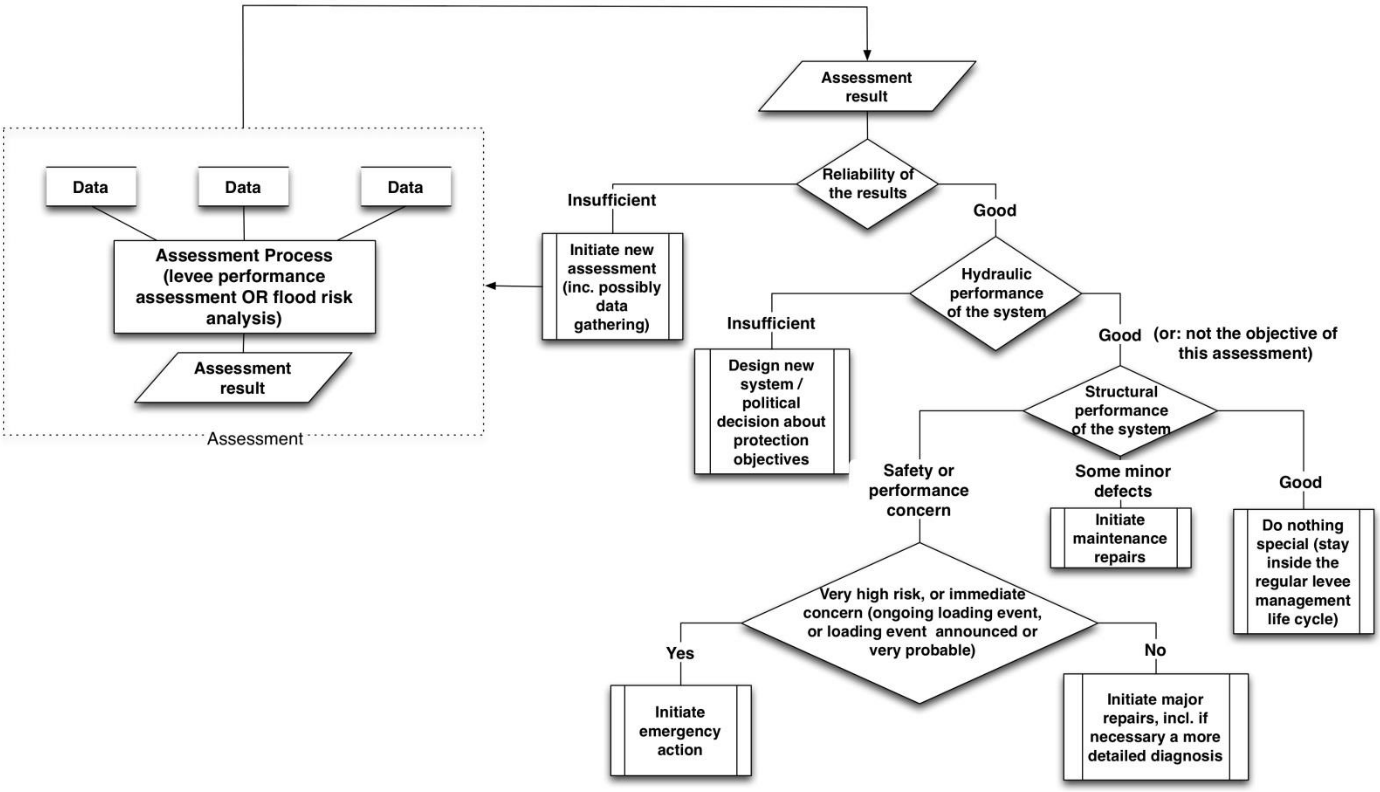

Figure 2. Decision making based on assessments and risk analysis - (Sharp et al., 2013) – Chap 5.

- An index based method to assess levee structural performance: to be able to integrate all types of data (results from visual inspection, different types of numerical data, complex information from reports), Irstea has developed an index-based method that formalizes data as status indicators, then combines these indicators in functional criteria, themselves combined in performance indicators (Peyras et al., 2015, Tourment et al., 2014, Bambara et al., 2018).

3 WATER AND SEWER NETWORK ASSET MANAGEMENT APPROACHES

3.1 *IAM: basic ideas*

Since the beginning of the 2000s, three basic ideas have been emphasized concerning water and sewer network IAM:

- IAM should be driven by the performance of the service provided by the infrastructure, within a paradigm of cost constrained management of the risks related to wear and obsolescence, taking into account the structural and functional vulnerability of the network;

- IAM should mobilize capacities within "operational", "informational", and "governance" fields of activities. Thus, for water and sewer networks, governance concerns decisions related to pipe renewal budget planning, risk priorities, coordination between IAM stakeholders (local authority, water or sewer utility, engineering consultants, elected representatives, users, stakeholders of other infrastructures and services), and compliance with sanitary and technical regulations. Operational issues are related to maintenance and annual renewal works, water network operation and monitoring, information system maintenance;

- IAM should logically fall within a Life-Cycle perspective and articulate the three temporalities of “strategic” long term (several decades, beyond human generations), “tactical” mid-term of budget planning (5-10 years), and “operational” short term of annual renovation work programming relying on pipe prioritization for works.

These principles fall within Life-Cycle Management (LCM) focusing on performance, risks and cost from the Life-Cycle perspective. The following sections give examples of IAM approaches developed by Irstea in line with these principles.

3.2 *Examples of methods developed for water networks*

Drinking water networks in France represent 900 000 km of pipes and 25 million connections, with a renewal value estimated between €300 and 450 billion. Despite the lack of public attention due to its mostly buried location, this infrastructural heritage is renewed yearly at an average rate of 0.5%, corresponding to an expense estimated between 1.5 and €2 billion. Maintaining the service provided by water networks therefore represents a huge financial stake when viewed in terms of the French GDP of about €2,400 billion, not to mention crucial health, socioeconomic and environmental stakes. Water network IAM therefore requires appropriate management policies in order to offset the inescapable wear and obsolescence of these assets.

3.2.1 *Performance driven IAM*

The performance of the service provided by an infrastructure is understood as the ability to manage risk defined here as the product of failure probability and the valuation of its impact on vulnerable elements (service users, people, the built and natural environment). Failure occurs when service quality does not meet a required level: e.g. service disruption, flooding due to pipe breakage, water polluted by pipe walls, water resources wasted through pipe leakage, insufficient service pressure or overlong water sojourn time due to poorly adapted pipe diameters.

Designing a relevant IAM strategy therefore involves ensuring the sustainability of the service at a satisfactory level of quality, while keeping both the service price acceptable for its users and its environmental footprint as low as possible. Such a trade-off can be found through rational and constructive consultation between all the IAM stakeholders, which may be greatly facilitated by long term numerical simulation results that allow the objective comparison of alternative strategic IAM options. The logical necessity of a strategic simulation tool is illustrated in Figure 3.

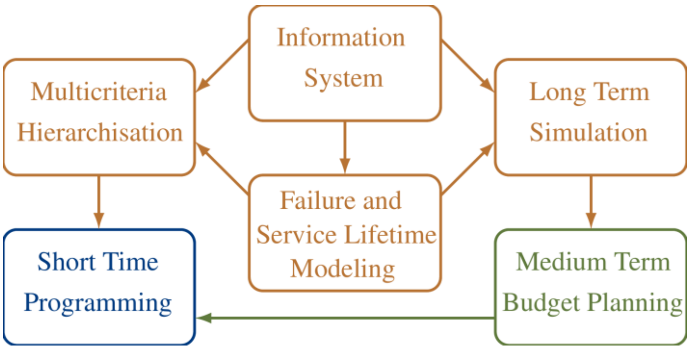

Figure 3. Logical necessity of long term simulation.

Performance driven IAM involves the development of failure prediction and impact valuation tools (Large et al., 2015). Efficient models are currently available for pipe breakage prediction (Le Gat, 2014), water network hydraulics and the analysis of water quality. Research efforts are nevertheless still needed, notably concerning water pollution by pipe wall chemical components (e.g. vinyl chloride monomers), pipe leakage prediction, the combination of several performance dimensions, and failure impact valuation. Performance can also be considered at the utility level, by making the link with financial and organisational stakes.

3.2.2 *Life-Cycle perspective*

IAM should logically fall within a Life-Cycle perspective and articulate the three temporalities (cf. Figure 3). Due to the necessarily low annual pipe renewal rate, IAM efficiency cannot be assessed on an annual basis. Helping IAM decisions to meet multi-objective performance requirements therefore involves the capacity to perform long-term numerical simulations to assess the long-term impact of IAM strategies on service performance. Multiannual investment plans (MIP) set out the mid-term efforts to be devoted each year to infrastructure renovation, whereas the annual renovation program (CARE-W ARP model) may allocate at best the annual effort between selective, constrained and opportunity renovation works; the combination of MIP and ARP, namely the IAM strategy, should allow meeting given performance objectives in the long term. Multiannual midterm programing is necessary on both the technical and financial levels to reduce the effect on the water bill (Nafi et al., 2008) and adhere to long term approaches.

3.3 *Examples of methods developed for sewer networks*

Sewer infrastructures (networks and treatment plants) provide the service of collecting and treating wastewater and storm water (although new techniques also exist for rain/storm water). Thus, in the case of failure, they may not only lead to polluting the natural environment but also to flooding streets, houses and economic activities, and they represent a possible threat to the safety of the population if drinking water networks are polluted, or on an even larger scale if they cause pathologies in levees. In France, their implementation occurred later than water networks and represent 340 000 km with 22 million connections, with an annual need for renewal amounting to €1.3 M (2003).

Here, we focus on sewer networks. Different approaches have been developed by Irstea within the RERAU Framework and with the researchers of INSA Lyon in particular, in line with the four basic ideas presented above.

3.3.1 *Performance driven IAM*

As with water networks the performance of sewer networks and their asset management rely on the fact that there is no single cause for the occurrence of failures, except when there is a collapse or a blockage: in general different dysfunctions affecting the hydraulic, structural and tightness functions of pipes (i.e. infiltration, exfiltration, root penetration) must be taken into account, as must their level of seriousness. This was a good reason for developing multi-criteria approaches within different projects for prioritization, as has been done already for water asset management within the CARE-W project. Different decision tools were developed in CARE-S (Saegrov, 2006), RERAU (Le Gauffre et al., 2005) and INDIGAU (Ahmadi et al., 2013) projects:

- to help short term prioritization at the pipe level: multi-criteria methods were developed using a 4 levels seriousness assessment. They consider the different dysfunctions and include the characteristics of the pipe and impacts to the human and natural environments (Ahmadi et al., 2013, Le Gauffre et al., 2005, Werey et al., 2006a). Density scores are calculated at the pipe level for each of the 12 dysfunctions and the thresholds are calibrated using expert opinions (Figure 4);

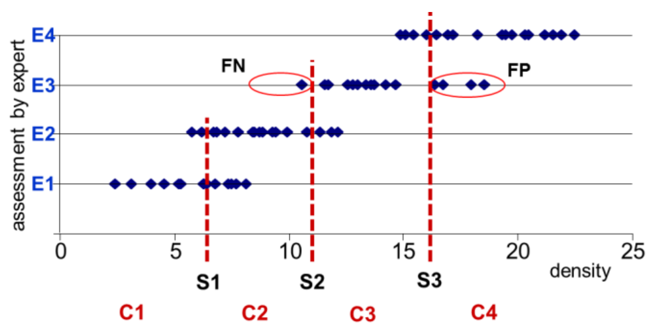

Figure 4. Expert opinions versus scores of a dysfunction indicator for a given set of thresholds.

- to provide long term analysis (Le Gat, 2008): a methodology was developed to model deterioration using Markov chains. It allows predicting changes in the level of seriousness;

- to assess the impacts of failures and works (renewal or trenchless rehabilitation): approaches were developed using both physical and monetary assessment methodologies (Werey et al., 2006b).

Concerning rainwater management, multi-criteria approaches were proposed with the aim of analysing the positive and negative impacts of best practices: to determine infiltration capacities (Moura et al., 2007), a cost benefit analysis (CBA) is being developed to also take into account positive effects (research underway for the French Agency for Biodiversity, by Werey and Rulleau in 2018).

3.3.2 *Cost and funding issues*

The question of cost assessment and funding allocation is still under review to reinforce the link between technical, financial and economic approaches.

Cost analysis can be performed for the different infrastructures to evaluate the internal cost for water or sewer utilities (ASTEE-AITF-ONEMA-FNCCR, 2017, Werey et al., 2017), by considering technical data, but also by taking into account external costs linked to the impacts of failures and positive impacts (benefits) linked to the multifunctional opportunities provided by best management practices for rain/storm water. External costs can be evaluated by empirical methods (Werey et al., 2015) or by economic valuation methods (Rozan et al., 2017). These kinds of approach (CBA and multi-criteria analysis) are also applied for flood protection systems.

3.4 *Urban management: coordination constraints and opportunities*

For both networks, IAM should explicitly take into account the constraints and opportunities related to urban management and coordination with renovation works of other adjacent infrastructures, particularly roadworks, and new urban infrastructures such as tramway lines and water/sewer networks. The IAM of spatially close infrastructures is an interesting issue that may help achieve economies of scale on the funding side as well as that regarding impacts to residents and the internal organization of the utility. In addition, making links between the significant data to be collected is of interest to both networks and interdependent decision tools and reflection on this issue is ongoing.

For instance, it is economically impossible to renew more than a tiny fraction annually, i.e. at most 1.5%, of the total network pipe length, because of the high cost of renewal works and funding constraints. Annual renovation programs must be chosen very carefully, and a delicate trade-off must be achieved between targeting the pipes suspected of most penalizing service performance (selective renovation after prioritization by multi-criteria decision tools (Le Gauffre et al., 2005)), and responding to land management operations that involve mandatory pipe changing regardless of their condition (constrained renovation, i.e. the construction of a new tramway line), or taking advantage of anticipated renewal opportunities (renovation opportunities). Cost evaluation is a big issue (Werey et al., 2003), considering repair and renewal as well as the costs of impacts (social, external costs), *i.e.* the sensitivity of consumers to water supply cuts or the effects of sewer dysfunctions.

The location of future land management operations, and especially of punctual road works, cannot be known beyond a few years ahead. In order to perform numerical simulations over several decades, land management constraints and road work opportunities must therefore be considered probabilistically. As proposed by Le Gat (Le Gat, 2016), modelling the probability that a given pipe will be concerned by either a land management operation that involves its mandatory change, or by a road work that gives an opportunity of more or less anticipated renewal, can be achieved through the combined modelling of pipe breakage and decommissioning intensities, based on exhaustive chronicle of such events observed in the water network over the past decade.

4 DISCUSSION

The life cycle management of the infrastructures studied relies on cyclic approaches with consideration given to short, medium and long-term temporalities. Levees and other flood protection structures function in systems grouping several works in the same watershed, and though they need to perform only occasionally, they depend on the entire system due to the lack of redundancy: a component failure leads to the failure of the whole system. Regarding networks, they are interconnected systems with redundancy if meshed. In that case, it is possible to limit the impact of a faulty component to a specific (urban) area. The purpose of this section aims is to emphasize the position of the infrastructure with respect to LCM and introduce the more recent preoccupation of sustainability.

4.1 *Performance, risk and cost management*

All the approaches developed place performance and risk at the heart of the development, *i.e.* the objective is to guarantee the performance of the service function in a cost effective manner. Depending on the infrastructure, the aim of the function is to ensure safety, water supply, and wastewater collection.

Costs have to be considered at two levels. The first concerns people, property and the guarantee of service provision. Indeed, in the case of a flood protection system, avoided impacts and costs are considered to promote projects or consider renewal programmes. Regarding water and sewer pipes, impacts to a population will of course be avoided as well as possible and be considered in the service objectives. However, here the service is first to provide water in terms of quantity and quality to all consumers and to collect wastewater, and treat it efficiently enough to discharge it into the natural environment. Thus the cost of impacts is a component of the performance indicators, but is not the only one. The second level of cost concerns the utility, institution or community which has to make the investment and carry out IAM maintenance and renovation. The critical issue is to decide between the two questions: What is the best time to renovate at the best cost? or Is it better to wait as long as possible without undergoing the next failure? This demands decision tools, good organisation for crisis management and making the link with the capacity of resilience assessed by an efficiency analysis.

4.2 The *IAM process relies on 3 fields of competence*

The IAM process involves three main dimensions whatever the infrastructure (cf. Figure 5 - case of water networks): operational, informational and governance issues.

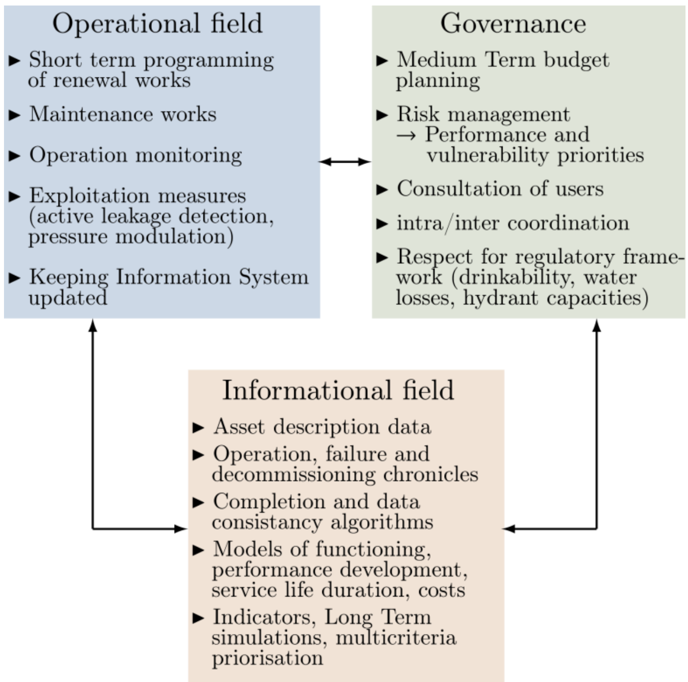

Figure 5. Three dimensions in water network IAM.

Harmonization between these fields is necessary and enabled through interactions with the informational field, where basic information about network assets (description, operation, failure and renewal chronicles) is processed and structured in modelling tools. These models can then be run to produce decision-aid indicators, and combined within long-term simulation or multi-criteria prioritisation algorithms. Interactions are likely to evolve over time. In France, the context is currently changing: the new competences of GEMAPI and NOTRe Act will lead to the creation of new organisations for water infrastructures or modify existing ones (flood protection, water and sewer networks, storm drainage).

4.3 *Life-Cycle information management*

IAM performance depends on available, reliable, and pertinent data and information during the whole lifecycle (cf. Figure 5). We want to emphasize that the informational field occupies a central place in a rational IAM construct. Since the physical infrastructure is strongly coupled with its informational duplicate, this leads to the concept of "informational capital". The question of the value of informational capital must be studied in close connection with the evaluation of the physical capital represented by the different assets.

Different tools such as the INSPIRE Directive (Infrastructure for spatial Information in Europe) and the COVADIS Standards (Commission de validation des données pour l'information spatialisée) can enhance IAM and reduce its costs through the pertinent structuring of information, better traceability and access to data, updating information records after actions, better sharing between services, etc.

4.4 *Implementing IAM for multi-infrastructures*

Urban territories usually concentrate different spatially close infrastructures: water and sewer networks are located under roads or pavements, water or sewage pipes can cross levees, roads can be located on levees and so forth. Physical influences involve potential structural or functional impacts generated by one infrastructure on another: *e.g.* an embedded water pipe can have a significant effect on the performance of an earth levee because of pipe leakages or because it changes local conditions (Aguilar-López et al., 2016, Di Maiolo et al., 2017). Taking into account both waste and rain water management raises the question of integrated urban water management (*i.e.* OMEGA project 2010-14: methodology for a management aid tool for integrated urban water) (Belmeziti et al., 2015). Moreover, operations performed on one infrastructure can trigger operations on another (Tscheikner-Gratl et al., 2016), *e.g.* sewer replacement is decided following camera inspections or due to pipe age, but also due to the planning of roadworks, as mentioned above (§ 3.4). Finally, although models have been proposed in the literature for the assessment of performance and impacts for individual facilities (Bambara et al., 2018, Curt et al., 2010), few works are currently dedicated to the potential structural dimension of the functional impacts generated by one infrastructure on another. To our mind, research is necessary to deal with IAM, considering different types of interactions between infrastructures.

4.5 *Single work management vs. pooled work management logics*

Due to the high criticality of levees and the lack of redundancy among elements that compose a protection system, IAM research has mainly been developed for the purpose of securing each levee segment, through systematic inspection and risk assessment operations (cf. Figure 2). These operations lead to:
- routine actions usually carried out immediately or very quickly after the detection of defects;
- repair or adaptation performed after thorough diagnosis including a risk analysis to prioritize the operations needed to mitigate the associated risk. They are usually planned according to a mid-term objective.

By comparison, IAM research in the field of water networks is developed more in line with a statistical approach based on modelling asset aging; this was justified by the very large number of elements that compose a network, and by the relatively lower criticality of water pipes, and the difficulty of inspection due to their buried location.

Both approaches may characterize what could be termed "single work/system management" logic in the case of levees, *vs.* "pooled work management" logic in the case of water pipes; these logics contrast with each other when comparing Figures 1 and 3. To some extent sewer pipes have an intermediate status; inspection is possible but not performed on the whole network. Extensive research was devoted to both formalizing single pipe inspection results and deriving risk assessment rules on the one hand (see *e.g.* Le Gauffre et al., 2005), and to developing long-term statistical predictions of the condition of sewer network segments on the other hand (Le Gat, 2008).

4.6 *Sustainability considerations*

Infrastructures are located in socio-ecological and socioeconomic environments and the expectation to integrate sustainability aspects in IAM is growing rapidly and globally (Shaw et al., 2012): social (e.g., quality of the service provided), environmental (e.g., life-cycle assessment (Loubet et al., 2016)), and economic (e.g., cost savings; impacts on residents and consumers (Rozan et al., 2017)) criteria should be considered explicitly in IAM methods and tools in addition to technical issues for facilities. There is no unified framework that combines resilience and sustainable development for the design, evaluation and maintenance of civil engineering infrastructures and convergence is slow.

Encouraging results have come from recent studies along these lines. Indeed, working on asset management led us to explore impact assessment focused on sewer and water network dysfunctions. More recently, we dealt with the assessment of best practices for rain and storm water management, storm control measures (Werey et al., 2017) and the management of both waste and rain water management (OMEGA project), crossing IAM with other sustainable functions of the infrastructure and the service. This has led to new interesting perspectives. Thus the question of positive impacts such as biodiversity development, urban heat island mitigation, and the installation of recreational activities permitted by multi-functionalities has brought about new developments (i.e. the evaluation of externalities) to help sewer utilities implement the best management decisions (renew pipes or change rainwater management). It also brings to light a link with other natural or artificial infrastructures like levees that favour green areas and biodiversity. The competences of GEMAPI are aimed at promoting a combined approach for managing the natural environment and flood prevention.

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