Review

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Review

Water Distribution Systems: Integrated Approaches for Effective Utility Management

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Abstract: Effective management of water distribution systems requires an integrated approach, but none of the available frameworks for one are in broad use in the water supply industry. Frameworks developed include a management standard of the American Water Works Association and Distribution System Optimization, a methodology for physical, hydraulic, and water quality performance assessment. The intelligent systems framework also offers a pathway to integration, but it lacks a definite structure. The voluntary aspect of adopting innovations within the fragmented and unregulated nature of the water utility industry poses a barrier to adoption of such innovations. Another barrier is the uncoordinated arrangements of water research stakeholders with different incentive structures. Intelligent water systems offer a way to incentive utilities to encourage implementation. They can provide a bottom-up approach where utilities see advantages, as opposed to a top-down approach where they are expected to adopt a method without seeing clear benefits. Research to develop new and improved tools is needed, but the research roadmap should prioritize implementation.

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1. The Challenge of Managing Water Distribution Systems

Water distribution systems are challenging to manage because they comprise complex networks with large numbers of interacting pipes, pumps, valves, and controls. These components are mostly hidden, usually of mixed ages and conditions, and management programs for maintenance and renewal are often inadequate. Despite these challenges and complexities, distribution systems are expected to deliver pressurized safe drinking water to households and other sites on a reliable basis [1]. Comprehensive and integrated approaches to managing distribution systems are needed, but they face barriers due to the realities of variable management capacities in utility organizations around the world [2].

Of the world's some eight billion people [3], only a fraction receives piped water service from distribution systems, although many more aspire to be connected to them. Global water service statistics report on access to safely managed drinking water, but they do not provide data on organized distribution systems [4]. The fraction of population being served by distribution systems is not known precisely, but many people living in urban areas of high- and middle-income countries receive water from them.

Regardless of their status, all distribution systems require effective management to assure reliable delivery of safe water at acceptable service levels. Even when distribution systems are available, their service levels as indicated by reliability, safety, and other metrics are variable and often poor [5,6]. Success depends on resources and management capabilities, which vary widely among utilities. As they search for help, utility managers and engineers seek guidance from diverse sources, including governmental [7,8] and intergovernmental organizations [9], as well as non-governmental organizations such as the International Water Association (IWA) and the American Water Works Association (AWWA) and other information sources such as the International

Benchmarking Network [10]. Many private sector firms are also available to troubleshoot distribution system problems, but solutions are often too expensive for the utilities.

Research about distribution systems management addresses topics from infrastructure performance to water quality and health issues [11]. The topics for this special issue on Integrated Distribution System Management (IDSM) focus on programs to support operations, such as leakage reduction, pressure management, water quality control and monitoring, and energy optimization [12].

The concept of IDSM covers this full range because systems can fail due to diverse threats, whether due to infrastructure breakdowns, operational mistakes, sabotage, or issues such as water theft. The scientific literature contains many reports about research into distribution system management, and an integrated perspective requires that they be assembled and viewed comprehensively.

A comprehensive approach to distribution system management must consider the overall set of responsibilities of the utility, which require an enterprise perspective. Distribution system management will be a management subprocess, and the paper begins with a conceptual model to explain this hierarchy of management levels. The discussion includes reviews of the research outcomes and implementation status in each of the elemental arenas of IDSM. The cited references show the historical evolution of distribution system research in the United States, where reports and publications began to increase sharply after about the year 2000. Although most references are from the US, with the increase in journals and publications about water issues, more citations from other countries became available and are included in the discussion.

Contributions of the paper include clarification of what is meant by "integrated" within a conceptual model based on utility industry research. IDSM is then placed in the context of the framework of Effective Utility Management (EUM), which has been developed as a roadmap for overall management of utilities [13]. The paper then reports on the status of research and implementation of key methods and technologies for distribution system management, and it suggests a roadmap for research and implementation of integrated approaches. An important goal of the paper is to suggest how to avoid confusion when the term optimization is used in the context of distribution systems management. A distinction is made between distribution system optimization (DSO), which has been offered as a comprehensive framework [fried], and process optimization, which focuses only on operations. The division into the two concepts is imperfect, but it should provoke useful discussion.

Information for the paper is drawn from the literature and the writer's long-term participation in distribution system research, water industry visioning reports, and a survey of distribution system organizations [14].

2. Integrated Distribution Systems Management

Management concepts that use the term "integrated" can be misunderstood unless the system elements to be integrated are specified explicitly. As an example, the framework of Integrated Water Resources Management (IWRM) has become popular, but the water management community lacks a common understanding of it [15]. In a similar way, researchers and users can understand the concept of IDSM in different ways. It is explained here as being part of the family of management systems that a water utility must organize and manage. A system must have a boundary to contain its core interacting elements, and the distribution system is distinct from the other infrastructure systems of the water utility. In that sense, IDSM means to manage the interacting components that deliver water downstream of the water source and treatment plant and make it available for service lines or other diversions that are not part of the distribution system itself.

The distribution system is thus within the hierarchy of systems involved from top to bottom in utility management. The conceptual framework presented in Figure 1 offers a comprehensive approach that shows how IDSM fits with best practices for utility management as well as with the technical methods specific to distribution systems. Treatment and distribution systems are linked because they are interconnected, and treatment outcomes affect the distributed water and the pipeline infrastructure. IDSM is shown to comprise capital, represented by asset management, and operations, where optimization is the goal. The model also shows the support systems for the utility, including finance, workforce, customers, community, and work with other stakeholders, which are emphasized in EUM.

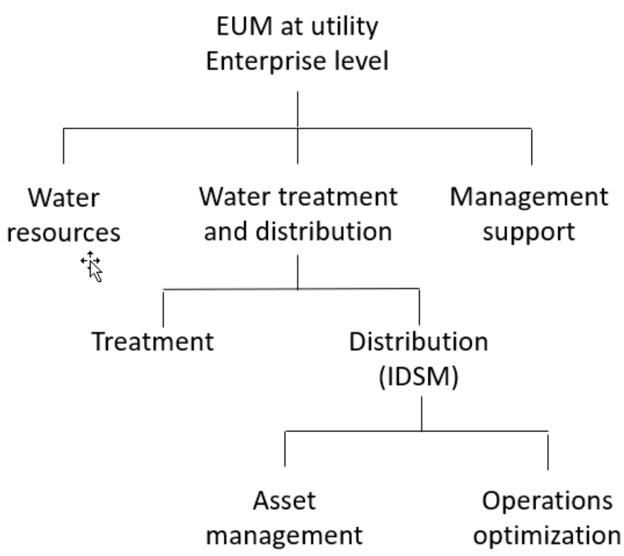

Figure 1. Hierarchy of utility management systems.

The EUM framework has ten attributes, with product quality as an integrated metric meant to capture total performance of the utility. Two attributes relate to operation of the water source and infrastructure (operational optimization and infrastructure strategy and performance) and another addresses water resource sustainability. The other six attributes address the organizational issues shown as management support on Figure 1.

The elemental arenas of an integrated approach to distribution system management are collections of tools for capital and operations management. For the capital side, asset management is an organizing framework for tools like risk-based prioritization and condition assessment. For operations, performance measurement for optimization, modeling, and water loss control are examples of tool categories.

3. Comprehensive Frameworks for Utility Management

A framework for utility management processes will organize them into an overall group that works in an integrated way. A general example is the enterprise management system, which is used often to describe integration of software systems for digital management. For water utilities, the EUM program is a general framework, also referred to as an approach, a set of approaches, and a management program [16]. EUM is a high-level integrated approach and IDSM is a subset of it. As most utility infrastructure is in distribution systems, IDSM is the most capital intensive and extensive technical system managed within EUM.

Among water utilities, the search for a general framework of distribution system management began before the year 2000. Prior to that time, little research had been published even about the capital or operating needs of water distribution systems. The increase in attention to distribution systems was driven by convergence of the disclosures about serious problems and development of new technologies. Examples of problem disclosures were the need to control lead and copper releases from distribution systems [17] and the frequency of water main breaks, which open distribution systems to contamination and threaten health [18]. Examples of new technologies were development of distribution system simulation models [19,20] and availability of data technologies to support emerging asset management systems [21].

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The search for an overall management approach was evident in early research sponsored by the American Water Works Research Foundation (AwwaRF), now named the Water Research Foundation (WRF). A 1995 AwwaRF report explained a general approach to address capital and operations in terms of performance categories of adequacy, dependability, and efficiency. Metrics for these were established in categories of structural, hydraulic, water quality, and customer perception. Adequacy addressed operational concerns like pressure and water quality, dependability focused more on capital issues like main breaks and inoperable valves, and efficiency addressed water losses and energy consumption [22]. While the recommended approach did not gain traction, it provided background thinking for two management frameworks that emerged soon afterwards. These frameworks were AWWA's G200 management standard for distribution systems [23] and DSO, which was to support AWWA's Partnership for Safe Water (PSW) program [24].

Actions by the US Environmental Protection Agency (USEPA) and several standards organizations led to creation of the G200 standard, which was developed by an industry task force [23]. The standard addresses "critical requirements for the operation and management of potable water distribution systems, including maintenance of water quality, system management programs, and operation and maintenance of facilities."

Management standards establish consensus requirements for utility management practices and adoption by utilities is voluntary. Options to encourage adoption by utilities were discussed in the National Research Council (NRC) report, such as to create or adapt federal regulations about key activities, use building and plumbing codes, link loans from the State Revolving Fund to adherence, and require them for access to capital and better bond ratings. Small water systems will have special issues with financial, administrative, and technological challenges and require an incremental approach with technical assistance and further incentives [1]. Most recent changes in G200 involve information technologies for data management, monitoring and control, failure risk management, and maintenance management.

In parallel with the G200 standard, the PSW supported development of DSO. Optimization in this sense is like process optimization or monitoring and controlling all subsystems in an integrated way to meet performance goals. The PSW program was a co-sponsor of the WRF project that developed the DSO method [24]. The NRC study had recommended integration of physical, water quality, and hydraulic performance [1] and DSO provided an integrative platform to merge these systemically with a few parameters. Physical, hydraulic, and water quality integrity were to be indicated by metrics for main breaks, pressure, main breaks, and chlorine residual. Utilities are guided to track them with numeric criteria and prepare certified self-assessment checklists.

The WRF study to develop the DSO method was comprehensive and featured extensive utility participation. By introducing the term optimization without laying groundwork for it, ambiguity remained, and most research papers still used the term optimization to refer to different management tasks than performance checking [25].

Among distribution system managers the concept of DSO has been adopted by only a few utilities, likely because it is still evolving and not required by regulators [14]. Utilities indicate lack of understanding of the concept, which is caused by both unfamiliarity with research literature and association programs, as well as ambiguity in how the term optimization is understood. Neither the NRC report nor the WRF project defined DSO explicitly. They use the term optimization in different contexts, like for treatment plants, placement of sensors, water quality management, or hydraulic network design [26].

While it is not always identified as such, the concept of the intelligent system can provide an overall framework for distribution system management. Alternative terms are smart or digital systems, but the term intelligent seems to have more traction [27]. Intelligent systems can merge capital and operating decisions into master control systems that manage information for operations, system condition, and customer alerts in an integrated manner.

The outcomes of AWWA Water 2050, a recent series of visioning workshops, support movements toward intelligent systems along the lines explained by the WRF [27,28]. This was evident from outcomes of the sustainability work group, which called for implementation of a new water utility paradigm to stress a total and integrated approach to water management, and those of the technology work group, which called for accelerated innovation and to transform water services through next-generation technology.

Intelligent distribution systems will extend the concepts of existing supervisory control and data acquisition (SCADA) systems by adding information technology tools. Systems are controlled by actuators (like pumps and valves), where system data (like pressure, flow, and quality) are fed into a decision process that is informed by a model, which could be part of a "digital twin." The sensors provide information about system condition to aid management decisions. Meters can provide information on water usage, and automated meter reading (AMR) has become practically a standard among utilities. Advanced metering infrastructure (AMI) systems can provide information for decisions like water loss controls. The concept of intelligent systems can be extended to end users via the Internet of Things (IoT).

Intelligent systems can seem like an ephemeral concept, only to be replaced later by a new one. However, they are innovative because they introduce a new paradigm for information access and operational control of distribution systems. The concept is evolving, and the water industry is experimenting with new approaches [29]. Its structure is being worked out as most utilities have some automation and remote data collection and/or communication systems. Presently, few utilities are using AMI, and the prevailing attitude seems to be to wait and see. This is consistent with the WRF study that found that utilities are not embracing intelligent technologies as rapidly as other industries despite potential benefits. Utilities report that data issues like false positives, along with cost, and maintenance, are important factors when they consider implementing intelligent systems [30].

Like with IWRM itself [31], the tool categories used in IDSM are scattered, and it is challenging to develop an overall framework. DSO and G200, the two existing frameworks that span capital and operations, are not used widely by water utilities [14]. The lack of awareness of them is concerning but distribution system managers focus on daily problems and may not voluntarily adopt new tools and research results. This is especially the case in smaller utilities which struggle to sustain operations. Intelligent systems may create pathways for more such utilities to benefit from comprehensive approaches that incorporate emerging technologies such as sensors, digital twins, and artificial intelligence. As more experience becomes available, AMI can provide useful information for capital and operations. Interest in it signals a bright future for an integrated approach for distribution system management through intelligent systems that will support the broader framework of EUM.

4. Sub-Processes of Integrated Distribution Systems Management

Clusters of management tools serve specific purposes within a comprehensive management framework and identifying them can improve understanding of the overall management [32]. An example is found in tool clusters for construction projects, such as for scheduling, cost estimating, quality and change management. These clusters can involve different stakeholders and involve different management sub-processes in the overall process of construction management [33].

For distribution systems, the sub-processes are for management of capital assets and operations. For capital, asset management is an organizing framework for tools like risk-based prioritization and condition assessment. On the operations side, optimization, modeling, and water loss control are examples of tool clusters.

As a general term, asset management can mean an accounting method used in any sector, beginning with financial assets. Within the infrastructure sectors, it has come to mean a method to coordinate management activities for all types of capital facilities or "fixed assets" in accounting rules [34]. Such accounting for fixed assets is practiced in diverse ways across all infrastructure sectors, and it is especially evident in the transportation and water sectors [35,36].

For water and wastewater systems, asset management is considered a data-centric framework of tools for managing systems like distribution networks. USEPA identified its main processes as to assess condition, determine goals, identify critical assets, determine minimum lifecycle costs, and

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develop a financing plan. This basic model has been adopted widely as a framework for the processes within asset management as used in the water sector [36]

The research trajectory of asset management started with the rapid rise of data management and geographic information technologies, which provided new ways to keep records and schedule work. These same tasks are needed across industry sectors, so an ISO standard has been developed to express a general model of how asset management works [37].

The research base for asset management is broad. The WRF has conducted over 300 projects relating to it, much of it in cooperation with research agencies in other countries. An early WRF project developed a research roadmap for it and additional research has filled in the knowledge base [38]. The WRF is now aligning the asset management concept with the One Water approach to address a unified collection of water systems including wastewater, drinking water, recycled water, and stormwater [39].

Two focal points of comprehensive research about asset management have been assembly of the WATERiD knowledge base [40], which is a platform for utilities to share information on asset management, and the Sustainable Infrastructure Management Program Learning Environment (SIMPLE), which was designed as a hub for asset management tools [41]. Currently, WateriD remains operational but SIMPLE is not active.

While asset management is a powerful tool, its status of implementation remains incomplete, as shown in an AWWA survey [42]. A lack of commitment to it was evident, although utilities use some of its tools. Only a few states have asset management requirements for drinking water utilities. A survey showed that about most utilities reported use of asset management systems, with around half using software packages, but the sample was biased toward leading utilities. Without a standardized reporting framework, utilities may not use asset management comprehensively, and simpler approaches may be appropriate [43].

Condition assessment research for management purposes and technological products has been active. It divides into general concepts and specific methods. General concepts refer to classifications such as non-destructive evaluation (NDE) versus methods like controlled destructive evaluation [38,44]. A comprehensive classification was provided by [46] with categories as conditions inferred from samples and conditions directly measured. The samples can include external direct assessments and statistical methods that consider pipeline data such as age and break history. Conditions directly measured include in-pipe condition assessment like leak detection and non-invasive methods such as pressure testing. All methods except statistical studies can use NDE technologies such as ultrasonic and electromagnetic.

Like asset management, implementation of condition assessment is developing piecemeal. Distribution systems involve so many components that utilities can only afford to fund NDE studies on their most critical components. No comprehensive report was identified to assess overall levels of implementation and not many utilities use condition assessment technologies on a systematic basis [47].

Condition information is needed to inform risk-based prioritization, which provides a method to identify the most urgent needs to be addressed within available funding. The innovation is use of data-centric risk analysis methods considering location of critical facilities and likelihood and consequences of failures. The process was not developed by research projects, although its methods such as risk assessment methods and pipe break simulation models were developed in formal projects. The use of such risk assessments for distribution system capital planning dates to about 2000. At that time, three general levels of prioritization were recognized, voting, ranking, and systems analysis, which requires the most data [48]. Economic models were being developed to estimate costs of failure [49], although studies of cost data showed that little data were available [50]. Risk models were developed to use structural properties and statistical parameters like age [51]. Research continues, and models are beginning to incorporate artificial intelligence and machine learning [52].

No studies to assess the degree of implementation of risk-based methods for prioritization were identified in the literature review. However, the general state of management in the water utility industry indicates that most utilities use the informal voting method when they prioritize at all. Some

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use structured approaches like prioritization spreadsheets [53], but few would use the more complex systems analysis method. The survey showed that most utilities lack formal prioritization methods and use regular capital improvement data such as street paving, coordination with other utilities, and system expansion [14]. In the survey, only two utilities reported using a pipe break simulation model to predict remaining life of the pipelines. Data issues apparently discourage utilities from using such modeling methods, and risk assessments may also be neglected by boards addressing broad needs, including social equity [54].

The concept of optimizing the daily operation of distribution systems is evolving but is more complex and less structured than treatment plant optimization. The licensing of distribution system operators, for example, is a more recent development than for operators of treatment plants [55]. Research papers on distribution system operation focus on strategies such as control of system components like pumps, valves, and tanks [56]. Sometimes the papers address broader topics, like design and failure prevention [57]. More papers address mathematical approaches to optimization of performance, but there is little evidence that the outcomes are being implemented by utilities on a broad basis [58–61].

As an operations management method, water loss control has become popular due to emergence of new methods and data, along with needs for greater efficiency in water management. It is a complex method because distribution systems comprise large arrays of pipelines, fittings, controls, and appurtenances for access, fire suppression, metering, and other functions. The challenges to control all leakage are daunting, and problems become more difficult in systems with management challenges [62].

The international water community banded together to develop the new method for water loss control. They were able to build on early work on flow analysis of water mains and later work on "Unaccounted-for Water" [63]. This set the stage by the 1990s to assemble the tools and methods for a comprehensive approach. Work was organized via committees of the IWA and AWWA. The first edition of AWWA's Manual of Practice M36 on Water Audits and Leak Detection was in 1991 [64]. The new method was developed, and IWA announced a standard method in 2000 and an AWWA Water Loss Control Committee adopted the method in 2003 [65].

The approach involves an analysis component (defining and calculating components of the water balance) and a management component (selecting indicators for non-revenue water and losses). The ratio of real losses to an estimate of uncontrollable losses determines the main performance indicator, the Infrastructure Leakage Index (ILI). The uncontrollable losses stem from many small leaks in water mains and service lines and estimates are based on regression equations that were developed from research.

The research-to-practice implementation process for water loss control continues. A survey by AWWA of regulatory policies among states measured implementation of the methodology [66]. Some state agencies require it, and many utilities use it without the pressure from regulators. However, without the regulatory pressure, the rate of adoption among utilities may slump. Also, the data-intensive nature of the method requires close attention to data quality, and this provides further challenges to making the method more effective.

Network models are used widely by utilities to study issues like fire flow, water age, system needs and capacity, asset condition, and problems of low and high-pressure areas. They evolved from hand calculation methods to become sophisticated software packages and with digital computers, modelers developed creative ways to solve network hydraulics problem [67,68]. Eventually, EPAnet became the core engine for most models, although developers added many new features. The innovation with hydraulic network models is in the development of rapid and effective software packages and their adaptation for many management purposes. They are also essential as the technological basis for digital twins, which involve data and decision support logic as well [19,20].

No assessment of the use of models by utilities was found in the literature, although many research reports about how the models perform. Use of the models increased quickly after 2000, especially as commercial versions became available. Distribution system managers and analysts have found many applications, and use of models is widespread among utilities today. Essentially 100%

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of the utilities surveyed use hydraulic models, although the sample is not representative of all utilities. Some utilities operate models in-house and others outsource them to consultants.

5. Issues for a Research Road Map of IDSM

While the research literature shows lack of consensus on the scope of IDSM, frameworks like EUM, DSO, and G200 signal how managers in the water industry view the need for comprehensive approaches that combine capital and operations management. These frameworks exhibit a hierarchy with organizational interests first, followed by management of separate operating systems and support functions. Such approaches exemplify systems thinking, which can be powerful but seem ambiguous. Clear explanations can help to minimize ambiguity and confusion about them. The conceptual framework illustrated in Figure 1 explains the hierarchy of management approaches and offers a way to align IDSM with comprehensive approaches like DSO and G200.

DSO was developed through a research program with extensive utility involvement. It is a comprehensive method that links physical, hydraulic, and water quality performance criteria. Its validity was verified through testing by water supply utilities, but awareness of it and implementation have been slow because of its complexity, added workload, and lack of incentives for voluntary adoption. G200 was developed by a water industry task force rather than through a research project, but participation of leading utility stakeholders in developing it speaks for its validation. Recognition and implementation of it also seems low, but more due to lack of utility awareness about it than to complexity.

Lack of implementation of DSO and G200 indicates that an alternative approach is needed, and the intelligent systems framework offers a possibility. The pieces are falling into place with elements such as hydraulic network models, AMI technologies, and the emerging concept of digital twins. The intelligent systems framework might help overcome the limits of workforce capacity and funding in utilities. Rather than through a comprehensive research program, it is likely to evolve through product development and testing in utilities with resulting demonstrations across the water industry.

Tools for the subprocesses of IDSM require further research and development, but more focus on implementation will be needed. Asset management is well-established but not implemented broadly as an identifiable framework. Utilities use some of its tools and methods, but use of advanced methods based on statistical models and capital budgeting is lagging. Condition assessment involves many options, but their use is scattered and not consistent. In a similar way risk-based prioritization and statistical models of main breaks are used in only a small fraction of utilities. Data on cost of failure is also lagging, likely due to lack of sharing of information across the water supply industry. Leading utilities continue to experiment with these tools, while others lack the capacity and incentives to do so. Incentives for adoption of asset management are needed. The lack of regulation of distribution system capital condition and reporting in the US seems to explain part of the problem. Voluntary actions normally focus on the issue of the day, and long-term and strategic management actions get pushed aside.

Many research projects use the term distribution system optimization across mixed sets of tasks such as design and control of main breaks and water losses, and this makes the scope of the concept ambiguous. Operational optimization is a subprocess of DSO that involves hydraulic and water quality performance, but it has not been developed with a label that is separate from DSO. By focusing on only operational matters like in treatment plant optimization, the ambiguity caused by scattered approaches might be reduced.

Within operations, water loss control stands out as a research-based management method with broad acceptance by the water supply industry. Its development trajectory shows how a new management method can be implemented through collaboration if essential drivers are in place and if technology leaders like in-house experts, consultants, or other gatekeepers are committed to it. While the impacts of such leaders only go part way toward technology adoption and diffusion, relationships in water associations provide the networks needed for the ongoing innovation.

The challenges faced by utilities to sustain condition and performance of complex water distribution systems point to a continued need for a research roadmap to improve their management.

However, the low levels of implementation of recent advances indicate a gap between published research and adoption of its outcomes by utilities. A road map for future research should consider how new developments can be implemented on a broader scale, and this will require insights into the unique management environments faced by utilities. As explained earlier, these management environments vary greatly in utility organizations around the world, as well as by the financial capacities of individual utilities everywhere.

Assessing how implementation can be fostered requires insight into how water research communities are organized. For distribution systems, these normally involve utilities, vendors, research organizations, regulators, and academics. Each of these research stakeholders has a unique role, which is determined by its mission and incentives. In an ideal world, utilities seek to improve performance and control cost, vendors want to develop and market products and services, research organizations want to develop projects that serve their constituents, regulators want to help utilities achieve compliance, and academics want to produce innovative and useful research products.

Two main issues must be confronted to strengthen the cooperation of these stakeholders and to incentivize implementation of research advancements. One is the fragmented nature of the water utility industry. Once utilities achieve compliance with health and safety regulations, they are not compelled to adopt innovations to improve their management. Such adoption is voluntary and will depend on the context of individual utilities.

This issue was addressed by the NRC [1] in its discussion of how to improve adoption of G200. None of the options listed have been adopted in the nearly two decades since the NRC report and future adoption seems unlikely at this point. Something different that will consider the many different contextual arrangements among utilities is needed.

The second issue is created by the divergence of incentives of the stakeholders in the research process. Regarding these, the research organization seems to be best equipped to serve as convenor of the parties for purposes of advancement and implementation. In the US, the WRF has emerged as the leading organization of this type and has over three decades of experience with project development and management. As a subscriber organization, the WRF must serve the utilities that pay for membership. Currently, the WRF has more than 1,000 utility subscribers, including some outside of the US [69].

The WRF's subscribers steer the organization's research agenda and critique its effectiveness. While no assessment of the overall implementation of its project results has been made, the sponsors of the WRF have expressed continued interest in development of research products that can be used. At the same time, thought leaders within the utilities advance ideas for innovation that provide seed for organization of future projects. Involvement of these thought leaders in project development does not guarantee implementation, as the experience with DSO mentioned earlier illustrates. Even when research developments seem promising, utilities may choose not to adopt them. A case in point was a project to develop a national mains failure database [70]. Although the benefits of sharing data seemed promising, utilities did not voluntarily participate because they judged those benefits did not justify the costs.

The challenge to develop a roadmap for IDSM is thus to foster innovation broadly across while addressing the fragmented nature of the water utility industry and the diverse incentives of the stakeholders. The fragmentation issue is being addressed by efforts at capacity-building, and these are largely driven by USEPA, the main regulatory agency [7]. This is logical because the federal regulatory agency is the only authority with the mandate and the means to promote capacity-building. While the programs have been active, the problem with capacity development is not a shortage of technologies but is more in the workforce and financial capacity of the utilities.

Regarding the diverse agendas of research stakeholders, the opportunity to foster IDSM seems to be focused on the advancement of technologies and methods for intelligent systems. As explained earlier, development of intelligent distribution systems is likely to proceed incrementally, and research advances can be added to the master framework for them with researchers pointing out how their outcomes can be used in an overall intelligent systems approach to IDSM.

6. Conclusions

As shown by development of the G200 standard and the DSO methodology, utility managers support a comprehensive approach to address all management functions for distribution system assets and operations. Lack of consensus about such a comprehensive approach and the low levels of implementation of the available frameworks indicate that something different and further research are needed.

Powerful tool sets for IDSM are available. Tools such as asset management, risk-based prioritization, distribution system network models, and an effective method for water loss control have been developed and tested. Research to improve them is still needed, but implementation of the tools is more urgent and should be prioritized in a research roadmap.

Incentives for implementation must confront the challenges and contextual arrangements posed by the fragmented and unregulated nature of the water utility industry. Utilities often do not implement research-based advances because they do not see immediate benefits. Also, water research stakeholders have diverse incentives and may not prioritize implementation. Vendors are stakeholders in water research and can deliver technologies to utilities on a for-profit basis. Water utilities can demonstrate the advantages of new technologies and methods by cooperating through the networks provided by water associations. Water industry research organizations like the WRF can convene forums comprising utilities and technology developers. Researchers can develop new concepts and methods, but it is desirable for them to be linked in partnership with utilities as well as to publish results in academic journals.

Advancement of intelligent systems offers an avenue to incentivize utilities to implement IDSM approaches. Intelligent systems can provide a bottom-up approach where utilities see advantages, as opposed to a top-down approach where they are expected to adopt a method without seeing clear benefits. Work toward developing a consensus model for IDSM can emphasize a conceptual framework with clear roles for management technologies like those explained in the paper. Comprehensive frameworks that have been developed can be mined to select the best features that can be used in a new model based on intelligent systems.

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