GUIDELINES FOR ESTABLISHING A HYBRID AIR QUALITY MONITORING NETWORK IN THE EANET REGION

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The term East Asia in this report refers to the Northeast Asia and Southeast Asia regions unless otherwise stated.

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Abbreviation in this document

ACAP	Asia Center for Air Pollution Research	MNB	Mean Normalized Bias
ASEAN	Association of South East Asian Nations	MOS	Metal Oxide Semiconductor
CEN	European Standardization Committee	NDIR	Nondispersive Infrared
CMAQ	Community Multiscale Air Quality Model	NO_2	Nitrogen Dioxide
CO	Carbon Monoxide	O_3	Ozone
DMH	Department of Meteorology and Hydrology	PID	Photoionization Detector
DQOs	Data Quality Objectives	PM	Particulate Matter
EANET	Acid Deposition Monitoring Network in East Asia	QA/QC	Quality Assurance/Quality Control
EC	Electrochemical	RGMs	Reference-Grade Monitors
EU JRC	European Commission Joint Research Centre	RH	Relative Humidity
FCEE	Faculty of Civil and Environmental Engineering	SO_2	Sulfur Dioxide
FID	Flame Ionization Detector	SOP	Standard Operating Procedures
FTIR	Fourier Transform Infrared Spectroscopy	TMACM	Technical Manual for Air Concentration Monitoring in East Asia
GAW	Global Atmosphere Watch	U.S. EPA	United States Environmental Protection Agency
GC	Gas Chromatography	UV	Ultraviolet Absorption
HAQMN	Hybrid Air Quality Monitoring Network	VOCs	Volatile Organic Compounds
IMHEN	Vietnam Institute of Meteorology, Hydrology and Environment	WHO	World Health Organization
ITB	Bandung Institute of Technology	WMO	World Meteorological Organization
LCSs	Low-cost sensors	WRF-Chem	Weather Research and Forecasting model coupled with Chemistry

1. Introduction

East Asia continues to be a major contributor to global air pollution, with elevated levels of surface ozone and particulate matter posing serious risks to public health, ecosystems, and regional economies. The enhancement of the **air quality monitoring** network in terms of the area coverage and density is required in East Asian countries to provide the basic information for the air quality management and policy making.

Recent advances in sensor technology have enabled the development and use of compact and budget friendly air quality sensors, hereafter referred to as **Low-Cost Sensors (LCSs)**, for air quality monitoring. While LCSs do not match the precision and durability of **Reference-Grade Monitors (RGMs)**, they offer significant advantages in affordability, flexibility, and ease of deployment, particularly in areas with limited infrastructure.

The **Hybrid Air Quality Monitoring Network (HAQMN)** is a monitoring framework designed to provide a scalable and cost-effective solution for air quality assessment by integrating RGMs with LCSs in a complementary manner. In the HAQMN, RGMs serve as anchor stations offering high-accuracy measurements that serve as benchmarks for data reliability. Meanwhile, LCSs are deployed extensively across the monitoring area, significantly enhancing spatial coverage and resolution. To ensure the accuracy of data collected by LCSs, the HAQMN employs co-location testing, where LCSs are temporarily placed alongside RGMs. This process allows for validation and calibration of LCS data, correcting for any discrepancies and improving overall data quality. By combining the precision of RGMs with the broad coverage of LCSs, the HAQMN delivers more reliable and spatially detailed air quality information than networks relying solely on LCSs.

HAQMN offers the following several key advantages:

- **Improved data resolution**, enabling more precise and localized assessments of air pollution exposure
- **Cost-effectiveness**, due to the lower purchase and maintenance costs of LCSs
- **Operational flexibility**, allowing deployment in remote or infrastructure-limited areas
- **Policy relevance**, by providing robust datasets that support health risk assessments and land use planning

The HAQMN concept contributes to the expansion and strengthening of air quality monitoring efforts in the Acid Deposition Monitoring Network in East Asia (EANET) member countries.

This document outlines **Guidelines for Establishing the HAQMN in the EANET region**, covering site and sensor selection criteria, recommended pollutants, monitoring frequency, data handling protocols, and best practices for data utilization. Detailed operational procedures of LCSs, including maintenance and Quality Assurance and Quality Control (QA/QC), are described in the *Technical Manual for Hybrid Air Quality Monitoring with Low-Cost Sensors: Implementation*

Guidelines in EANET. The operational procedures of RGMs will be referred to the *Technical Manual for Air Concentration Monitoring in East Asia (TMACM, 2013).*

This guideline aims at **providing information on deploying LCSs together with the ordinary monitoring network of RGMs by local and national government and research institutions**. The intended audience includes communities, researchers, environmental agencies (e.g., air quality, environmental quality, natural resources, health), especially senior governmental officers who manage the air quality monitoring action plans.

2. Objective of HAQMN

The HAQMN supports regulatory, policy, and public health goals by delivering reliable and scalable air quality data within the limited budget and human resources. HAQMN is designed to integrate high-accuracy RGMs with widely deployable LCSs, aiming to improve spatial coverage and enhance data accessibility.

Key principles of HAQMN:

- **Complementarity:** LCSs are intended to complement, not replace, RGMs.
- **Data Quality Assurance:** Validation, correction and robust QA/QC procedures are essential for the effective deployment of LCSs.
- **Contextual Design:** Network design must be tailored to each country’s technical capabilities, environmental conditions, and institutional context

In practice, LCSs in the HAQMN are to be deployed for monitoring purposes alongside RGMs after ensuring good quality LCSs data provided by the parallel monitoring tests utilized for validation. The design and implementation of HAQMN must reflect the environmental context (e.g., humidity, temperature variability), logistical feasibility (e.g., access to electricity and communication infrastructure), and institutional capacity for data management and interpretation.

This approach aligns with international guidance from organizations such as World Meteorological Organization (WMO)/ Global Atmosphere Watch (GAW), European Commission Joint Research Centre (EU JRC), and United States Environmental Protection Agency (U.S. EPA), which emphasize the importance of HAQMN in building inclusive, scalable, and scientifically robust air quality management systems.

3. Design of HAQMN

The HAQMN uses a mix of two types of equipment: RGMs and LCSs, which can monitor air quality across a wide area in an efficient and cost-effective way.

3.1. Network Structure

In the HAQMN system, the RGMs are strategically placed as central quality anchors to ensure data reliability. Surrounding each RGM, the LCSs are distributed in nearby areas to expand spatial coverage and enhance resolution. In some cases, three sensors may be considered a network; in other instances, a network may be comprised of hundreds of sensors. This spatial arrangement allows LCSs to benefit from the calibration and other QA/QC provided by RGMs, while extending monitoring into regions where RGMs alone are not feasible due to financial or logistics constraint. The hybrid structure enables comprehensive air quality monitoring across urban cores, surrounding rural zones, and isolated locations with limited infrastructure.

3.2. Applications of HAQMN in EANET Region

Figure 3.1 presents various examples on how the HAQMN can be designed within EANET region. Each example is adjusted to match the unique environmental conditions and available infrastructure in that region. Design of HAQMN is divided into several categories, based on the purpose and goals of air quality monitoring in each area.

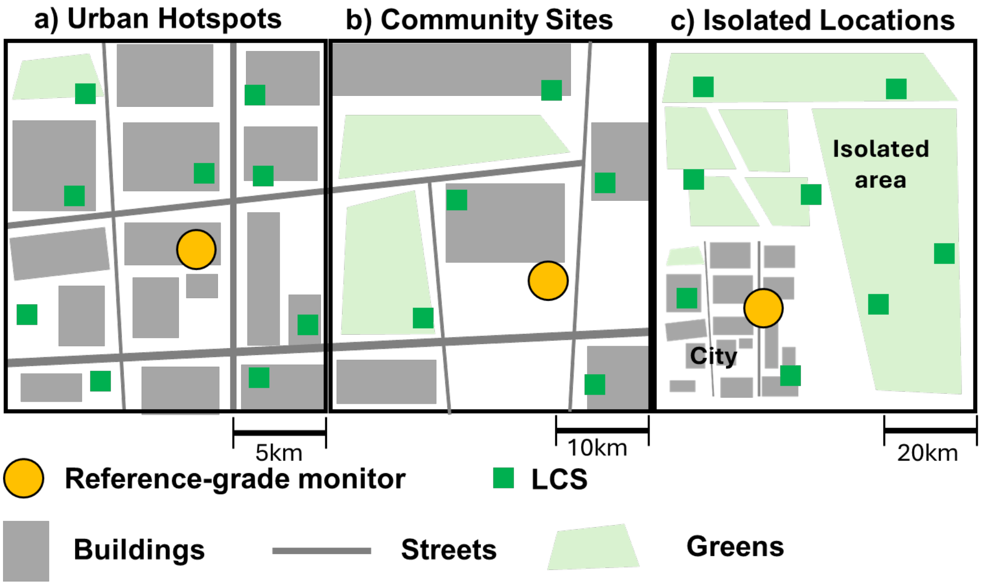


Figure 3.1. Illustration of HAQMN implementation design: a) Urban hotspots, b) Community sites, and c) Isolated locations.

(a) Urban Hotspot Investigation (Fig.3.1 a)

In urban environments where air pollution is highly variable, the HAQMN can be used to establish dense monitoring networks. LCSs are deployed in a grid-like configuration across metropolitan areas (typically 5-to-10-kilometer mesh) to capture fine-scale spatial gradients of pollutants. Data from these sensors are calibrated against nearby RGMs to ensure accuracy. This approach enables improved understanding of pollution sources, hotspot identification, and supports urban planning efforts.

(b) Community Site Augmentation (Fig.3.1 b)

Existing RGMs located in residential areas, whether urban or rural, can be supplemented by strategically placing LCSs around them. The typical spatial scale is 10-to-20-kilometer mesh. This configuration enhances resolution for assessing pollutant inflow and distribution within populated zones. It is particularly effective for evaluating neighborhood-scale exposure and validating local emission control measures.

(c) Monitoring in Isolated Locations (Fig.3.1 c)

In isolated or ecologically sensitive regions—such as forests or reforested zones—where stable power supplies and maintenance infrastructure for RGMs are not available, LCSs serve as a practical alternative. Their low power consumption and compact design allow deployment in previously unmonitored environments, including forested and highland areas. Data collected from these regions are crucial for evaluating the long-range transport of air pollutants and understanding their ecological impacts. Given the larger spacing between LCS units in such terrains (often exceeding 20 km), rigorous attention must be paid to Quality Assurance (QA)/ Quality Control (QC). This includes implementing cross-checks with RGMs where available and among LCS units themselves to maintain monitoring precision.

3.3. Comparative Advantages of HAQMN

When considering the design of an air quality monitoring network, three main approaches can be compared: a network relying solely on Reference-Grade Monitors (RGMs), a network composed only of Low-Cost Sensors (LCSs), and the Hybrid Air Quality Monitoring Network (HAQMN) that combines both. Each approach has distinct strengths and limitations.

RGM-only Network

The main advantage of an RGM-based network is the provision of highly accurate and precise data, which can be directly compared with national environmental standards and used for regulatory compliance. However, the establishment and operation of such a network require significant financial resources. Installation is usually limited to infrastructure-equipped sites (e.g., shelters with stable power and climate control), which increases overall costs and limits spatial coverage.

LCS-only Network

An LCS-based network is inexpensive to deploy and offers flexibility in locating, enabling wider spatial coverage even in locations without major infrastructure. Nevertheless, the limitations of LCSs include sensor-to-sensor variability, reduced long-term stability, and lower accuracy of absolute concentration values. These weaknesses restrict their stand-alone use for regulatory purposes.

HAQMN

The HAQMN approach leverages the advantages of both technologies. LCS data are periodically compared with co-located RGMs and adjusted accordingly, which significantly improves their accuracy. At the same time, the affordability of LCSs allows the establishment of a denser monitoring network within the same budget compared to an RGM-only system. This combination results in a sustainable, cost-effective solution that delivers both data reliability and spatial resolution, making HAQMN particularly suitable for informing policy, urban planning, and health risk assessments.

4. Monitored substances

LCSs are capable of measuring a range of air pollutants that are commonly regulated and pose significant public health concerns. According to international guidance documents, including the *EU JRC Technical Guidance (2022)*, the *WMO GAW Report No. 293 (2024)*, and the *US EPA Air Sensor Guidebook (2014 and 2022 versions)*, the following pollutants are identified as suitable for monitoring with LCSs:

- **Particulate Matter ($PM_{2.5}$)**
- **Nitrogen Dioxide (NO_2)**
- **Ozone (O_3)**
- **Sulfur Dioxide (SO_2)**
- **Carbon Monoxide (CO)**
- **Volatile Organic Compounds (VOCs)** (limited to specific substances, depending on sensor)

While LCSs have expanded the capabilities of air quality monitoring, their measurement accuracy, detection range, and environmental resilience vary depending on the pollutant and sensor design. Therefore, pollutant selection should consider national regulatory priorities, expected ambient concentrations, and the intended purpose of monitoring (e.g., background assessment, source apportionment, exposure estimation). Table 4.1 summarizes commonly targeted air pollutants in HAQMN, organized by their relative importance for HAQMN deployment and the associated technical considerations.

Table 4.1 Pollutant-Specific Considerations for HAQMN Deployment

Pollutant	**Priority ***	**Key concern**	**LCS Suitability**	**Key Considerations**
$PM_{2.5}$	High	High concentration in Asian region, Health impact	Good (light scattering)	Affected by humidity
O_3	High		Moderate (EC, MOS, UV)	Cross-sensitivity with NO_2
NO_2	High	Traffic-related emission, Precursor of O_3	Moderate (EC, MOS, UV)	EC sensors may overestimate due to O_3 interference
SO_2	Medium	Point-source emission (e.g. Volcano)	Limited (EC only)	Better in industrial or volcanic regions
CO	Medium	Identification of mobile and biomass burning sources	Moderate (EC, MOS, NDIR)	Cross-sensitivity with NO
VOCs	High	Precursor of O_3	Limited (PID only)	Only Total VOCs measured; high variability

Note: *Priority levels are indicative based on need of Asian countries, EANET scope, and LCS performance. Electrochemical (EC); Metal oxide semiconductor (MOS); Ultraviolet absorption (UV); Photoionization detector (PID); Nondispersive infrared (NDIR).

To ensure efficient and meaningful data collection, pollutant prioritization supports a phased or targeted deployment strategy for LCSs within the HAQMN. Initial deployments should focus on pollutants like $PM_{2.5}$ and O_3, for which sensors are commercially available, and which are the main concern of air quality issues in East Asia. Additional pollutant types may be incorporated in later phases, where feasible, based on evolving monitoring needs and sensor advancements.

Tier classification system

To get useful results from LCSs, it's important to choose the appropriate sensor for the monitoring. One needs to think about why one is doing the monitoring, for example, checking long-term pollution trends or identifying pollution sources, and then matching that goal with the sensor's ability. There are several LCS guidelines that provide the LCS classification system. US-EPA adopted the Tier classification depending on monitoring purposes (*Air Sensor Guidebook (2014))*, and European Standardization Committee (CEN) also adopted similar classification (*Technical Specification (TS 17660-1) (2022)).* In EANET, the Tier classification and required accuracy are set as shown in Table 4.2, referring the guidelines from U.S. EPA and CEN. The accuracy of the sensor is usually considered via the **Mean Normalized Bias (MNB)**. Table 4.2 shows required MNB for each Tier.

Table 4.2. Tier-Based Classification of Data Quality Objectives

Tier	**Monitoring Purpose**	**MNB Requirement**	**Use Cases**
Tier I	Use for Information	Low (±50–100%)	General spatial patterns, public awareness, education, community science
Tier II	Supplemental Monitoring	Moderate (±30–50%)	Hotspot Detection, spatial analysis, network optimization, urban source mapping, project evaluation
Tier III	Research and Regulatory Support	High (≤ 30%)	Scientific studies, exposure assessments, regulatory support

Table 4.3. Recommended Tiers for Target Pollutants in East Asia

Objective	**Target pollutant**		
	$PM_{2.5}$	**O_3, NO_2, CO**	**Others (VOCs, SO_2)**
Use for Information	Tier I	Tier I	Tier I
Supplemental Monitoring	Tier II	>Tier I	>Tier I
Research and Regulatory Support	Tier III	≥Tier II	-

-: VOCs and SO_2 sensors are unstable and underdeveloped in East Asia conditions (high concentrations, high humidity, high temperature). We would not recommend using LCS for Tier III for VOCs and SO_2.

Table 4.3 displays recommendation of tier based on target pollutants in East Asia. The Tier I tolerance allows higher variability and bias, suitable for general education or community projects with minimal correction. The Tier II demands moderate precision, typically requiring calibration against RGMs to support targeted interventions or regional planning. The Tier III supports formal research and regulations, requiring rigorous calibration, co-location with RGMs, and strict QA/QC procedures. In the context of HAQMN implementation in EANET member countries, the DQOs for Tier II or Tier III are preferable.

If an LCS unit is equipped with multiple sensors, each sensor must be individually identified the Tier classifications shown in Tables 4.2 and 4.3, and it must be determined for each sensor whether it will be used for monitoring.

5. Recommended Locations for LCS installation in HAQMN

In designing a HAQMN, monitoring stations should be strategically placed to balance national air quality objectives, cost efficiency, and data representativeness. The monitoring station should be arranged to:

- Capture spatial and temporal variation in air pollution
- Be scalable and adaptive to evolving monitoring goals

Based on findings from *EU JRC (2022), GAW 293 (2024), EPA Guidebook (2022), and EANET TMACM (2013)*, the following LCS siting recommendations are proposed for HAQMN:

- **Urban Hotspots**: Roadside, intersections, industrial perimeters
- **Community Sites**: Schools, public parks, residential zones
- **Isolated Locations**: Background, which is far from anthropogenic sources, co-located with meteorological stations

The size of the HAQMN should be determined based on the objectives of the air quality monitoring program. Each classification aligns with specific spatial scales and monitoring purposes as outlined in Table 5.1. For example, urban hotspots typically cover densely populated areas with heavy traffic or industrial activity across 4 to 500 m, where pollutant concentrations tend to be highest. Community-level sites span 500 m to 4 km and are suited for assessing localized pollution near schools, residential zones, or public spaces. Isolated locations, often background or reference sites, range from 100 to 1000 km and contribute to tracking regional pollution transport and supporting secondary standards.

To ensure consistent and reliable measurements across such diverse conditions, the HAQMN applies parallel testing not only for sensor validation but also for confirming sensor performance before installation under real-world deployment scenarios. This structured approach enhances the network's adaptability, enabling it to meet both national air quality objectives and regional coordination goals across East Asia.

Table 5.1. Relationship Between Monitoring Type, Spatial Scale, and Intended Goals

Type of Monitoring	**Scale**	**Example Monitoring Goals**
Collocated (parallel test)	1–10 m	Precision, accuracy, bias
Urban Hotspots	e.g. 4–500 m	Highest concentration, source impact, population impact
Community sites	e.g. 500 m–4 km	Highest concentration, source impact
Isolated locations	e.g. 100–1000 km	Background, secondary standard

There is no fixed standard for the number of LCS units to be deployed within a given area. The appropriate number depends on several factors, including the target pollutants and their typical spatial variability, the objectives of the project, the characteristics of the area (e.g., urban, suburban, or rural), key meteorological conditions, and available budget. Table 5.2 shows several studies worldwide that deployed LCS for air quality monitoring. In India, large-scale networks (39–44 LCS) covering semi-rural to urban areas (2,400–2,528 km^2) were used to identify hotspots, burning sources, and broaden monitoring for regional emissions (*Singh et al., 2023; Madhwal et al., 2024*). In Greece, 16 LCS were installed over 125 km^2 urban areas to gain more detailed understanding of local emission sources (*Kosmopoulos et al., 2022*). In Siberia, 14 LCS across 348 km^2 urban zones aimed to improve satellite $PM_{2.5}$ detection and track forest fire movement (*Lin et al., 2020*). Pollutants monitored include $PM_{2.5}$, NO, NO_2, O_3, and CO. Among these, $PM_{2.5}$ sensors are considered the most stable and widely applied, which is reflected in their dominant use in research for emission characterization and remote sensing enhancement.

Table 5.2 Examples of LCS Deployment Studies for Air Quality Monitoring Worldwide

Pollutant	**Country**	**Area**	**Purpose**	**Number of sensors**	**Ref**
$PM_{2.5}$, NO, NO_2, O_3, CO	India	Semi-rural and urban, downwind direction	Identify pollution hotspots and burning sources	~2400 km^2 39 LCS	*Singh et al., 2023*
$PM_{2.5}$	India	Urban-rural	Expand monitoring coverage to assess regional emissions	2,528 km^2 44 LCS	*Madhwal et al., 2024*
$PM_{2.5}$	Greece	Urban	Gain detailed understanding of local emission sources	125 km^2 16 LCS	*Kosmopoulos et al., 2022*
$PM_{2.5}$	Siberian	Urban	Enhance satellite $PM_{2.5}$ detection and track forest fire spread	348 km^2 14 LCS	*Lin et al., 2020*

LCSs should be mounted at a stable height (generally between 1.5 and 10 m) depending on target substances. The sampling inlet must be positioned to avoid artificial turbulence and be shielded from direct precipitation and excessive solar heating.

In addition to the spatial scale considerations, LCS sites should meet the following criteria:

- Be easily accessible for maintenance
- Be free from nearby obstructions (e.g., buildings, trees) near the sampling inlet
- Be located where communication signals (e.g., Wi-Fi, cellular etc.) and power supply are feasible (or where alternatives like solar power can be deployed)
- Be documented with metadata, including land use, elevation, meteorological conditions, and proximity to pollution sources

6. Monitoring frequency and temporal resolution

LCSs are capable of measuring pollutants at very high frequencies, from minute-level intervals to hourly averages, and in some cases can transmit data in real time. While this enables detailed observation of pollution dynamics, overly frequent measurements can create technical challenges, such as exceeding the sensor's storage capacity or overwhelming limited processing power.

Therefore, time resolution should be chosen carefully in line with monitoring objectives and resource availability. **Hourly averaging is generally recommended**. For example, hourly average concentrations are used for $PM_{2.5}$, NO_2, SO_2 and so on. Both hourly means and the daily maximum 8-hour average should be calculated for O_3, following practices adopted by several East Asian countries and the World Health Organization (WHO).

Year-round monitoring is strongly recommended to estimate seasonal and annual variations. This allows for reliable evaluation of daily fluctuations, long-term pollution patterns, while also ensuring comparability across countries and regions.

7. Principles of measurement

The measurement principles of official RGMs in the East Asian countries are summarized in Table 7.1 along with the working principles of LCSs. It is crucial to understand these principles, LCSs specifications and limits as well as the environmental conditions of countries to be deployed in order to suitable LCSs.

Because using RGMs is the basis for obtaining highly accurate data in HAQMN, periodic maintenance for RGMs is strongly recommended. Moreover, RGMs equipment has limitations depending on the principles of measurement, and accurate values may not be obtained under extreme circumstances such as extremely high concentration of pollutants. Therefore, the data obtained by RGMs should be verified by referring to *TMACM* (2013) before comparing it with LCS data.

Table 7.1 Available methods to measure target pollutants using RGMs and LCSs

Target pollutant	**RGMs**	**LCSs**
Particulate matter		
$PM_{2.5}$	Beta-ray absorption Filter oscillation Light scattering	Light scattering Optical particle counter
Reactive gases		
SO_2	Ultraviolet fluorescence Solution conductivity	EC sensor
NO_x	Chemiluminescence Absorption spectroscopy	EC sensor MOS sensor UV sensor
O_3	Ultraviolet fluorescence Chemiluminescence Absorption spectroscopy	
CO	NDIR	EC sensor MOS sensor NDIR sensor
VOCs	FTIR, GC-FID	Online PID (for total VOCs)

Note: Electrochemical (EC); Metal oxide semiconductor (MOS); Ultraviolet absorption (UV); Fourier transform infrared spectroscopy (FTIR), gas chromatograph with flame ionization detector (GC-FID).

Best Practices for Sensor Deployment

To ensure reliable measurements:

- Select sensors that match the expected ambient concentration ranges.
- Avoid placing sensors near direct pollutant sources (unless source impact is the monitoring target).
- Ensure a stable power supply and consistent airflow conditions.
- Ensure good LCSs data quality by performing regular calibration and verification e.g. field test by the parallel monitoring test LCS with RGM.
- Collect and use meteorological data (e.g., temperature, relative humidity (RH), wind) to support accurate data interpretation.

8. Basic operation of HAQMN

Effective management and maintenance of both LCSs and RGMs are essential to ensure data reliability and the long-term sustainability of HAQMN. An implementation plan for HAQMN should be established, including maintenance schedules, standard operating procedures (SOPs), and field/maintenance records for both RGMs and LCSs. Practitioner training should also be conducted.

The operation and maintenance of RGMs can follow the *TMACM*. For LCSs, and also refer to the *Technical Manual for Hybrid Air Quality Monitoring with Low-Cost Sensors: Implementation Guidelines in EANET*.

LCSs are more sensitive to environmental variations (e.g., temperature, RH, air pressure) than RGMs, and are prone to sensor degradation over time. Therefore, a structured maintenance protocol must be followed to address these vulnerabilities. Figure 8.1 shows the example of the HAQMN operation and its QA/QC procedure.

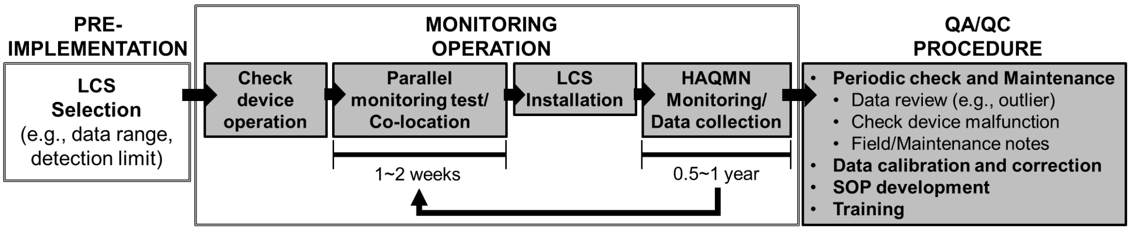


Figure 8.1. Example of the HAQMN operation and its QA/QC procedure

Parallel Monitoring Test/Co-location is a critical component of HAQMN implementation. All LCSs must undergo initial parallel monitoring (co-location) testing with an RGM before installation. This test should last at least one week, and test results shall be utilized for calibration of LCSs or developing a correction model (usually simple linear model between RGM and LCS data) for LCS data. To account for seasonal variability, additional co-location tests should be conducted regularly, at least once during the dry season and once during the wet season in the case of Southeast Asian countries. The LCS raw data should be corrected basically using simple linear regression between the LCS and RGM measurement. The other correction methods are described in LCS technical manual Section 5.3.2.

During **HAQMN monitoring,** Periodic check and Maintenance for RGMs and LCSs should be implemented at least once a month, including the following points:

- Visual inspection of a monitoring station security, power, communication status, structural stability (e.g. mounting brackets, support poles)
- Verification of LCS housing integrity, and checking for corrosion, or external damage
- Visual inspection of air pumps, fans and cleaning of inlets and internal filters
- Review of time-series graphs for each air pollutant to detect data loss or anomalies such as spikes
- Weatherproofing and lightning protection systems must be inspected seasonally, especially before and after wet or stormy periods.

LCS sensor replacement should be implemented according to the recommendation from the manufacturer and result of the parallel monitoring test (e.g. usually LCS sensor unit can be used for 1 to 5 years depending on the sensor type and measurement species.)

QA/QC should be conducted to satisfy Tier classification system (c.f. Table 4.2 and Table 4.3):

- Screening LCS and RGM data for anomalies and outliers
- Validating LCSs data using the results of parallel monitoring test
- Tracking sensor aging to determine appropriate replacement intervals

Maintenance records must be kept in standardized format and include information such as sensor installation dates, installation site location, environmental conditions, parallel monitoring results, power/communication issues, nearby infrastructure changes, repair history and personnel responsible. Additionally, **technical training for the practitioners** and **Standard Operation Procedures (SOP)** should be integrated into the QA/QC programs.

9. Effective data utilization obtained by HAQMN

The HAQMN empowers governments and environmental authorities to improve air quality management by integrating LCS data with high spatial resolution and accurate RGM data.

Identification of Hotspots and Priority Intervention Areas

The dense spatial coverage achieved through LCS deployment enables the timely identification of pollution hotspots, particularly in urban centers, traffic roads, and industrial clusters (Fig. 9.1 for example). These high-resolution insights facilitate the prioritization of pollutants, localization of emission sources, and development of targeted response strategies, including emission reduction plans, zoning regulations, and infrastructure upgrades.

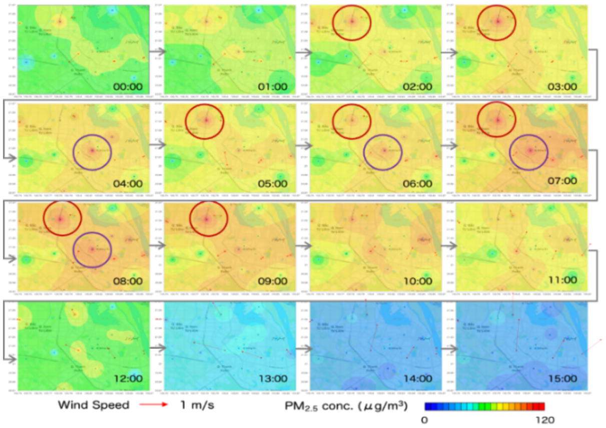
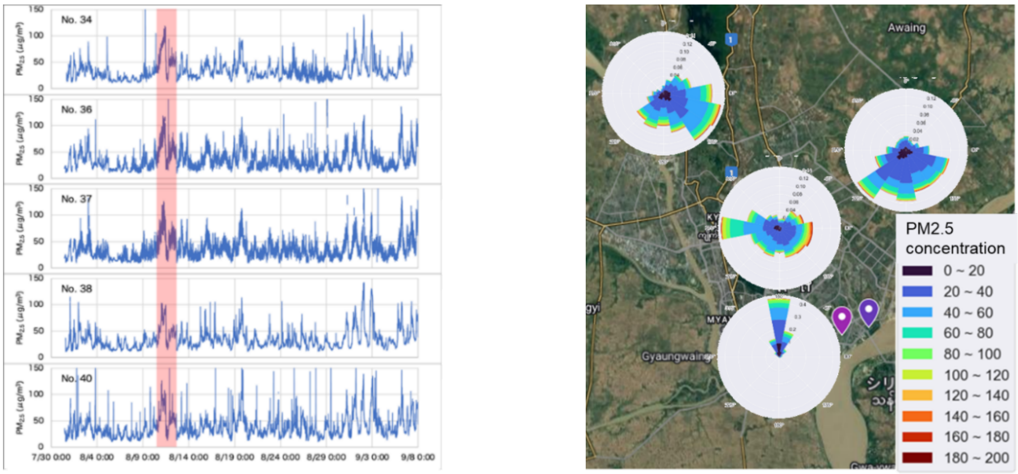


Figure 9.1 Examples of identifying the hotspots

Visualization for Policy Design and Evaluation

The visualization tools such as interactive maps (GIS), colored charts (heatmaps), and graphs with time-series, can turn complicated monitoring data into clear and useful visuals (Fig. 9.2 for examples). These tools help users to easily understand spatial and temporal variation of pollutants and the abatement measures to improve air quality. These tools enhance policy formulation and evaluation by enabling transparent planning, informed budget distribution, and real-time tracking of regulatory implementation. Customized visual outputs also support cross-sector collaboration and streamline reporting under international environmental frameworks.



a) Temporal variation

b) Pollution Source Direction Plot

Figure 9.2 Examples of the visualization for evaluating the air quality

Integration with Satellite Observations

This section shows the potential of combining data obtained from satellites and from HAQMN. When combined with satellite remote sensing data, the HAQMN enhances spatial resolution, enabling comprehensive assessments of regional pollution transport and surface-atmosphere interactions. Satellite data provides broad-scale information on aerosol distribution, concentrations of atmospheric pollutants such as NO_2 and SO_2, and the occurrence of events like wildfires or dust storms. In contrast, HAQMN delivers detailed ground-level measurements of pollutants such as $PM_{2.5}$ and O_3, capturing fine-scale temporal and spatial variations. This integration strengthens the accuracy of emission inventories, supports cross-border pollution tracking, and addresses monitoring gaps in underserved or inaccessible locations.

Support for Atmospheric Modeling

The HAQMN data feeds directly into atmospheric models (e.g., Weather Research and Forecasting model coupled with Chemistry (WRF-Chem), Community Multiscale Air Quality Model (CMAQ)), which simulates pollutant dispersion, analyzes source-receptor relationships, and evaluates policy scenarios. These model results will be basis of long-term environmental planning, including the design of low-emission zones, industrial transition pathways, and urban air quality management strategies.

Forecasting and Exposure Risk Management

With time-series data from LCS networks, short-term air pollution forecasting systems can be developed to predict upcoming pollution episodes. These forecasts allow governments to issue timely health advisories, manage school and hospital operations, protect vulnerable populations, and initiate emergency interventions such as traffic rerouting or temporary industrial curtailment.

Machine Learning and Advanced Analytics

Machine learning algorithms provide deeper insights by identifying sensor anomalies, classifying pollution sources, and detecting emerging trends. These technologies support dynamic resource allocation, optimize network expansion, and enable real-time evaluation of policy effectiveness. Some modern data analysis methods, like unsupervised learning, can find hidden patterns in pollution data that regular analysis might miss. This can help discover unexpected pollution sources or trends that were not clearly visible before.

Alert and Early Warning Systems

The HAQMN facilitates the development of robust air pollution alert systems. When pollutant levels exceed critical thresholds such as those defined by WHO guidelines or national ambient air quality standards, automated alerts can be dispatched to government agencies and emergency responders. This enables swift, data-backed interventions to safeguard public health and maintain regulatory compliance. A successful example is Haze Warning System for ASEAN provided by Asean Specialized Meteorological Center.

Public awareness and education

Data from HAQMN and LCS can be effectively utilized for educational and awareness programs, helping communities understand the current status of the air quality in their communities, pollution-causing behaviors and develop personal protection strategies against air pollution exposure. Furthermore, the publicly available datasets serve as valuable resources for academic research and advanced studies, including investigations into correlations between air quality and health outcomes, impacts of climate change on air pollution patterns, and assessments of government policy effectiveness in environmental management.

10. Conclusion

This guideline is designed for high-level decision-makers, offering a general and concise introduction to establishing a HAQMN within EANET. While it outlines the strategic use of LCSs for air pollutant measurement, detailed procedures for QA/QC and reference maintenance should be consulted in the Technical Manual for HAQMN and TMACM respectively.

The shift toward hybrid monitoring networks is both practical and forward-looking, addressing the dual need to reduce costs and respond to pressing societal challenges. LCSs, being affordable, compact, and energy-efficient, are particularly suitable for deployment in isolated or resource-limited areas. They also support public engagement, hotspot detection, and policy development.

This guideline may serve as a useful reference for countries aiming to expand their air quality monitoring capabilities through HAQMN. To enhance its effectiveness, further case studies, improved data analysis methods, and strengthened regional collaboration are recommended, ultimately contributing to healthier, data-informed communities across East Asia.

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