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REVIEW

A process approach to quality management doubles NEON sensor data quality

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Abstract

1. A quality management system is critical for ensuring that the data and services provided by an organization meet the needs of its mission. With a mission to collect long-term open-access ecological data to better understand how US ecosystems are changing, the National Ecological Observatory Network (NEON) is a highly standardized measurement network distributed across the United States and Puerto Rico collecting data on the biosphere and its interfaces with the pedosphere, hydrosphere and atmosphere.
2. In order to achieve high-quality, comparable data across the network, a quality management system was developed by applying the seven ISO 9001:2015 principles of quality management: *customer focus*, *leadership*, *engagement of people*, *process approach*, *improvement*, *evidence-based decision making* and *relationship management*. The resultant system is integrated throughout NEON's organizational structure with an approach that connects people and operational processes throughout the data life cycle (*process approach*).
3. We describe the system with respect to sensor data (automated measurements), demonstrating its effectiveness through examples, lessons learned and a continuous history of improvement towards quality goals, including a doubling of data quality in NEON's meteorological and soil datasets since 2015 and substantial gains in other sensor datasets.
4. Owing to a focus on quality management principles and particularly the interconnectedness of human and information systems, NEON's quality management system can serve as a model for networks with a variety of organizational structures and sizes.

KEYWORDS
data quality, National Ecological Observatory Network, quality assurance, quality control, quality management, sensor network

1 | INTRODUCTION

Environmental measurement networks present the opportunity to understand broad-scale patterns and processes by synthesizing information collected across many discrete locations. One of the largest single-provider ecological measurement networks in the world, the National Ecological Observatory Network (NEON) harnesses a high level of standardization to collect consistent, comparable, high-quality data across many sites and over many years in order to better understand how US ecosystems are changing. Achieving and maintaining a highly standardized network presents many challenges. Not only is NEON large and diverse in the number and type of distributed measurements, but also in organizational structure and operational processes. Objectives and activities must be coordinated, and procedural updates, problems and solutions must be communicated across a distributed, multi-faceted workforce. Meeting these challenges requires a quality management system (QMS) that connects people, information and operational processes throughout the data generation chain, from sensor preparation through field data collection, data processing and publication.

Data quality is the degree to which data are fit for use by data consumers (Wang & Strong, 1996). Standardization has long been recognized as essential for meeting quality requirements of distributed environmental measurements. Beginning in the 18th century, meteorological societies developed standardized, calibrated instrumentation and regulated observation procedures (Kington, 1974). Organizations like the World Meteorological Organization (WMO; established 1950) carry this work forward today, publishing technical standards and guidelines for generating high-quality, comparable sensor measurements (e.g. WMO, 2008). Since the late 1900s, cross-disciplinary networks such as FLUXNET (Baldocchi et al., 2001) and the Long Term Ecological Research program (LTER; Hobbie et al., 2003) have harnessed standardization to share and synthesize data collected at independently run stations to understand large-scale and long-term ecosystem dynamics. Individual site investigators coordinate on measured and derived quantities, general processing steps and data formats. NEON builds off of these historical efforts, incorporating standards and guidelines from relevant scientific communities into its design and operational requirements and additionally unifying sensors and measurement infrastructure, collection and maintenance protocols and processing algorithms.

Beyond a foundation of standardization, the vast majority of modern-day scientific literature concerning quality in sensor networks has been devoted to detecting and rejecting poor-quality outcomes (quality control; QC), and largely in post-processing (e.g. Campbell et al., 2013; Pastorello et al., 2014). As a result, automated data QC methods have become quite sophisticated, involving numerous algorithms (e.g. Hubbard et al., 2005; Leigh et al., 2019), objective choice of test thresholds (e.g. Durre et al., 2008), and decision structures for data flagging (e.g. Smith et al., 2014). However, data QC is a vital but small fraction of an effective QMS. To achieve acceptable data quality, controls (QC) must be applied throughout the data generation chain and then verified to work effectively over time (quality assurance; QA). A QMS provides a structured framework of interlinked QC and QA processes that collectively ensure the final quality of a product or service. Yet, there is comparatively very little scientific literature on QMS frameworks for sensor networks and how they are applied effectively and efficiently at the network scale (although some examples exist, e.g. Fiebrich et al., 2010; McCord et al., 2021).

This paper aims to address this gap, demonstrating how a process approach to quality management yields an integrated, end-to-end QMS that enables achieving standardized, high-quality data across a national-scale network. Our approach draws heavily on quality management principles developed in industry, which has long addressed the challenge of meeting quality requirements across large and diverse organizations. The International Organization for Standardization (ISO) was initially established out of efforts to unify industrial standards in the mid-20th century and provides seven foundational principles applicable to any organization: *customer focus*, *leadership*, *engagement of people*, *process approach*, *improvement*, *evidence-based decision making* and *relationship management* (ISO, 2015a). NEON's QMS focuses on these ISO principles rather than specific tools or techniques in order to create an evolving system that continuously improves and maintains relevance through time. It also extends the applicability of NEON's QMS to networks narrower or larger in scope and with different organizational structures. We begin with an overview of different approaches to environmental measurement networks in order to set the context in which NEON's QMS operates. We then provide the general framework of the QMS, followed by descriptions of each QMS component with examples, lessons learned and/or metrics that demonstrate its effectiveness. Finally, we discuss overlap with and relevance to other networks and future improvements.

2 | ORGANIZATIONAL APPROACHES OF ENVIRONMENTAL MEASUREMENT NETWORKS

Environmental measurement networks have a wide range of organizational structures that fall on a spectrum from bottom-up to top-down. Bottom-up networks consist of a coalition of independently managed stations, whereas top-town networks are directed by a single entity that manages all sites and data infrastructure. Organizational structure has implications for the scope and distribution of QMS components (Table 1), and also plays a significant role in research capabilities and culture, both of which propagate to the network's quality programs (Peters et al., 2014).

2.1 | The National Ecological Observatory Network

Although much of the QMS we describe in this paper applies to all of NEON's measurement systems, we focus here on the sensor systems, which collect automated measurements. Sensors at

TABLE 1 Characteristics of bottom-up, hybrid and top-down measurement networks

Characteristic	Bottom-up network	Hybrid network	Top-down network
Example networks	FLUXNET (Baldocchi et al., 2001); AmeriFlux (Novick et al., 2018); LTER (Hobbie et al., 2003)	ICOS (Franz et al., 2018); TERN (Cleverly et al., 2019)	NEON (Schimel et al., 2007); USCRN (Diamond et al., 2013)
Sensor preparation (*selection, configuration, calibration*)	Site or member specific. Some centralized resources may be available (calibration fixtures and loaned sensors)	Site or member specific, adhering to minimum requirements. Centralized resources may be available	Performed according to requirements by centralized personnel
Field data collection and maintenance (*measurement methods, installation and maintenance procedures*)	Site specific based on individual research priorities	Optimized for each site while adhering to minimum requirements	Unified set of operational requirements and standard operating procedures across sites
Data processing (*Algorithm and software choices, processing procedures*)	Site or member specific. Some higher-level processing may be performed centrally	Site or member specific, adhering to minimum algorithm requirements. Higher-level processing performed centrally	Centralized data processing from raw data to all higher-level data products
Monitoring, problem tracking and issue resolution	Handled by each network member	Mostly handled by each network member. Automated alerts may be issued centrally if data stream to a central facility	Shared and coordinated between network headquarters and field teams
Assessment and Improvement	Individual network members self-assess and self-prioritize improvements. Possibly some iterative quality assessment with network management	Centralized network-wide evaluations lead to improvement themes to be addressed individually by network members	Major assessment efforts and improvement themes directed centrally, with guidance from internal and external advisory bodies

NEON's 47 terrestrial sites measure soils, meteorology, surface–atmosphere exchange, atmospheric chemistry and phenology (Metzger et al., 2019). Sensors at NEON's 34 aquatic sites measure physical, biological and chemical properties of water and a basic suite of meteorological measurements. Together, about 68 different types and over 8,000 total sensors are deployed at any one time across the network, producing upwards of 75 data products hosted on the NEON Data Portal (https://data.neonscience.org/). Both terrestrial and aquatic sensor suites are collocated and coordinated with NEON's airborne remote sensing observations (Musinsky et al., 2022) and in-situ sampling bouts (Parker & Utz, 2022). Furthermore, a mobile deployment platform can be deployed in rapid response to natural phenomena and can be requested by the research community for separate investigations. Supporting NEON's measurement network are approximately 170 personnel based out of NEON headquarters in Boulder, CO, and 130 permanent staff based out of 17 field offices dispersed across seven time zones throughout the United States, including Alaska, Hawaii and Puerto Rico.

Requirements are the backbone of NEON's top-down architecture that fully integrates the sensor systems, resulting in standardized observations designed for inter-site comparability and analysis of feedbacks across disciplines, spatial and temporal scales. This is achieved through decomposing the scientific objective (here: addressing grand-challenge questions in the environmental sciences; National Research Council, 2000) into requirements for architecture, hardware, software and operations (Metzger et al., 2019). Pre-operational planning and setup of the network has already occurred according to these requirements, including critical QA elements such as siting and exposure, instrument selection and engineering design, which were verified during the observatory commissioning process and are not covered here. Some requirements are routinely checked during nominal operation and are noted throughout remaining sections. A list of documents with expanded details of NEON's quality system are provided in the supplemental material.

3 | FRAMEWORK OF NEON'S QUALITY MANAGEMENT SYSTEM

The seven ISO 9001:2015 principles of quality management (ISO, 2015a, 2015b) guide both the design and evolution of NEON's QMS (Table 2). The combined application of the principles is also expressed in the Plan-Do-Check-Act cycle (Taylor et al., 2014), an iterative cycle to control and continuously improve operational processes and products. While the Plan-Do-Check-Act cycle is evident in much of NEON's QMS, we refer to the principles themselves (*in italics*) as they are demonstrated throughout the remainder of this

TABLE 2 The seven ISO 9001:2015 quality management principles, their ISO statements (ISO, 2015a), and application to environmental measurement networks

Principle	ISO statement	Application to environmental measurement networks
Customer focus	The primary focus of quality management is to meet customer requirements and to strive to exceed customer expectations	Create confidence in the data and services by following accepted standards and best practices for collecting, processing, and serving data. Solicit and respond to user (i.e. customer) feedback
Leadership	Leaders at all levels establish unity of purpose and direction and create conditions in which people are engaged in achieving the organization's quality objectives	Promote data quality as a network goal. Organize people such that goals and strategies propagate across dispersed field teams and centralized personnel. Provide training and tools that facilitate knowledge transfer and efficient use of time and resources
Engagement of people	Competent, empowered and engaged people at all levels throughout the organization are essential to enhance its capability to create and deliver value	Distribute quality-related procedures and training among all roles (e.g. technicians, scientists, software developers, managers). Define pathways to communicate issues and make improvements in every role
Process approach	Consistent and predictable results are achieved more effectively and efficiently when activities are understood and managed as interrelated processes that function as a coherent system	Understand and take advantage of how materials, information and operational processes are connected throughout the data generation chain. Safeguard and monitor their integrity and establish robust connections between them
Improvement	Successful organizations have an ongoing focus on improvement	Create processes that continuously identify, prioritize and act upon opportunities for improvement
Evidence-based decision making	Decisions based on the analysis and evaluation of data and information are more likely to produce desired results	Generate performance metrics for critical operational processes and data quality (e.g. maintenance frequency, data flagging rate, user satisfaction). Use performance metrics along with information from other trusted organizations and the scientific literature to inform assessments and improvements
Relationship management	For sustained success, an organization manages its relationships with interested parties, such as suppliers	Identify and communicate with internal and external stakeholders (e.g. suppliers, data users, internal departments) to ensure awareness and buy-in of changes, problems, and solutions. Invite collaboration (e.g. through working groups, open-source software) to identify and enact improvements

paper to show how they translate into a successful QMS for a large-scale environmental measurement network.

NEON's QMS is integrated within its organizational structure. Quality-related processes are distributed among NEON departments (*engagement of people*) and are connected by materials and information exchanged between them (lower portion of Figure 1; these are discussed in detail in subsequent sections). Managing connections between departments and processes is a key aspect of NEON's *process approach*. Centralized issue management routes and tracks requests, problems and other communication within and across departments and from the user community. Centralized configuration and version management applies technical and administrative direction over components and operational processes in order to protect their integrity and safeguard standardization (Shipwash, 2019). Components such as instruments, site configurations and drawings as well as documentation such as protocols and procedures are identified and tracked through all phases of the life cycle. Changes are thoroughly vetted via stakeholder review and approval (*relationship management*) and a complete history is maintained. The terms 'configuration-managed' and 'version-controlled' in this paper refer to components and documentation managed in this manner.

While the centralized issue management and configuration and version management systems form the technical backbone to connecting departments, NEON's decision-support framework (upper portion of Figure 1) forms the strategic backbone. It is a two-way, hierarchical process that unifies goals and strategies across the observatory (*leadership*) and empowers groups to make decisions and develop coordinated solutions appropriate to their scope (*engagement of people*). At the base of the hierarchy are topic-specific integrated product teams (IPTs) that bring together small groups of stakeholders to manage cross-departmental observatory functions (*relationship management*). For example, NEON's Configuration and Design IPT includes representatives from the Science, Instrumentation, Field Science, Field Support, and Quality Assurance departments to oversee physical changes such as site layout adjustments. Budgetary needs or proposed changes that exceed an IPT's scope are elevated to the Operations IPT, which is a leadership team spanning all departments in order to ensure that the needs and goals of the entire observatory are considered and that major initiatives are coordinated (*leadership*). The Observatory Director guides major initiatives and/or changes in observatory scope and budget, with additional oversight by

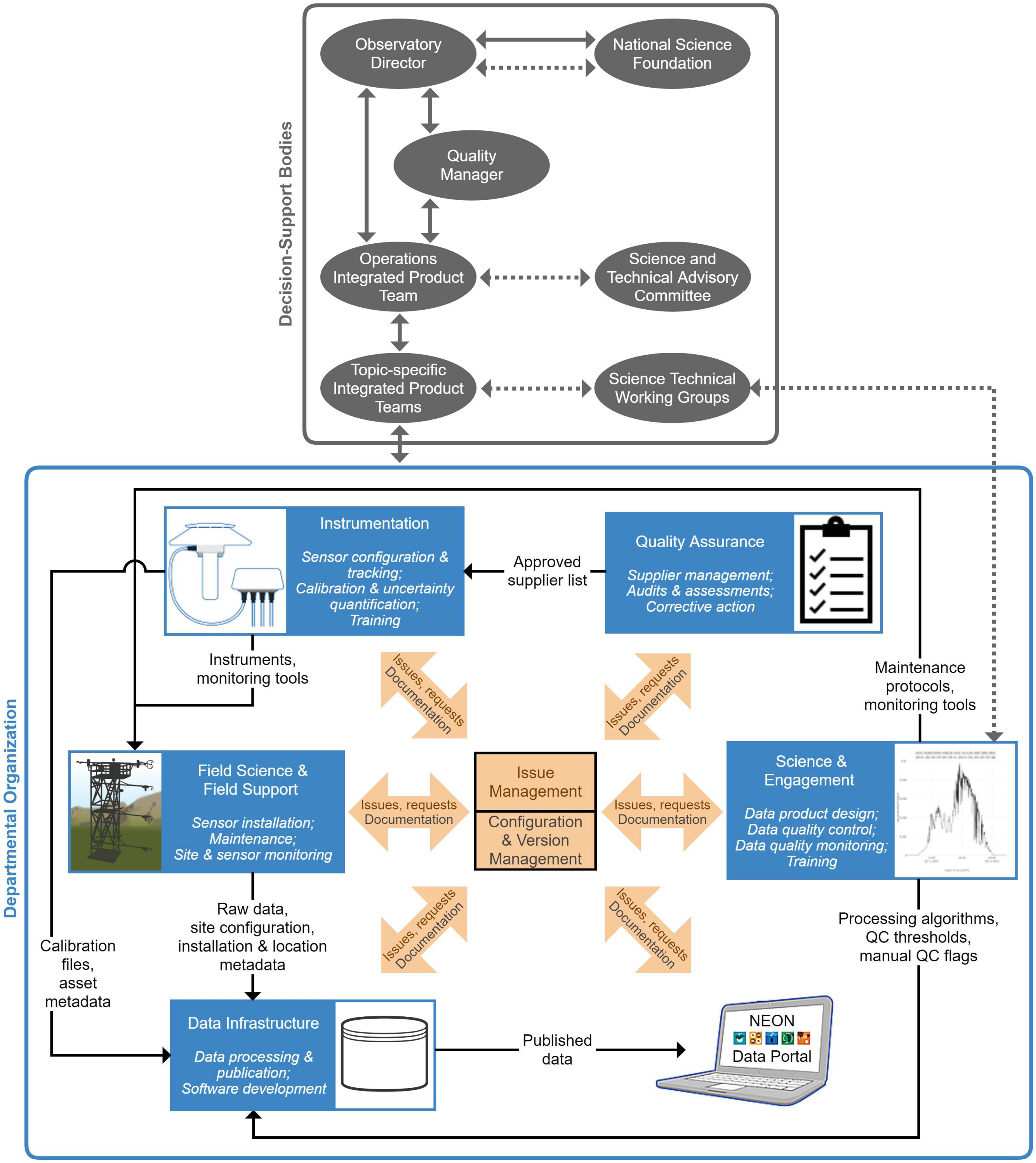

FIGURE 1 NEON's departmental organization (lower portion) and decision-support framework (upper portion). Blue boxes with white text show departments and their quality-related functions. Black arrows and text depict the flow of quality-related materials among departments. Centralized issue management and configuration and version management systems are shown in light orange with brown and grey text respectively. Wide arrows with the same colour scheme depict how these systems centralize their functions. The upper portion shows NEON's hierarchy of decision-support bodies that bridges departments as well as the external scientific community to enable a coordinated approach to achieving quality goals. Decision bodies and decision flow are in grey ovals and arrows respectively. Dashed arrows depict non-binding input and advice.

NEON's Quality Manager who directs audits and assessments to review performance and ensure the overall effectiveness of the QMS (*evidence-based decision making, improvement*). Adjacent to these decision-making bodies are advisory groups appropriate to each level made up of external experts and stakeholders that provide input and advice on user community needs and best practices (*customer focus*, *relationship management*). These include Scientific Technical Working Groups (TWGs; see Section 4), NEON's Science and Technical Advisory Committee, and at the highest level the National Science Foundation.

The following sections describe the QMS processes involved in the observatory functions and connections displayed in Figure 1.

4 | LEVERAGING THE SCIENTIFIC COMMUNITY IN QUALITY MANAGEMENT

The scientific community contributes to NEON's QMS in several ways including serving on review boards and advisory groups, submitting feedback directly via NEON's data portal, participating in surveys, and discussing issues and improvements with NEON staff at workshops, conferences and other events that reach over 5,000 people per year (*customer focus*, *relationship management*) (A. Crall, unpublished data). One of the most impactful ways that NEON leverages the scientific community in quality management is through Technical Working Groups. NEON has over 20 TWGs organized around various topics (e.g. surface–atmosphere exchange, soil sensors). NEON scientists often directly consult with TWGs, and TWG recommendations feed into the IPT decision-making process (Figure 1).

TWG objectives include advising NEON on technical and methodology issues as well as priority areas and solutions for improving data accessibility, usability and quality despite time and budget limitations (*customer focus*). As an example, NEON sought input from the Soil Sensor TWG on the most desirable treatment of data collected by an early version of the throughfall precipitation sensor which was prone to jamming, making it difficult to distinguish dry periods from a jammed sensor (Figure 2). In addition to targeted advice, TWGs also serve as a direct injection point for broader scientific community endeavours into NEON, maintaining NEON's relevance and responsiveness to evolving scientific questions and priorities (*customer focus*).

5 | SENSOR PREPARATION

Sensors are the source of all of NEON's instrumented data products. Critical attention is therefore paid to sensors well before they are deployed to the field, including the management of suppliers, configuration and tracking, calibration and validation.

5.1 | Supplier management

NEON's supplier management process, directed by the Quality Assurance Department, defines the requirements for the qualification of suppliers, including those that provide sensors and components (*relationship management*). Quality requirements flow to suppliers through a procurement statement of work. Upon approval, suppliers are added to a critical supplier list and assigned a risk classification. Review and re-qualification occur every 1–3 years depending on risk classification, and issues are addressed using NEON's corrective action process (see Section 8.3). One lesson learned in refining supplier management was the need for recurring dialogue with suppliers in order to prepare for changes such as firmware upgrades and phasing out of sensor

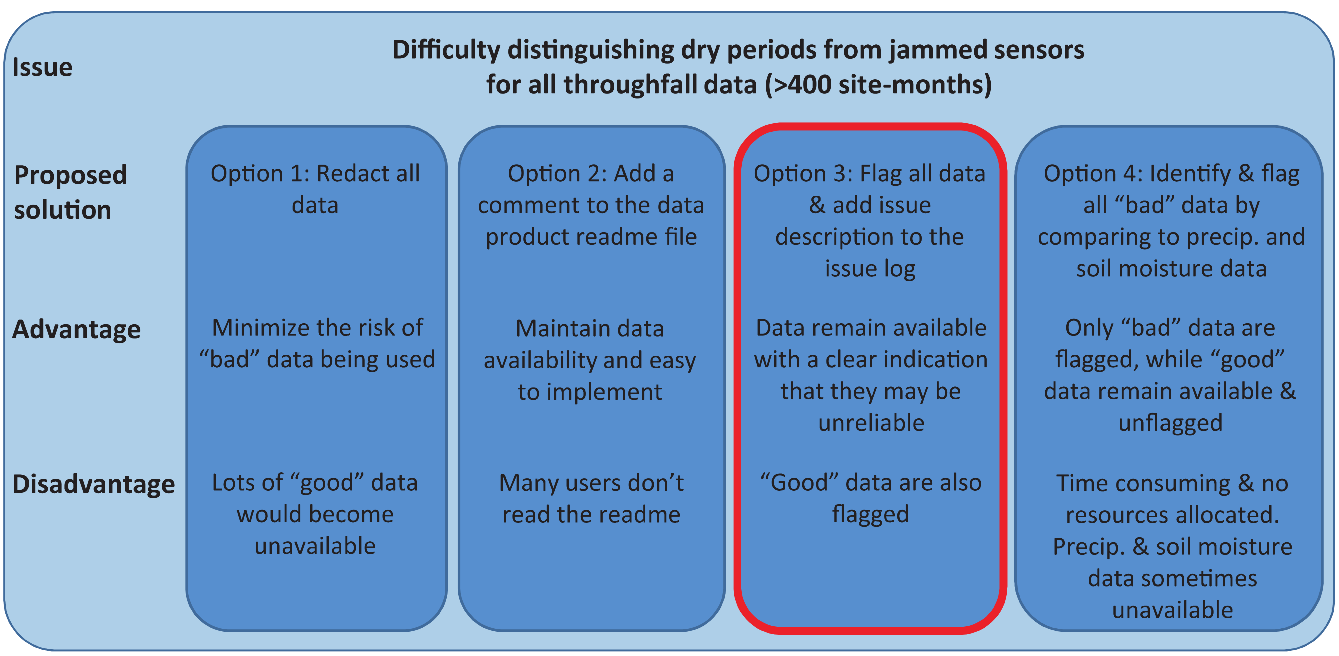

FIGURE 2 Options discussed with a technical working group to mitigate a quality issue in published data. The TWG recommended (and NEON adopted) the solution outlined in red.

models. A sensor obsolescence strategy to address the latter is currently in development (see Section 10).

5.2 | Sensor configuration and tracking

To safeguard basic measurement integrity, the Instrumentation Department inspects and configures all sensors prior to shipment to the field (*process approach*). The configurable options are researched, selected and controlled via the configuration management process in order to capture measurements that fulfil NEON requirements. Sensors are tracked throughout their life cycle using a small memory chip embedded in each sensor cable that stores the sensor's unique identifier, the data expected from the sensor, and other important metadata used by the data acquisition system at each site to identify and validate the connected device (*process approach*).

5.3 | Calibration and validation

Routine calibration and validation of instruments ensures that sensors meet performance requirements throughout their lifetime (*process approach*). NEON's in-house metrology laboratory within the Instrumentation Department performs these functions, meeting ISO requirements for testing and calibration laboratories (ISO, 2017).

During calibrations, all traceability, uncertainties and performance for sensor measurements are recorded and evaluated against requirements (Csavina et al., 2017). Approximately 8%–10% of sensors and dataloggers are removed from circulation each year for failing requirements, exemplifying this critical quality control mechanism and the need for robust supplier management. For sensors requiring field calibration, the metrology laboratory provides version-controlled protocols and training materials for the Field Science department (*relationship management*). Calibration activities result in machine-readable files that contain inputs for processing algorithms to convert raw readings to calibrated measurements and/or generate uncertainty estimates and quality flags (see Section 7).

6 | FIELD DATA COLLECTION AND MAINTENANCE

Operations become dispersed at great distances as sensors are deployed to the field. Maintaining standardization and adherence to requirements across a national-scale network thus requires strong links and feedbacks between dispersed field teams and centralized personnel and resources, including training, documentation and data systems for sensor installation and maintenance.

6.1 | Training

Training ensures competency of staff (*leadership*) and improves measurement consistency by reducing variation in the implementation of procedures (*process approach*). Field Science staff are trained using a centralized, standardized and version-controlled curriculum consisting of self-guided modules, standard operating procedures (SOPs), hands-on instruction (Figure 3), performance-based and written assessments and an annual in-person training with headquarters staff and external researchers. Weekly remote meetings, an online forum, training centre and sensor information library keep field staff up to date on new procedures and training materials and allow for collaborative learning and problem solving (*engagement of people*, *relationship management*, *improvement*).

Of the many lessons learned in refining the training process, a collaborative approach that joins together subject matter experts in the Science & Engagement and Instrumentation departments with Field Science staff stands out as the most critical for developing useful training materials (*engagement of people*). Field staff understand how to integrate tasks into an effective workflow and are early detectors of implementation issues that impact the availability and quality of data. One outgrowth of this collaborative approach was the development of prioritization hierarchies (i.e. guidance on what

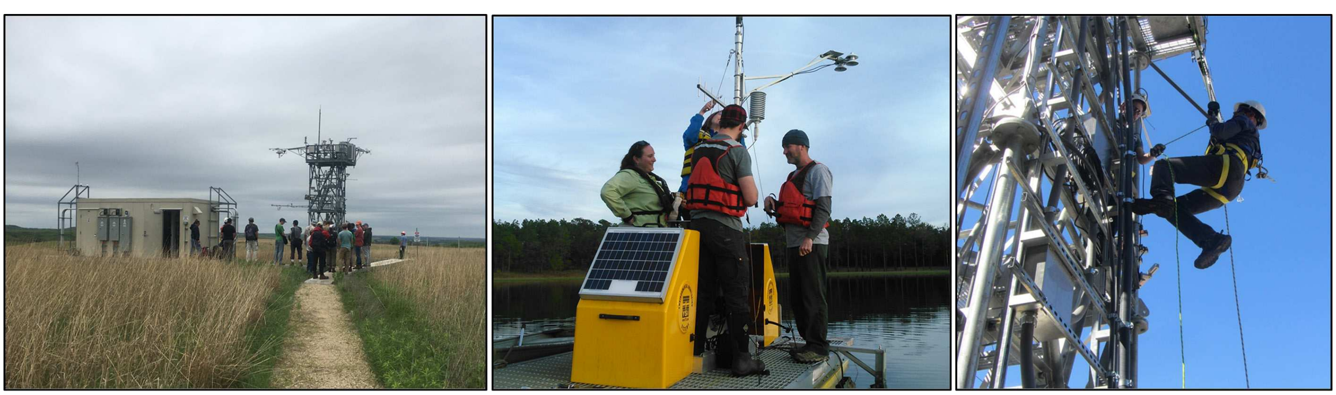

FIGURE 3 Field science training at Konza Prairie site in Kansas (left); instrumented buoy training in Florida (centre); and tower fall protection training at NEON Headquarters in Boulder, Colorado (right).

to focus on when not all tasks can be completed during a site visit—see Section 6.3). This challenged subject matter experts to think about the whole system and not just the individual components (*process approach*).

6.2 | Sensor installation and location metadata

Accurate metadata on a sensor's physical location on the geoid and its spatial relationship to other sensors, to various degrees of precision, is critical for many environmental analyses. For example, hydrologic analyses of groundwater flow direction and magnitude within a NEON aquatic site require centimetre-scale horizontal and vertical distances between pressure transducers. NEON sensors and infrastructure are installed according to tolerance requirements that trace all the way back to NEON's scientific objectives (Metzger et al., 2019). To achieve and maintain these tolerances and record locations to the required precision, Field Science staff follow version-controlled SOPs detailing sensor installation, physical verification and geolocation recording (*process approach*).

In addition to physical installation, each sensor is virtually installed by linking its unique identifier to that of a location in a relational database. The layout of the entire network is represented by a hierarchy of locations that represent its structure (e.g. domain → site → tower → measurement level → boom arm → sensor). Each location is associated with properties used to validate and restrict sensor installation according to the site design as well as store important metadata for processing and dissemination, such as a complete history of its geolocation (*process approach*). Accommodating changing site configurations and sensor geolocations in metadata storage, processing and publication has been an important lesson learned.

6.3 | Maintenance

Routine preventive and corrective maintenance are critical to maintaining consistent instrument performance and sensor uptime across the network. Preventive maintenance activities and their frequency are detailed in version-controlled SOPs so that they are applied consistently by distributed Field Science staff (*process approach*). Corrective maintenance is conducted by Field Science and Field Support staff in consultation with subject matter experts across NEON via the centralized issue management system (*engagement of people*). Before arriving on-site, technicians remotely view sensor values, diagnostics and automated monitoring reports in order to plan maintenance activities and prepare needed supplies (see Section 8). Depending on corrective maintenance needs (instrument failures, etc.) and environmental conditions, it is often not possible to perform the full suite of preventive maintenance activities. In this scenario, technicians use a prioritization hierarchy (Figure 4) to complete the most important maintenance in the time available. The prioritization logic aims to minimize the overall negative impact to NEON's scientific objectives (*leadership*), taking into account the redundancy of a measurement, risk of failure and the scope of impact of a particular maintenance task (*process approach*).

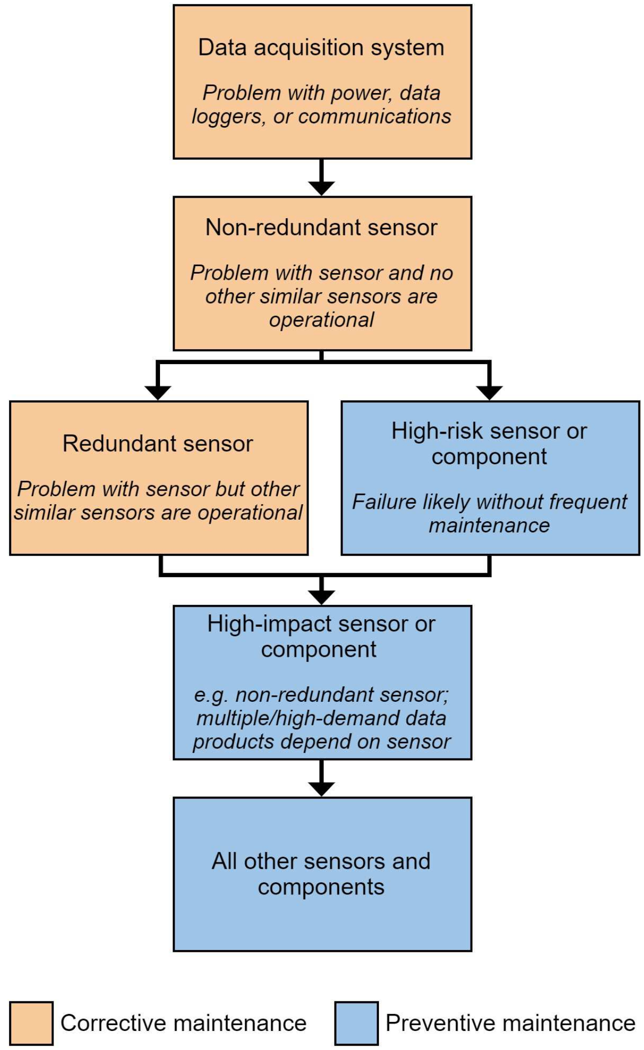

FIGURE 4 General prioritization hierarchy for conducting corrective and preventative maintenance with limited time. Tasks nearer to the top are higher priority. The hierarchy is filled with specific sensors according to the site design.

7 | DATA PROCESSING

Raw sensor data streaming from field sites to NEON headquarters requires processing to yield products useful for research. Successful utilization of NEON's data products highly depends on a design that fulfils user needs, robust software to produce them and serving them in a manner that facilitates their use.

7.1 | Data product design and quality control

Data products are designed by scientists in the Science & Engagement department according to established scientific methods and in consultation with scientific TWGs and other experts (*customer focus*, *relationship management*). The algorithms and processing steps, including uncertainty estimation and quality control for each data product are detailed in a version-controlled Algorithm Theoretical Basis Document (ATBD) and published with the data, informing data reliability and applicability, and allowing for more confident use (*customer focus*).

Data products undergo a suite of automated QC tests that assess and communicate the operational validity of each reported value. Most data are subjected to a generic suite of tests (Hubbard et al., 2005) at the original measurement frequency, joined by additional tests specific to the instrument or conditions of measurement. As data are aggregated into averages (e.g. 30 min) for publication, so are the results of QC tests. Quality metrics summarize the results of individual QC tests over the averaging interval and a final quality flag summarizes all quality metrics into a binary 'good' versus 'suspect' indicator for each published record (Smith et al., 2014). A manual override of the final quality flag is available for issues that escape automated detection (see Section 8.2). These multi-level indicators of data quality allow for propagation of quality information into higher-level data products and also aid efficient identification and tracing of poor-quality data to their root cause (*process approach*).

7.2 | Software development

NEON's software systems support many internal and external stakeholders, each identifying enhancements and adjustments to improve the quality and usability of NEON data. To effectively handle multiple simultaneous requests and align priorities across the observatory (*leadership*), representatives across the Science & Engagement, Instrumentation and Data Infrastructure departments join together in the Data Services Prioritization IPT to review, approve and prioritize software development (*engagement of people*). Here again, this collaborative approach was a lesson learned from past misunderstandings of needs, priorities and limitations across previously disconnected groups and departments. Bringing stakeholders together for prioritizing shared resources instead promotes this understanding and fosters a shared sense of ownership that reduces internal conflict and elevates the most pressing improvements for the network as a whole. An example of this process occurred when NEON scientists discovered significant instrument drift in CO_2 concentration measurements. Utilizing NEON's decision-support framework (Figure 1), the Surface-Atmosphere Exchange (SAE) Group within the Science & Engagement department developed a drift correction algorithm in consultation with the SAE Technical Working Group. Owing to its relatively small scope of work and high impact, the Data Services Prioritization IPT scheduled the needed software development for swift implementation, increasing the proportion of CO_2 concentration measurements meeting tolerance requirements from 18% to 88%.

NEON software development follows the Agile model (Abrahamsson et al., 2017), an incremental, iterative process characterized by short development and feedback cycles. Working software is produced early in the process so that stakeholders may review, approve and redirect as realities and priorities change (*relationship management*). To minimize errors in NEON data products, new or updated processing software is validated by a collection of tests that execute during the software build process and must pass prior to generating a deployable artefact, such as a Docker image (*process approach*). All software and deployable artefacts are version controlled using repository managers (e.g. Github, Quay.io). A software systems architect ensures a wholistic view of NEON's software systems to minimize undesired impacts of system changes (*leadership*, *process approach*).

7.3 | Data processing and publication

Data processing has evolved due to lessons learned over NEON's history to minimize any transformation of raw data before it is stored centrally within Data Infrastructure, enabling the correction of calibration, installation, location metadata or software errors when they are inevitably discovered (*process approach*). Another lesson learned has been to use structured files, such as Avro, Parquet and HDF5 formats. Such structures allow inclusion of provenance information, including calibrations, location information and QC thresholds, which are critical to building confidence in data quality (*customer focus*) and for tracing quality problems back to their source (*process approach*).

Data publication follows FAIR data principles (Wilkinson et al., 2016)—findable, accessible, interoperable and reusable, all fulfilling a *customer focus*. After a provisional period in which adjustments may be made as necessary, data are included in annual releases that provide static, permanently available data packages with findable DOIs. Released data packages as well as provisional data are accessible using standardized communication protocols via the NEON Data Portal or application programming interface (API). Interoperability is facilitated through standardized vocabularies and metadata following the requirements for the Ecological Metadata Language (EML). Reusability is aided through a data usage policy and provenance documentation provided with data downloads, including the ATBD, definitions of data terms, location information and an issue log that describes known problems and data changes.

8 | MONITORING, PROBLEM TRACKING AND ISSUE RESOLUTION

Much of the utility of instrument data comes from their continuity, that is, availability at frequent, regular intervals. Gaps in data availability and periods of poor quality diminish this benefit. NEON's QMS organizes people and information to monitor operational processes throughout the data generation chain and promptly communicate, trace and resolve issues.

8.1 | Site, sensor and data monitoring

Table 3 describes the type, time-scale and functionality of NEON's monitoring tools, all of which feed into the central issue management system when issues are identified. The time-scale of monitoring and alerting method vary according to the time-scale of the process and how correctable issues are after the fact (*process approach*). Active alerts (automatically generated incidents/emails) are generated for issues resulting in irretrievable data loss, whereas passive alerts (dashboard views) are used for issues that can be corrected by reprocessing or republication. Dashboards for monitoring tools organize monitoring data to provide high-level overviews of the entire network down to specific errors and quality concerns (Figure 5).

Monitoring tools developed organically as systems came online and challenges were discovered. This often resulted in overlapping and uncoordinated efforts, and in many cases monitoring tools are still 'owned and operated' by specific departments. An effort is underway to consolidate tools in a centrally accessible location so that they are discoverable across the organization (*leadership*, *process approach*).

8.2 | Data quality trouble tickets

Despite best efforts, some quality issues evade automated detection. Although potentially involving any operational process in the data generation chain, these issues typically involve a sensor set being out of science requirements but still producing plausible data, such as an animal nest blocking a precipitation gauge (Figure 6). Data Quality Trouble Tickets (DQTTs) are designed to handle these situations, leveraging vigilance and expertise across the observatory (*engagement of people*) to identify, review and resolve quality concerns as well as a formal pathway to communicate them in published data (*process approach*, *customer focus*). Anyone may report a DQTT through the central issue management system (including through the NEON website). It is then reviewed by a subject matter expert and, if warranted, the affected data are indicated as suspect by manually raising the final quality flag. Details and justification for manually raised flags are recorded in machine-readable format and provided to end users in publication metadata (*customer focus*). Since 2018, an average of 52 DQTTs have been reported each month across the sensor systems, highlighting their importance for accurately communicating quality and also for identifying areas to improve or where automated tests may be needed.

8.3 | Issue tracking and resolution

The central issue management system facilitates an organized and coordinated approach across NEON for reporting problems, requesting advice or services, assigning resources based on impact and urgency and tracking progress towards resolution (*process approach*, *engagement of people*). User feedback and requests are also routed through this system, seamlessly integrating them with internal operations (*customer focus*). Staff in all departments and several IPTs conduct regular meetings to discuss reported incidents. Tested solutions are documented in 'how-to' articles searchable by all NEON staff, helping to preserve and disseminate knowledge and aid consistent application (*leadership*, *improvement*).

Frequent or especially egregious incidents are escalated to NEON's structured corrective action process (based on ISO, 2015b), which ensures responsiveness to significant challenges by determining actions based on causal analysis (*evidence-based decision making*, *improvement*). Staff use a risk-based matrix (Figure 7) to identify and prioritize issues requiring corrective action. Under the authority of NEON's Quality Manager (*leadership*), a cross-functional team is formed to perform immediate containment, conduct root-cause analysis, and work with IPTs and/or TWGs as necessary to implement actions to reduce or eliminate the cause(s) of the issue. Corrective action reporting is provided

TABLE 3 Focus and function of monitoring tools

Focus	Time interval	Functionality
Site status	Real-time	Services critical to data collection (power, communications, device command and control). Active alerts
Sensor connectivity	Real-time	Sensor connectivity, data transmission and database ingest. Active alerts
Sensor health	Near real-time (24-hr lag)	Algorithmic tests to check instrument assemblies for malfunction. Built-in interpretation logic issues active alerts in plain language (Figure 5c)
Data processing	Daily	Status of data processing. Logs indicate failure causes (e.g. missing metadata required for processing). Passive alerts
Data publication	Monthly	Status of the publication process. Identifies data that have been (re)processed but not published. Passive alerts
Published data quality	Monthly	Monitors completeness and quality of published datasets. Passive alerts

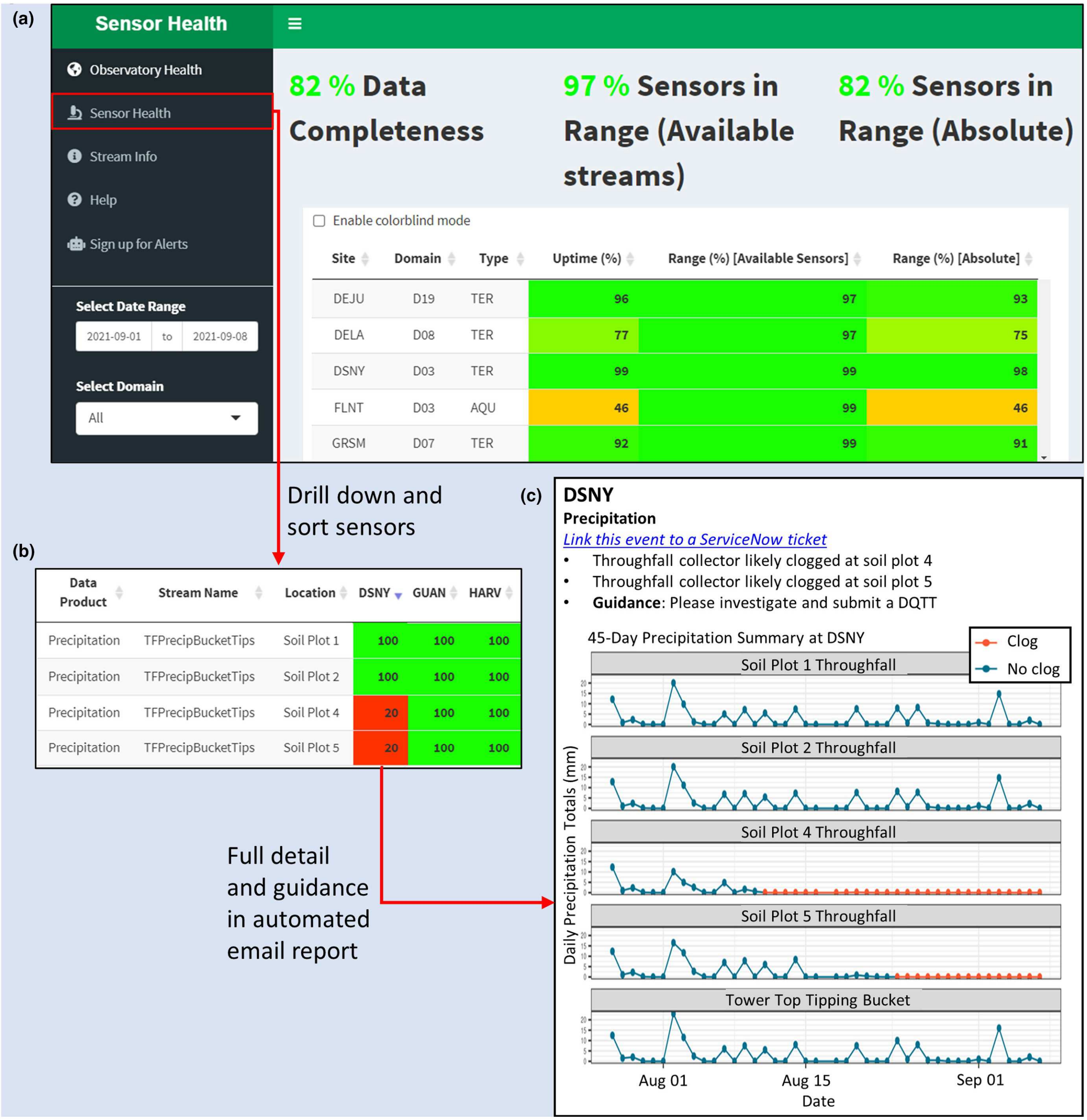

FIGURE 5 The NEON sensor health monitoring dashboard shows (a) colour coded, high-level summaries of sensor data availability and quality. Users can drill down and sort sensors (b) to identify problematic data streams. Automated email alerts (c) provide supporting information, the ability to link to a ticket in the centralized issue management system, and pre-determined guidance for how to handle issues.

to all relevant stakeholders, including the user community through issue logs and/or news articles on the NEON website (*relationship management*, *customer focus*).

An example of the corrective action process occurred when a trend of incidents revealed a high failure rate of NEON's aquatic nitrate sensors. The sensors emit flashes of UV light to measure the nitrate concentration and were initially configured to emit 50 flashes per reported value. An investigative team including members from the Science & Engagement and Instrumentation departments traced the failures to burnout of the sensor's light source. Further analysis revealed that the flashes could be reduced from 50 to 20 and still achieve the required precision. Changes to the sensor configuration, calibration procedure and processing algorithm were coordinated by the relevant IPTs utilizing the configuration and version management process (see Section 3), resulting in a doubling of sensor life while still meeting quality requirements.

9 | AUDITS AND ASSESSMENTS

Ascertaining the competency and degree of compliance of the data's provenance is critical to the reliable assessment of data quality (Snee et al., 2014). This premise guides NEON's audits and assessments, which perform periodic checks and analyses to determine whether the observatory is effectively delivering the intended data and services (*evidence-based decision making*, *customer focus*). Audits assure observatory integrity by comparing actual conditions with NEON requirements and quality standards (e.g. ISO 9001, ISO 17025). For example, NEON's field audit program verifies site and sensor configuration, location and orientation. Assessments evaluate NEON's operational performance, often aggregating user surveys (Crall, 2018) or monitoring data (see Section 8.1) and comparing it to target values. Both audits and assessments are collaborative (*relationship management*) and adverse findings are addressed through the corrective action process (*improvement*). High-level assessments are presented to advisory groups for review and advice on the most pressing or impactful improvements to meet user needs (*customer focus*). Major improvement initiatives are then coordinated down through the decision-support hierarchy into specific actions by IPTs, TWGs and departments (Figure 1; *leadership*, *improvement*, *process approach*).

FIGURE 6 An animal nest discovered in a throughfall precipitation gauge at the NEON Great Smoky Mountains National Park (GRSM) site, causing diminished rainfall measurements. A data quality trouble ticket was created and reviewed via the issue management system. Affected data were manually flagged.

Indicators of published data quality, such as completeness (Equation 1) and validity (Equation 2), are key high-level assessments. Multiplied together (completeness × validity; Equation 3), these metrics portray the cumulative effect of all processes within the observatory to serve complete and valid data to the user community. An observatory-wide baseline target of 90% is set for each of these metrics (81% multiplied, completeness × validity). For complex, higher-level data products the metrics are mathematically compensated in accordance with the increasing number of upstream dependencies (see NEON.DOC.004764 in Table S1).

$$\textit{completeness} = \frac{\textit{actual published records}}{\textit{expected published records}}. \tag{1}$$

$$\textit{validity} = \frac{\textit{actual published records passing all quality checks}}{\textit{actual published records}}. \tag{2}$$

$$\textit{completeness} \times \textit{validity} = \frac{\textit{actual published records passing all quality checks}}{\textit{expected published records}}. \tag{3}$$

CATEGORY	THRESHOLD FOR INITIATING CORRECTIVE ACTION	IMPACT/PRIORITY MATRIX		
		LOW	MEDIUM	HIGH
TREND OF INCIDENTS	2 over 12 months, or 1 incident showing a trend	<10 sensors or sites (or assessed based on impact)	≥10 sensors or sites (or assessed based on impact)	Observatory-wide trend
REPUTATION	Unsatisfactory user community feedback	Any topic	Overall rating or performance	Risk for loss of contract or future work
DATA QUALITY	Data consistently published with a quality issue	One data product at one site	Multiple data products at one site or one product at multiple sites	Multiple data products at multiple sites
	Data loss or corruption	Recoverable with minimal effort	Recoverable with high effort	Permanent
PUBLIC WEBSITE	Unexpectedly unavailable > 2 hours	> 2 hours	> 4 hours	> 8 hours

FIGURE 7 Excerpt from NEON's risk-based matrix for identifying and prioritizing issues requiring corrective action.

The continual application of assessment and improvement in NEON's QMS is reflected in the near continuous increase in complete and valid data over NEON's published sensor data holdings (Figure 8), more than doubling since 2015 for meteorological and soil datasets and showing similar improvements in aquatic and surface–atmosphere exchange data. Much improvement remains to be made, especially in the aquatic subsystem, by utilizing the QMS described here.

10 | DISCUSSION

Several aspects of NEON's QMS presented above have been mentioned and/or described in the relatively sparse literature on comprehensive quality systems for distributed environmental measurement networks (Table 4). We argue that what sets NEON's QMS apart from previously described systems, and hence the main values of this paper are its comprehensiveness, scalability and, most critically, the strength of focus on the integration and connections among people and systems (*process approach*). Human- and process-integration pathways such as a decision-support framework and centralized issue management, configuration management and version control are necessary to cross-inform, cross-coordinate and balance competing priorities. Integration among human and information

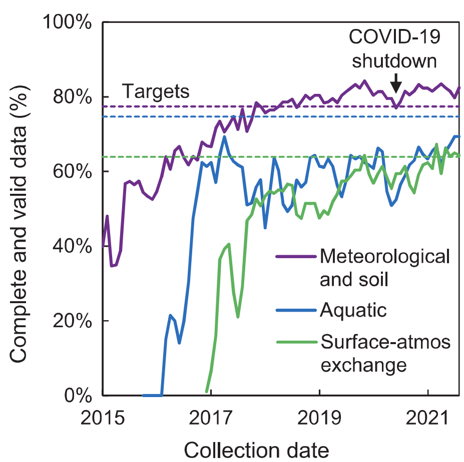

FIGURE 8 Continual improvement in complete and valid published data records (completeness × validity, Equation 3) along with corresponding targets for the three main divisions of sensor data products over NEON's full collection as of September 2021. Different starting points correspond to the initiation of the sensor set. Targets average below the observatory-wide default of 81% due to mathematical compensation for the number of upstream dependencies in complex, higher-level data products, especially applicable to the surface–atmosphere exchange subsystem. For context, a recent review of data availability across well-established FLUXNET sites found average daytime availability of surface–atmosphere exchange measurements ranged from 30% for CO_2 flux to 68% for sensible heat flux (van der Horst et al., 2019). A review of soil moisture measurement networks found that data completeness tended to range from 70% to 90% (Zhang et al., 2017).

systems is also achieved through audits and assessments, creating feedback loops for improvement through the identification of new goals and actions that cascade through decision-support bodies and departments. These represent the most critical lessons learned in developing NEON's QMS.

The comprehensive integration of NEON's QMS is largely afforded by NEON's top-down network organization. However, adherence to quality management principles and a particular focus on *process approach* are similarly applicable for bottom-up and hybrid networks, where components of the QMS are handled by individual network members (Table 1). In fact, all of the QMS components described in this paper can be applied at smaller or larger scales and different organizational structures. Recognizing that most organizations operate under a set budget, the conscious decision and degree of adopting a QMS becomes a matter of prioritization to implement the most critical QMS components towards achieving the targeted mission with the available time and resources. With this understanding, the following discussion suggests initial steps and provides examples of how the QMS described here may be scaled and adapted to other measurement networks.

We propose the development of any QMS begin with the organization of people in a decision-support framework (e.g. Figure 1; *leadership*, *engagement of people*). From the smallest, resource-limited projects to the largest, resource-rich networks the alignment of goals and efforts across people and groups underpins a *process approach* because developing and maintaining connections among systems requires people working together. For bottom-up and hybrid networks, the development of quality objectives by central committees for pursuit by member sites (e.g. Schultz et al., 2015) is an example of a decision-support framework that connects individual decision structures with network goals.

Following the organization of people, centralized issue, configuration and version management are crucial QMS components even for small networks and individual site teams in order to connect roles and ensure the integrity and flow of information (*process approach*). A small site team may not be as susceptible to inter-departmental information loss as a large network, but the departure of knowledgeable staff can be equally detrimental. Systems (preferably electronic) and defined processes that track problems, site configurations, measurement protocols, code versions, etc. help retain information flow and knowledge transfer through personnel changes and generate critical data for assessment and subsequent prioritization of improvements. There are several software utilities that facilitate these functions free of cost for a small number of users (e.g. Github, JIRA), making them accessible to even the most resource-limited projects. Subsequent enhancements can include machine-readable, standardized formats for metadata such as site and sensor configurations, calibrations and geolocations that aid post-correction of errors and simplify format conversion when transferring information between individual members and network management.

Additional QMS components (e.g. the remainder of Table 4) should be prioritized according to the project goals and resources. Implementing a comprehensive QMS for any network

TABLE 4 General overlap between NEON's QMS and published comprehensive quality systems of other distributed environmental networks. Individual details of system components may differ

QMS component	Literature reference
Decision-support framework	Shafer et al. (2000); Schultz et al. (2015)
Integrated workflows among teams and operational processes	Abeysirigunawardena et al. (2015); Hudson et al. (1999); McCord et al. (2021); Shafer et al. (2000)
Proper sensor procurement, configuration and routine calibration traceable to applicable standards	Fiebrich et al. (2010); Schultz et al. (2015)
Training program and standardized protocols for data collection and maintenance	Fiebrich et al. (2010); Hudson et al. (1999); Schultz et al. (2015)
Monitoring and swift routing of site and sensor health issues	Lakkala et al. (2005); Shafer et al. (2000)
Standardized data processing, publication and data management	Boden et al. (2013); Isaac et al. (2017); Fiebrich et al. (2020)
Data quality control with flagging framework that aggregates the results from several quality analyses and allows manual adjustment and/or annotation of the quality assessment	Fiebrich et al. (2010, 2020); Shafer et al. (2000); Abeysirigunawardena et al. (2015)
Assessments and audits against performance targets	Hudson et al. (1999); Schultz et al. (2015)

size, structure or resource availability can be made less daunting by initializing QMS components at the minimum viable level to sustain operations and subsequently identifying incremental improvements through assessment. For example, monitoring can begin as limited as recording the battery voltage available from most dataloggers, informing the assessment and improvement of sensor uptime and data availability. Coordinated application of QMS components by member sites in bottom-up and hybrid networks can be facilitated by centralized curation of training materials, SOPs, monitoring tools, processing software and assessment procedures (*leadership*). For instance, the bottom-up AmeriFlux network has developed a strong foundation of knowledge sharing and coordination among member sites through a management team that centrally organizes conferences and workshops, an annual training course, calibration services and travelling intercomparisons (Novick et al., 2018). Assessments against quality objectives can be done at a high level by central network management (e.g. network-wide data quality) and explicitly connected to lower-level assessments (e.g. instrument uptime) performed by individual members. Linking high-level and low-level assessments can coordinate coarse-to-fine scale improvement areas and guide individual member sites on the most critical aspects to monitor and improve for overall site and network performance (*process approach*, *relationship management*, *evidence-based decision making*, *customer focus*, *improvement*). Prioritization hierarchies for conducting site maintenance and repair with limited resources can be tailored for each member site based on these assessments.

An effective QMS did not arrive at NEON on day 1 and nor is it complete, as evidenced by the history and trajectory of continued improvement in complete and valid instrument data (Figure 8). Slated improvements focus on strengthening the embodiment of quality management principles throughout the data generation chain. (a) A sensor obsolescence strategy is being developed based on obsolescence risk assessment best practices (Rojo et al., 2012) in order to maintain standardization over time as sensors become obsolete or no longer available (*relationship management*). (b) Sensor drift is being analysed to optimize re-calibration intervals to increase resource efficiency and minimize damage due to shipment and installations (*evidence-based decision making*). (c) Targeted, more concise maintenance recording aims to improve compliance in recording preventive tasks (*relationship management*), which will enable preventive maintenance frequency to be optimized by explicitly linking it to data quality (*evidence-based decision making*). (d) Recent advances in scalable, reproducible science (Metzger et al., 2017; Novella et al., 2019) are being incorporated to modularize and containerize processing software for improved robustness and portability (*process approach*). Parts of this approach have already invited collaboration across the scientific community in designing and extending NEON data products (Metzger et al., 2017) (*engagement of people*, *customer focus*). (e) Monitoring enhancements are aimed at real-time anomaly detection (Leigh et al., 2019) in order to improve issue response time and resultant data quality (*process approach*). (f) Finally, assessments are being expanded to cross-validate NEON's instrument data with that of other environmental networks as well as NEON's own in situ sampling and remote sensing products. Intercomparisons can reveal quality issues and provide insight into uncertainties due to measurement methodology and data processing (e.g. Frank et al., 2016) that are important to understand for confident data use (*customer focus*).

11 | CONCLUSION

A quality management system is the mechanism by which a measurement network may achieve the data and services that fulfil its mission. We have demonstrated how an effective end-to-end quality management system has been developed for a national-scale network by applying the seven ISO principles of quality management: *customer focus*, *leadership*, *engagement of people*, *process approach*, *improvement*, *evidence-based decision making and relationship management*. A special focus on the interconnectedness of human and information systems (*process approach*) enables a distributed workforce and operations to act as a coordinated unit to produce standardized, high-quality data through space and time. Its application has resulted in a doubling of data quality in NEON's meteorological and soil datasets since 2015 and substantial gains in other sensor datasets. This framework can be adapted as needed for networks of varying size and structure.

AUTHORS' CONTRIBUTIONS

C.S. led the writing of the manuscript. All authors contributed critically to the development and operation of NEON's quality management system, writing and editing of the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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This manuscript contains no data or code.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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