Critical Infrastructure Protection at the Local Level

Water and Wastewater Treatment Facilities

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ABSTRACT

The increasing number of Industrial Control System (ICS) vulnerabilities, coupled with continuing revelations about ICS compromises, emphasizes the importance of securing critical infrastructure (CI) against cyber threats[1],[2]. The ability to adversely affect the operation of an ICS through cyberspace is exacerbated by the increasing use of automation and implementation of common routing protocols to communicate with control devices [3]. Local water treatment facilities are particularly vulnerable to this attack vector due to the need to manage key functions with minimal staff. Reacting to specific cyber risks without developing a holistic method for managing risk provides only a modicum of protection. This monograph demonstrates how focusing on risk management as a mitigation strategy – not individual risks – maximizes the security efforts at the local level.

Some basic information technology (IT) security practices such as access control, physical security, and operations security can be applied to ICS security. However, determining which security controls to select and evaluating their effectiveness requires a process or framework that holistically considers risk across the enterprise. A risk management framework (RMF) allows an organization to assess risk in terms of impact to overall business operation, instead of assessing risks isolated to particular divisions within the organization. The National Institute of Standards and Technology (NIST) RMF, National Infrastructure Protection Plan RMF (NIPP-RMF), and NIST Cybersecurity Framework for CI are three complementary frameworks water facilities can employ to facilitate risk mitigation in a cost-effective way[4], [5], [6], [7], [8].

Keywords – industrial control system; cyber; critical infrastructure; water treatment facilities; wastewater.

I. INTRODUCTION

Over the last century the position of the United States as a world leader depended on a strong economy, strong democracy, and exceptional military capability. As technological improvements increased the capability and capacity of the United States to maintain its position in the world, these improvements simultaneously created greater dependencies on CI.

According to Presidential Decision Directive (PDD) 63, CI is composed of physical and cyber assets essential to the minimal operation of the economy and the government. Homeland Security Presidential Directive (HSPD) 7 provided further details on what types of acts would compromise CI[9]. President Obama's Executive Order 13636, in concert with Presidential Policy Directive (PPD) 21 (which replaced HSPD-7), expounds on the work of earlier administrations by specifically defining 16 different CI sectors and reiterates which government agencies support each sector. "Water and wastewater treatment" is identified in all four executive directives and orders as a CI sector, the Environmental Protection Agency (EPA) is assigned as the government proponent for water sector protection in HSPD-7, and this is reiterated in PPD-2[10], [11], [12].

Water and wastewater treatment is essential for ensuring clean drinking water, preventing disease, and protecting the environment[13]. Efforts at the beginning of the 20th century were primarily aimed at ensuring the purity of drinking water. In the late 1990s and early 21st century, protecting water sector resources from malicious actors was recognized as a security priority as awareness of vulnerabilities grew[14].

Particular concern about vulnerabilities in ICSs – the systems responsible for controlling CI operation (figure 1) – increased as experts identified the possibility of exploiting vulnerabilities remotely through the internet[1],[2]. ICSs are composed of multiple devices, including Supervisory Control and Data Acquisition (SCADA), Human Machine Interface (HMI) devices, Radio Terminal Units, Main Terminal Units, and Programmable Logic Controllers (PLCs), each of which have vulnerabilities. Increased use of common routing protocols to communicate with these devices exacerbates the issue of ICS cybersecurity[3].

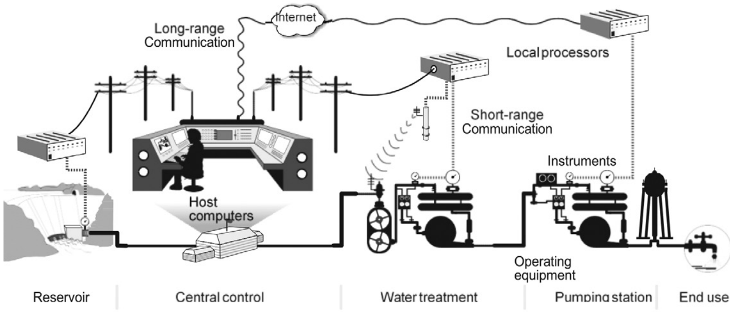


Fig. 1 Components of a control system in a water treatment and distribution facility (p.3) [31].

II. THREATS AND VULNERABILITIES IN ICSS

Many different CI sectors have been adversely affected through cyberspace. Disruption to air traffic control systems in Worcester, Massachusetts, in 1997 was caused by a teenager disabling part of the phone network. In 2000, a disgruntled contractor at the Maroochy Shire Water Treatment facility in Australia caused hundreds of thousands of gallons of sewage to flow into streams by controlling facility equipment from a laptop computer. In 2003, the Structured Query Language worm Slammer disabled safety monitoring systems at the Oak Harbor, Ohio, nuclear power plant for nearly five hours[15].

Recent findings by members of both the public and private sectors exacerbate the concern over the vulnerability of ICSs to attack. In 2016, the Industrial Control System Cyber Emergency Response Team of the Department of Homeland Security (DHS) found 700 security vulnerabilities in the 300 systems it analyzed[16]. Positive Technologies, Inc., a network security company, identified 197 vulnerabilities in ICS components of major manufacturers in 2017[17].

In late 2017, Schneider Electric, a major manufacturer of ICS components, revealed its components had been compromised by hackers. The malware, labeled Triton, was a zero-day (previously unknown) vulnerability in Triconex Tricon safety system firmware. The malware escalated privileges and then dropped a remote access tool (RAT) in the system to await further instructions. The RAT was intended to manipulate emergency shutdown processes to keep the system operational, allowing further invasive action. Triton continued system analysis and reconnaissance as it worked, exfiltrating information back to the source. The attacker, who was never identified, demonstrated an elevated level of sophistication[18].

In 2010, the malicious code known as Stuxnet was revealed as the cause of the degraded capability of the Iranian nuclear refinement facility at Natanz. Specifically, it attacked Siemens PLCs that controlled the centrifuges, causing them to spin at erratic rates[19]. This attack, which is widely considered to be the first confirmed act of cyber war, is believed to be an effort of the U.S. and Israel to thwart the Iranian nuclear weapon development program[20]. This initially generated a great deal of excitement in the IT community, but many members of the ICS sector believed the attack was not important to their operations, as it targeted centrifuges belonging to Iran, not U.S. infrastructure[1].

While cyber threats to CI in general have been more prevalent in the last two decades, there is a long history of attacks on the water sector. During World War II, the Japanese poisoned Soviet water sources with typhoid bacteria; Soviets flooded the area south of the Istra Reservoir near Moscow to slow the German advance in 1944; Israeli water infrastructure was attacked by Yasar Arafat's Fatah in 1965; neo-Nazis attempted to poison urban water supplies in the U.S. in 1972; and two Al-Qaeda operatives were arrested in 2002 with plans describing how to poison U.S. water systems[21],[22].

Fear of terrorist attacks, especially on water facilities and water supplies, increased in the 1990s and early 2000s, leading to formalized efforts to protect CI. In 1998, PDD-63 aligned federal agencies with particular infrastructure sectors to better coordinate protection efforts. PDD-63 established Information Sharing and Analysis Centers (ISACs) for public-private security cooperation to facilitate threat data sharing between the government and the private sector[10]. In response to the 2001 terrorist attacks, the Bush Administration passed the Public Health Security and Bioterrorism Preparedness and Response Act of 2002. It directed that vulnerability assessments of CI be conducted in each sector, allocated funding for the protection of water sector facilities, and increased penalties for attacks on water[23],[24],[10].

Water is a particularly vulnerable resource. Approximately 17 percent of the drinking water treatment facilities in the U.S. provide service to 92 percent of the populace[13]. This means a terrorist or other malicious actor targeting one of approximately 2,700 facilities could have an inversely proportional impact on public health and may be able to delay the detection of a compromise. One way to execute an attack is to introduce toxic substances through a service point (a fire hydrant, for example) via backflow. Backflow occurs when the pressure gradient of the water in the distribution system is overcome by a source with higher water pressure (figure 2). This can accidentally occur when backflow prevention devices, like check valves, fail due to wear or nonmalicious acts[25].

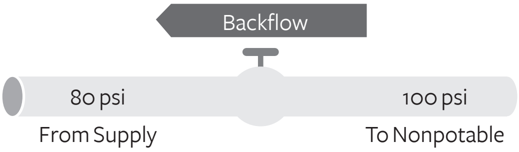


Fig. 2. Backflow due to Backpressure [25].

There are numerous examples of such accidental incidents, including: a glycol contamination of a West Virginia county health department due to a faulty check valve; the failure of a backflow preventer on an elementary school boiler feedline, causing drinking water contamination; and, ironically, an incident at a Boston hotel in 1974 where an American Water Works Association conference was being held (chromium entered the drinking water through a submerged inlet cross-connection to the building air conditioning system)[25].

Backflow devices are designed to prevent accidental contamination but can be defeated by a determined attacker and are not a reliable safeguard against malicious actors. Attacking through backflow only requires the actor to overcome the ambient water pressure with a pump capable of creating a higher pressure and injecting a contaminant. If injected correctly, a contaminant can be carried throughout the rest of the system from a strategic point. Using a highly toxic contaminant only requires a few gallons to be introduced to have widespread impact. Devices that detect contamination are not ubiquitous and could be modified to present a false negative to personnel monitoring them[22].

As shown in figure 3, a marked increase in attacks on water sector ICSs occurred from 1999-2012. Although some of the upward trends can be attributed to late disclosure or better detection of vulnerabilities, the increasing number of ICS equipment able to be accessed remotely makes it more vulnerable to attack. In the U.S., the connection of ICS components to the internet increased by 10 percent from 2017 to 2018[17].

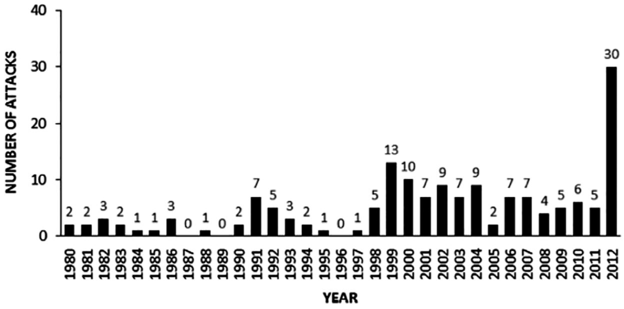


Fig. 3. Recorded trends on water CI (p.4) [21].

Further compounding the issue is the recent development of system control applications for mobile platforms. This improves the productivity and efficiency of local water facilities but exposes ICSs to cyber threats not previously encountered[26]. For example, Bolshev and Yushkevich found 147 vulnerabilities in 34 vendor applications used for managing ICS components[3]. Another research team, Rios and McCorkle, set out to find 100 security flaws in ICS software in 100 days but found 665 flaws in the same amount of time; 75 of the flaws were easily exploitable. The latter team's research was based on open source information from the internet[27],[1].

Terrorists are not the only ones who could exploit such ICS vulnerabilities. Cybercriminals may target the systems because they are less secure and serve as a means to another end. In 2006, a computer used for controlling water system devices in Harrisburg, Pennsylvania, was compromised and used for spam email distribution[28].

Feasible attacks on water sector assets through cyberspace are only one facet of a complex security problem. Interdependency between the water sector and other CI sectors amplifies the potential for catastrophic damage (see figures 4 and 5). The water sector depends on CI such as electricity to operate pumps, petroleum for backup generators, and the chemical sector for the disinfection of water. Conversely, other CI sectors need water for manufacturing, cooling equipment, and agricultural production.

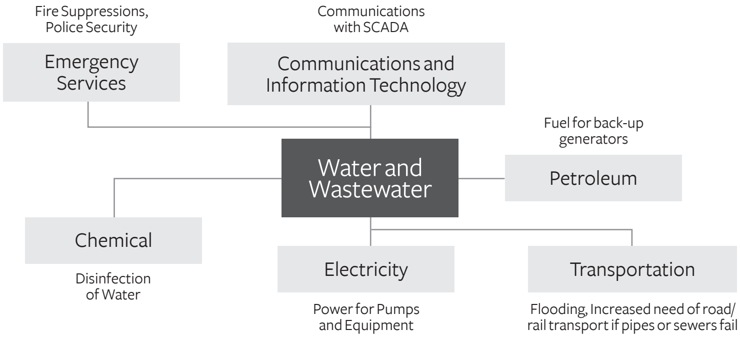

Fire Suppressions, Police Security
Emergency Services
Communications with SCADA
Communications and Information Technology
Fuel for back-up generators
Petroleum
Water and Wastewater
Chemical
Disinfection of Water
Electricity
Power for Pumps and Equipment
Transportation
Flooding, Increased need of road/ rail transport if pipes or sewers fail

Fig. 4. Dependence of the water sector on other CI (adapted from [21]).

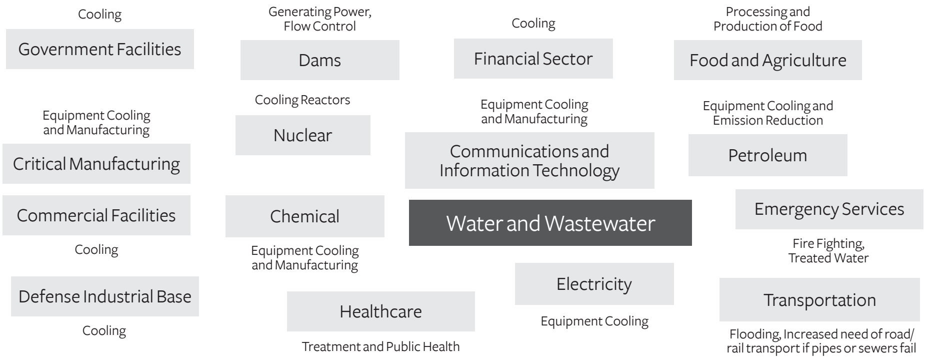

Cooling
Government Facilities
Generating Power, Flow Control
Dams
Cooling
Financial Sector
Processing and Production of Food
Food and Agriculture
Equipment Cooling and Manufacturing
Critical Manufacturing
Cooling Reactors
Nuclear
Equipment Cooling and Manufacturing
Communications and Information Technology
Equipment Cooling and Emission Reduction
Petroleum
Commercial Facilities
Cooling
Chemical
Equipment Cooling and Manufacturing
Water and Wastewater
Emergency Services
Fire Fighting, Treated Water
Defense Industrial Base
Cooling
Healthcare
Treatment and Public Health
Electricity
Equipment Cooling
Transportation
Flooding, Increased need of road/rail transport if pipes or sewers fail

Fig. 5 Dependencies of other CI on the water sector (adapted from [21], [38], [11], [33]).

Denial or disruption of water service can have cascading effects. For example, an uncontrolled release of a large volume of wastewater, as happened in Australia in 2000, could have a catastrophic effects on public health, environmental well-being, and commercial facilities[29]. Attacks on transport systems used to pipe water from sources to agricultural production sites could cause significant financial harm[24]. Catastrophic damage to water mainline pipes inflicted by opening and closing main gates too rapidly, causing a hammering effect, could collapse sections of pipe, immobilizing traffic and delaying emergency service response time. In addition, it could cause backsiphonage (figure 6).

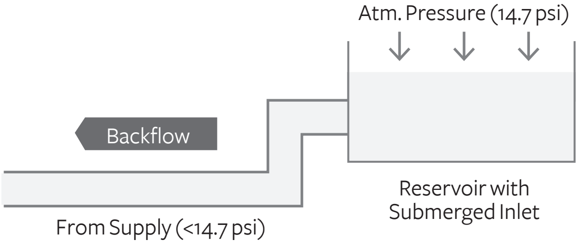


Fig. 6 Backsiphonage [25].

Backsiphonage is a type of backflow caused by a zone of negative pressure in a water system – if a cross-connection exists, atmospheric pressure pushing against a contaminant will force it into the water supply that contains zero negative pressure[25]. These types of attacks on distribution systems and other CI are a concern expressed by many in the sector [30], [31].

III. CHALLENGES TO SECURING THE WATER SECTOR

Securing facilities from cyber threats is challenging for many reasons. These include funding, the age of equipment, and education[1],[8],[31]. One of the main challenges water sector decision-makers face in securing their facilities is obtaining enough funding. Organizations' funding can vary depending on the size of their facilities and the number of people they service. Organizations with larger facilities have better opportunities to account for security in planning their budgets because they are better resourced than organizations with smaller facilities[2],[32].

Though it serves fewer people than a large urban facility, denial of service to a rural facility could have an equivalent impact by degrading public confidence in water supplies and causing other second and third-order effects. These could include pressure on local and state government to provide potable water for extended periods of time, decreased revenue from business and tourism, and disruption to agricultural and manufacturing operations[33],[27],[2],[21],[26].

Most of a local water facility budget is earmarked for operations and maintenance. The Congressional Budget Office noted that 67 percent of funding for water infrastructure is spent on operations and maintenance by state and local governments[8]. Such a limited budget for efforts other than infrastructure maintenance requires conscious decisions to invest in security by facility and sector leadership. Therefore, efforts by local water facilities to implement monitoring software or hardware security appliances may be limited or impractical.

Another factor in securing ICSs is the age of their equipment. Securing SCADA, PLCs, and HMIs is challenging because much of it is 20 to 30-years-old and designed with reliability and safety in mind, not security[1],[8],[31]. Systems initially used obscure, proprietary protocols for communication and were isolated from other early computer systems. "Security through obscurity" was a common approach[14]. The growing interconnections between previously isolated systems and the internet, along with the use of common protocols like Transmission Control Protocol / Internet Protocol, expose ICSs to previously unidentified threats[3]. Like the use of mobile computing platforms, using newer technologies to manage equipment designed before the advent of the internet poses risks.

Some gaps in ICS security exist due to a lack of awareness of cyber threats and their impact to operations. An example is the focus on cybersecurity of IT (corporate network) versus operations technology (OT) security. Engineers understand the process flow and operation of ICS components, but are often not aware of the vulnerabilities in their connected systems. Conversely, IT personnel often do not understand the unique nature of SCADA systems and how patching vulnerabilities might interfere with system processes[1]. Reviews by the National Cybersecurity and Communications Integration Center identified common network issues, such as the improper use of virtual machines; poor configuration of Virtual Local Area Networks; improper management of Bring Your Own Device implementations; and, where IT and OT efforts were combined, a lack of OT monitoring[34].

Staff at a local water facility in New England interviewed by this author corroborated many of the challenges noted in other reports and studies. They stated that their operation was largely dependent on revenue from the businesses and households they service. Much of their revenue has been reinvested in maintaining the infrastructure, while the majority of the budget allotted for wastewater treatment was spent on the removal and incineration of sludge. Most of the pump stations dated to the 1980s and remote connectivity to the system were limited but possible through the telephone system. While the operators and supervisors were highly skilled at their jobs, their understanding of how cyber threats associated with an IT network could affect their OT network was less developed.

IV. MANAGING RISK

In light of these vulnerabilities and challenges, steps can be taken to advance the security of the water sector. Some basic IT security practices, such as access control, physical security, and operations security, can be applied to ICS security. However, determining which security controls to select and evaluating their effectiveness requires a process or framework that holistically considers risk across the enterprise. An RMF allows an organization to assess risk in terms of impact to overall business operations, instead of assessing risks isolated to particular divisions within the organization. The NIST RMF, NIPP-RMF, and NIST Cybersecurity Framework for CI are three complementary frameworks a water facility can employ to facilitate risk mitigation in a cost-effective way[13], [4], [29], [35],[36],[37].

A. NIST RMF

The NIST RMF was developed to improve information security, strengthen risk management processes, and encourage reciprocity between federal agencies. It is a holistic approach to risk that incorporates IT security into enterprise risk management, emphasizing continuous monitoring and linking of risks to organizational and executive-level operational decisions. It is the successor to the Department of Defense Information Assurance Certification and Accreditation Process (DIACAP). DIACAP emphasized compliance with the patching of system vulnerabilities, whereas the RMF broadly considers many facets of information system security[6].

The NIST RMF consists of six steps (figure 7). Step one categorizes the system and information processed based on an impact analysis. The second step identifies a set of basic security controls based on categorization and tailored to the organization's assessment of risk. Step three implements the selected security controls, documenting how they were deployed. The fourth step assesses the security controls to determine effectiveness in meeting security requirements. Step five authorizes system operation based on determination of acceptable risk to operations, assets, individuals, and other organizations. The last step is continuous monitoring of controls for effectiveness, documentation of changes to the system or environment, and reporting of the security state to organization officials[38].

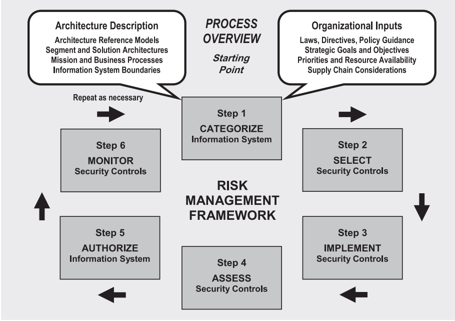

Architecture Description
Architecture Reference Models
Segment and Solution Architectures
Mission and Business Processes
Information System Boundaries
PROCESS OVERVIEW
Starting Point
Organizational Inputs
Laws, Directives, Policy Guidance
Strategic Goals and Objectives
Priorities and Resource Availability
Supply Chain Considerations
Repeat as necessary
Step 1 CATEGORIZE Information System
Step 2 SELECT Security Controls
Step 3 IMPLEMENT Security Controls
Step 4 ASSESS Security Controls
Step 5 AUTHORIZE Information System
Step 6 MONITOR Security Controls
RISK MANAGEMENT FRAMEWORK

Fig. 7 NIST RMF[4].

The NIST RMF is a baseline framework that can be applied to both governmental and non-governmental organizations[38]. The process can be applied to any type of IT system. It does not consider specific types of systems.

B. NIPP-RMF

The NIPP-RMF is specifically designed with CI in mind. Presented in the 2013 NIPP, it recognizes the importance of a public-private partnership and the differing constraints on private versus government organizations[5]. NIPP-RMF is broad in its application, accounting for dissimilar operating environments and both natural and man-made threats. It emphasizes the importance of information sharing to build resilience and improve threat reduction. Figure 8 provides an outline of its main components[5].

The NIPP-RMF complements other efforts, such as the Threat and Hazard Identification and Risk Assessment process conducted by regional and urban jurisdictions to establish capability priorities[5]. The CI community shares information and builds upon best practices and lessons learned to fill gaps in security and resilience through the RMF.

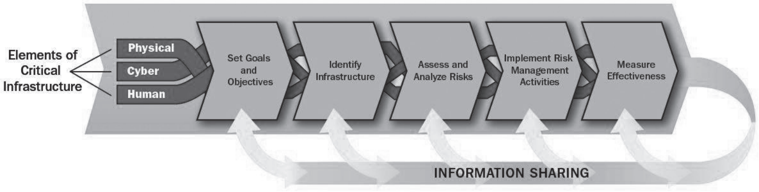


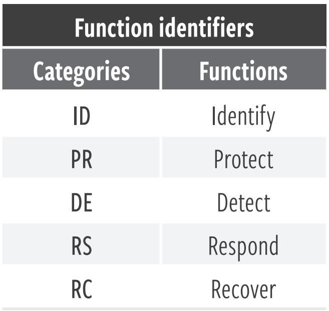
Fig. 8 NIPP-RMF [13].

The first step is set at the national level, with input from each CI sector. The second step includes identification of all assets, systems, and networks for continued operation, considering dependencies and interdependencies. Step three, assess and analyze risks, rely on the analysis of threats, vulnerabilities, and consequences. Information sharing is essential in this step. Step four, implementing risk management strategies, involves the prioritization of activities to manage risk based on costs and potential to reduce risk. The final step in the process measures the effectiveness of controls. Continuous monitoring is essential to the risk management process, as is informing leadership whether the controls in place are effectively mitigating risk[5].

C. NIST Cybersecurity Framework for CI

The Cybersecurity Framework for CI is a risk management construct developed specifically for CI cybersecurity by NIST and numerous stakeholders in the private sector. It is composed of three distinct sections, including the Framework Core, Framework Implementation Tiers, and Framework Profile[6]. The framework uses holistic business risks as drivers for cybersecurity activity instead of the compliance-related endeavors previously associated with cybersecurity[39]. Integrating cybersecurity with the overall business operations process informs decision-makers where they can best apply resources to enable operations.

The functions of identify, protect, detect, respond, and recover are part of the Framework Core. They provide a strategic view of the life cycle management of cybersecurity risk. The core provides a method for communicating industry standards, guidelines, and practices across the organization, from the strategic level to the operational and tactical levels. It identifies key categories and subcategories for each function and correlates them with existing guidelines and best practices for desired outcomes. The five primary core categories are shown in figure 9[6].



Function identifiers	
Categories	**Functions**
ID	Identify
PR	Protect
DE	Detect
RS	Respond
RC	Recover

Fig. 9 Function identifiers [6].

Framework Implementation Tiers define how an organization views cybersecurity risk and how it manages risk. They describe the level of management, from reactive to adaptive and agile. This permits an organization to "see" itself and determine how risks are managed. For instance, intrusion detection and response may have a well-developed process, while a natural disaster contingency may have little planned response action, providing the organization an assessment of agile in the first instance and reactive assessment in the second. Identifying differences between response levels informs the Framework Profile[6].

The Framework Profile represents the outcomes based on the business needs selected from the framework categories and subcategories. Profiles can be used by an organization to identify areas for cybersecurity improvement. Profiles can inform the current state of security and present the desired end state. Based on the gaps between current and end state profiles, the organization can assess risk and allocate resources based on what is most important for business operations[6].

Implementation of the framework is not without challenges. The Government Accountability Office (GAO) found that many CI sectors have not implemented the cybersecurity framework due to a lack of resources, lack of knowledge and skills to implement it, and regulatory and industry requirements preventing implementation. Some CI sectors had concerns over the disclosure of vulnerabilities or other priorities, such as physical security and direct support to customers. Some sectors perceived no cyber threat at all and believed that there was no need to use the framework[32].

While some of these arguments are relevant, they indicate a lack of knowledge of the framework's purpose and intent. The Cybersecurity Framework for CI clearly states[6]:

The Framework complements, and does not replace, an organization's risk management process and cybersecurity program. The organization can use its current processes and leverage the Framework to identify opportunities to strengthen and communicate its management of cybersecurity risk while aligning with industry practices. Alternatively, an organization without an existing cybersecurity program can use the Framework as a reference to establish one (p.4).

Addressing cybersecurity concerns within a limited budget with personnel who are primarily involved in operating facilities or performing IT functions is difficult at best. The framework maps to industry standards without dictating which ones a facility must use. How leadership applies the resources they have depends on the risks they identify and their perceived threat to business operations.

V. PRACTICAL TOOLS FOR ASSESSING RISK

Risk assessments are critical in determining where the greatest vulnerability and return on investment are for a facility. All three frameworks call for assessing risk. Several tools are available to water facilities at no cost to help organizations practically identify and mitigate risks. Some of these tools are automated programs that map the network to help operators understand the flow of data, while others are computer-driven queries that populate a spreadsheet with recommended best practices. Several of these tools are discussed below[40],[41].

The Cybersecurity Evaluation Tool (CSET) is free, downloadable desktop software that guides operators and system owners through a step-by-step guide to assess cybersecurity practices[40]. It correlates answers obtained through queries with accepted industry practices for securing networks. Data entered into the system is protected by the Protected Critical Infrastructure Information program; this enables private sector entities to pass information to DHS without fear of litigation or public disclosure[40].

The Vulnerability Self-Assessment Tool (VSAT) is a water sector-specific tool developed by the EPA to help water facilities identify the most vulnerable areas and find the most cost-effective measures to reduce those risks[40]. Like CSET, it is freely downloadable, but can be run from a web browser. Data is not retained by the EPA, protecting sensitive information about individual facilities.

A third tool is the Design Architecture Review (DAR) assessment, which reviews network architecture and security controls, looking at data flow, communication sharing, and proper communication channels[42]. The Network Architecture Verification and Validation (NAVV) assessment, another type of review, passively monitors data traffic to determine whether there are leaks across boundaries and identifies anomalous behavior[40]. Neither of these assessments requires connection to the OT or IT network at a facility.

National Cybersecurity Assessment and Technical Services is a team that can conduct penetration testing to test the security measures implemented by a facility. This is a valuable resource to determine whether measures put in place after a security review are effective, achieving step 5 of the NIPP-RMF[40].

The Cyber Resilience Review (CRR) is the sixth type of assessment freely available through DHS. It can be done as a self-assessment program or facilitated by DHS experts. It is designed to help organizations use the cybersecurity framework. The CRR addresses efficiency by balancing risks and costs, provides a roadmap by determining the best standard for an organization to use, and addresses the internal and external challenges of an organization[43].

The risk assessment tools outlined above are free of charge. As an example, VSAT can be used to assess risk and increase the security posture of a facility. Beginning with the choice of quantitative or qualitative method for assessing risk, it leads a user through specific questions about the water utility, including questions about assets, countermeasures, and threats. The current risk to the facility based on the threats/assets input and existing countermeasures is provided as an output. Improvement recommendations are presented after completing the baseline assessment and a cost/risk analysis is used to develop new packages of countermeasures that conform to existing budgets or can be executed over a period of time. Finally, the VSAT can generate analysis result reports developed using the inventories of assets, threats, and countermeasures.

The tool has a demonstration mode with prefilled data to enable new users to understand the relationship between different values and the impact on operations if a component fails or is attacked. Key parameters and areas where data are entered are outlined below.

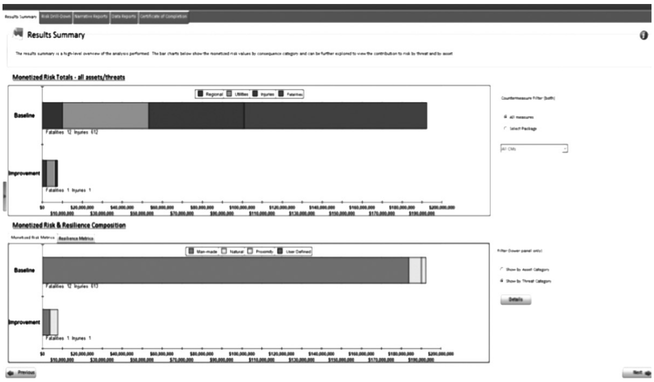
The Asset Selection screen is where facility-specific assets can be selected for analysis. The screen is prepopulated with common assets, such as generators, pumps, wells, instrumentation, and valves. Customization can be done by editing existing assets for system-specific items.

The countermeasures section of the VSAT allows user-defined countermeasures to threats to be entered. Similar to the asset selection, it is populated with common countermeasures. The countermeasure inputs, along with the asset inputs, form the baseline risk assessment for the facility. Unique inputs can be added to the countermeasure screen to tailor it to the water facility.

The Baseline Analysis performs analysis on one asset/threat combination at a time. It indicates the relative financial cost of a compromise. It queries the ability to reduce the consequence levels of an incident, given the ability to detect, delay, or respond. The system asks for the likelihood of occurrence and, combined with the previous responses, provides baseline risk and resiliency metrics.

Subsequent queries request potential improvements to existing countermeasures and the likelihood of damage if a vulnerability is successfully exploited. These queries provide results of cost savings and reduced likelihood of damage, expressed as percentages. These queries allow a facility to compare its existing security posture to its future posture if countermeasures are improved and displays this as a monetized amount of risk reduction.

Finally, the Results and Reports section summarizes the vulnerability assessment. The section can represent the data in a narrative format or as a chart. The section can also display the monetized risk metrics and resilience metrics of the assessment. The Results section may be used to drill down on the specific risks related to an asset/threat combination. Figure 10 shows the monetized risk output associated with the threats and vulnerabilities and other data input in the earlier portions of the query.



Results Summary

The results summary is a high-level overview of the analysis performed. The bar charts below show the monetized risk values by consequence category and can be further explored to view the contribution to risk by threat and by asset

Monetized Risk Totals - all assets/threats

Countermeasure Filter (both)

● All measures

○ Select Package

All CMs

Monetized Risk & Resilience Composition

Filter (lower panel only)

○ Show by Asset Category

● Show by Threat Category

Fig. 10 Results Summary [44].

On the whole, the water sector has completed more assessments to identify vulnerabilities than any other sector[42]. While this places water and wastewater facilities ahead of peer CI, the challenge of securing decades-old SCADA equipment remains.

VI. PRACTICAL WAYS TO IMPLEMENT AN ACTION PLAN

Based on the assessment results, decisions can be made regarding which areas are most important to address. In reality, a local facility will still have a small budget for security and may not be able to apply resources to some areas highlighted as a risk, nor have the operational capacity to maintain them over the long term. However, some security improvements can be made at a low cost.

Information sharing and coordination is an area where risk management gains can be made with minimal effort. Free information updates from organizations such as the Water ISAC (WaterISAC) are available for water facility managers to stay abreast of trends in cyber threats[44]. Coordinating with local emergency services, critical partners (such as electric service providers), and public health agencies prior to an incident can improve response and recovery operations[45].

Training, education, and coordination are first steps, but the implementation of software, hardware, and physical security requires finesse. OT and IT networks have similarities, but the specialized nature of ICS equipment sometimes prevents patching or other standard IT security measures from being implemented[7]. Updating ICSs by replacing old equipment in wholesale fashion is not feasible for most facilities[14]. Costs associated with expansive security software and hardware implementation are often prohibitive for local facilities[8].

Using technology such as preprocessors can be an inexpensive and effective way to reduce some common risks to water sector ICSs (figures 11 and 12). Researchers at the University of Louisville demonstrated this concept in 2012. A preprocessor is a security module built on a small circuit board that is placed before a field SCADA device with either a software interface at the HMI point or another board in the same location to allow control of the field unit. This does not require replacement of equipment being added in-line to existing architecture. A Gumstix® circuit board was used in this experiment at the cost of only a few hundred dollars[7],[48].

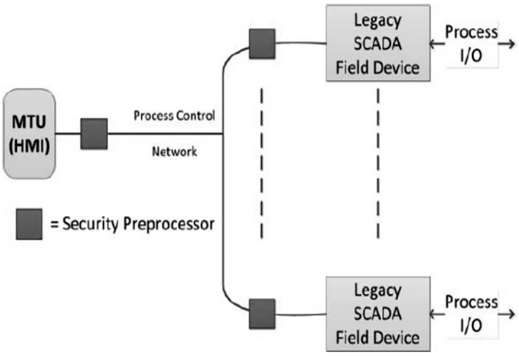


Fig. 11 Preprocessor integrated with ICS architecture [7].

The device provides authentication and authorization on behalf of the SCADA device. By configuring the Modbus protocol – a common protocol used in ICSs – to incorporate a connection request, challenge, and challenge-response, and incorporating Role Based Access Control (RBAC), users are only able to perform functions for which they have authorization (see figures 11 and 12). The device uses a simple operating system known as "OKL4" to reduce overhead. Further research by Schreiver indicates that a Bloom filter is a viable option for enforcing RBAC that limits the amount of bandwidth required to operate[7], [48].

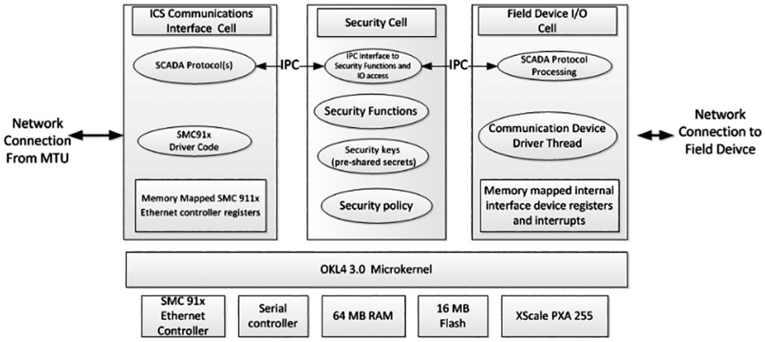

ICS Communications Interface Cell
SCADA Protocol(s)
IPC
SMC91x Driver Code
Memory Mapped SMC 911x Ethernet controller registers
Security Cell
IPC Interface to Security Functions and IO access
Security Functions
Security keys (pre-shared secrets)
Security policy
IPC
Field Device I/O Cell
SCADA Protocol Processing
Communication Device Driver Thread
Memory mapped internal interface device registers and interrupts
Network Connection From MTU
Network Connection to Field Deivce
OKL4 3.0 Microkernel
SMC 91x Ethernet Controller
Serial controller
64 MB RAM
16 MB Flash
XScale PXA 255

Fig. 12 Preprocessor architecture [7].

VII. FIELD IMPLEMENTATION

The implementation of the cybersecurity framework and the tools previously highlighted by water and wastewater treatment facilities has varied. In its February 2018 report on framework implementation by the GAO, the EPA reported it does not have the statutory ability to collect information on implementation of the framework by the water sector, and that it had no plans to implement a methodology to do so[32].

This perspective was not unique to the water sector. A dearth of information on framework implementation was ubiquitous across all 16 CI sectors[32]. The water sector is the most proactive of the CI sectors in leveraging assessment resources, however. From 2009 to 2014, 128 on-site assessments were conducted by the sector, which was double the number conducted by the next closest sector in the same amount of time[43].

Reasons for not leveraging security assessment tools at the local level included lack of awareness of tool availability, limited understanding of cyber threats to the facility or sector, lack of personnel to dedicate to conducting security risk assessments, reluctance to share sensitive information, and an absence of directives from higher echelons to implement risk assessments [32], [2]. The primary focus of the facilities is to provide the service which they are mandated to provide. While security was not entirely ignored, water reclamation and purification was prioritized over other activities. Time to dedicate to security considerations was limited[32],[52].

One local facility manager who was interviewed depended on the state to manage security concerns. The manager was unaware of WaterISAC or the tools available. While the importance of security was not misunderstood, daily operations had primacy.

In 2015, the EPA published the results of a pilot test of a contamination warning system (CWS) conducted jointly with five water utilities across the U.S. Its purpose was to examine detection of and response to drinking water contamination. Cybersecurity was an important component of the program, with an emphasis on the detection of contamination (with a minimum of false positives), operational reliability, and early detection to improve response time[32],[52].

The report highlighted the importance of communicating the value of the program to personnel, the impact to daily operations, and how it enhanced core job functions. Support from senior management, education of key leaders, and inclusive engagement across the staff were particular lessons learned. In the latter instance, it was discovered one pilot site did not engage its IT personnel and found the design of the information system to be infeasible because it conflicted with IT requirements. While the report focused on a CWS, the challenges of incorporating the multiple facets of a new process are applicable to instituting and assessing cybersecurity at the local level of the water sector[52].

VIII. CONCLUSION

The increasing number of ICS vulnerabilities identified by researchers and industry experts, coupled with continuing revelations about ICS compromises, emphasizes the importance of securing CI. The security of water sector ICSs is undeniably important in its own right, but is also important for other CI sectors. Water sector ICS security is necessary for safe drinking water, environmental safety, growing food, cooling equipment for businesses and hospitals, and manufacturing.

As the water sector ICSs increasingly leverage routing protocols and automation equipment to reduce manning requirements and increase productivity, the potential for system vulnerability exploitation will increase. Evolving threats to water CI through cyberspace place an increased burden on local water facilities to protect their resources. They are especially challenged as they often do not have the training or equipment to identify and mitigate the risks to their systems. They may be able to apply only limited risk reduction measures by allocating personnel, funding, and materiel against specific threats.

Defending water sector ICSs from attack cannot be viewed as a separate function relegated to IT personnel or system operators; rather, it must be viewed as part of a whole-of-business approach to risk. Leveraging the NIST RMF, NIPP-RMF, and Cybersecurity Framework for CI as methodologies for categorizing cyber risk will aid organizations in holistically viewing risk across the enterprise. These RMFs aid organizations in allocating resources to achieve the greatest returns on their investments.

Several assessment tools exist to help executives and operations personnel apply the principles of the NIST RMF, NIPP-RMF, and Cybersecurity Framework for CI. Some, like CSET, CRR, and VSAT, can be performed at a local level without external support. Others, like NAVV and DAR, are facilitated by DHS at no cost to the local facility; these tools help identify vulnerabilities on the network and areas for improving network security. Some cost-effective measures, such as installing preprocessors at legacy water sector facilities to prevent unauthorized system access, can be implemented.

Using the NIST RMF, NIPP-RMF, and Cybersecurity Framework for CI with best network security practices, local water sector leaders can advance the security of their facilities while preserving the operational purpose of their facilities.

ACKNOWLEDGMENT

I would like to thank Dr. Roxanne Everetts for her mentorship and guidance, Dr. Chen for reading my paper and providing input, and my wife Erin and les trois soeurs for their patience and support.

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