National Assessment on Acid Deposition and Air pollution in Vietnam

Institute of Meteorology, Hydrology, Environment and Marine Sciences (IMHEMS)

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Chapter 1. Basic information on National Monitoring Activities

1.1. Outline of the activities on acid deposition and air pollution in National Monitoring plan

Vietnam has officially joined the EANET since August 1999 and the Institute of Meteorology, Hydrology, Environment and Marine Sciences (IMHEMS) is assigned as Vietnam's national focal point in the EANET network. At present, the **EANET** network in Viet Nam consists of 7 monitoring stations. Of these, 5 stations are operated by the **Institute of Meteorology, Hydrology and Environment and Marine Sciences (IMHEMS)** in accordance with the EANET's Technical Guidelines, while the remaining 2 stations are managed by the **Viet Nam Meteorological and Hydrological Administration (VNMHA)** and operated under the technical guidelines of the meteorological and hydrological sector. Historically, the EANET network in Viet Nam has primarily focused on monitoring acid deposition, including **wet deposition** and **dry deposition**, as well as assessing their impacts on inland aquatic environment.

With regard to ambient air quality monitoring, the Ministry of Agriculture and Environment (MAE) has assigned this responsibility to the Viet Nam Environment Agency (VEA), specifically the Centers for Environmental Monitoring (CEM). To strengthen national air quality management, the Vietnam Government has recently promulgated Decision No. 224/QD-TTg, dated 7 March 2024, approving the *National Environmental Monitoring Master Plan for the 2021–2030 Period, with a Vision to 2050*, and Decision No. 2530/QD-TTg, dated 19 November 2025, approving the *National Action Plan on Air Pollution Mitigation and Air Quality Management for the 2026–2030 Period, with a Vision to 2045*.

To date, VEA has established and operates a total of 27 automatic and continuous ambient air quality monitoring stations, distributed across urban areas in 22 centrally governed provinces and municipalities. Specifically, 4 stations are located in Ha Noi, 2 in Ho Chi Minh City, 2 in Da Nang, and one station in each of the remaining provinces and municipalities. Under the *National Environmental Monitoring Master Plan for the 2021–2030 Period, with a Vision to 2050*, MAE plans to establish an additional 16 automatic ambient air quality monitoring stations during the 2021–2030

period. Consequently, by 2030, the total number of automatic and continuous ambient air quality monitoring stations operated by VEA is expected to reach 43 stations.

At the provincial level, 30 provinces and municipalities have established and are operating automatic and continuous ambient air quality monitoring stations, with a combined total of 95 stations.

1.2 Monitoring program on acid deposition

1.2.1 Wet deposition monitoring

Acid deposition monitoring in Vietnam has been conducted according to the common methodologies specified in the "Technical Documents for Wet deposition Monitoring in East Asia" in order to obtain the equivalent quality of monitoring data. The samples were monitored in 24 hours, from 9:00 am to 9:00 am of next day and weekly composite samples can be analysed in Ha Noi, Hoa Binh, Ho Chi Minh, and Can Tho sites. Samples are taken in every precipitation event in Da Nang, Cuc Phuong sites and pH, EC was automatic measured each mm of rainfall; These samples are the combination of 10-days from 2010 to 2012) and 7-days (weekly) samples from 2013 to now.
The monitoring parameters include: pH, EC, F-, Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+, Na^+, and NH_4^+; meteorological parameters (temperature, humidity, wind velocity, wind direction, rainfall, ultra-violet) and the analytical Method include: pH meter, EC meter, IC for anions and NH_4^+, Na+, AAS for cations.

1.2.2 Dry deposition monitoring

The dry deposition was monitored using Filter Pack method with monitoring interval of seven days, from 9:00 am Monday of this week to 9:00 am Monday of next week. The monitoring parameters include: Gases: SO_2, HCl, HNO_3, NH_3 and ions Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+, Na^+, and NH_4^+ in the aerosol. The analytical methods are pH meter, EC meter, IC for anions and NH_4^+, Na^+, AAS for cation. Figure 1.9 shows the Wet Sampler with pH, EC automatic measurement each mm of rainfall.

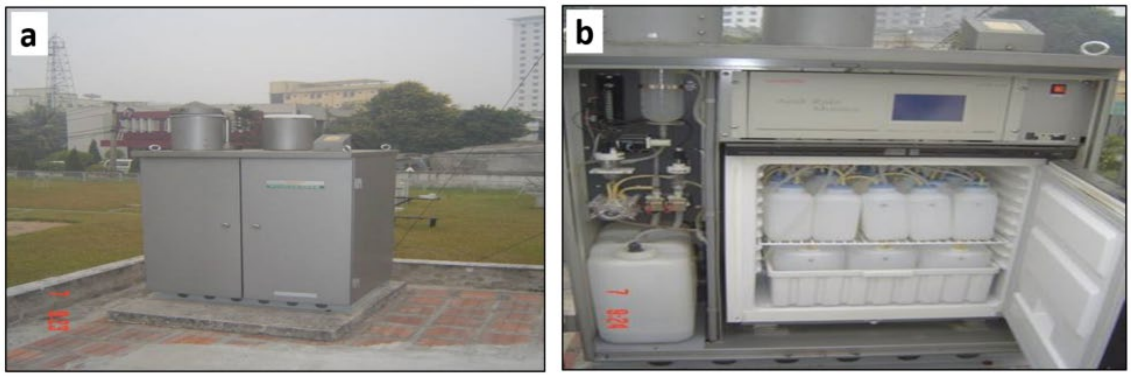


Figure 1. Wet Sampler (Kimoto MCSAM-6-VB).

1.2.3 Inland aquatic environment

Inland aquatic environment were monitoring quarterly (4 times/year) with monitoring parameters

include pH, EC, Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, alkalinity and COD, NO_2^-, clarity. Such parameters were analysed with methods including pH meter, EC meter, IC for anions and NH_4^+, Na^+, AAS for cation, titration method for alkalinity at pH 4.8 endpoint, $KMnO_4$ method for COD and colorimetric method for NO_2^-. The Figure 1.10 shows some pictures of equipment for Acid Deposition Monitoring Analysis.

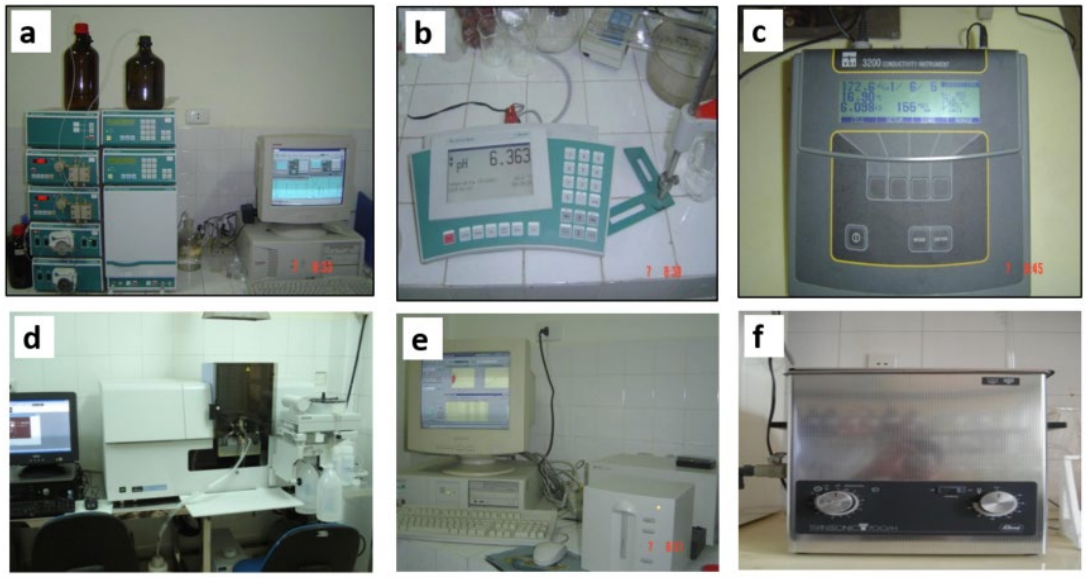


Figure 2. Equipment for Acid Deposition Analysis (a) IC Metrohm Mic 3, (b) pH meter – 793, (c) EC meter – YSI 3200, (d) AAS800 of PerkinElmer, (e) UV-Vis –HP8453 and (f) Ultrasonic bath.

1.3 Monitoring stations

At present, the EANET network in Viet Nam consists of 7 monitoring stations including Yen Bai, Hoa Binh, Ha Noi, Cuc Phuong, Da Nang, Ho Chi Minh City, and Can Tho. Of these, five stations are operated by the Institute of Meteorology, Hydrology and Environment and Marine Sciences (IMHEMS) in accordance with the EANET's Technical Guidelines, while the remaining two stations are managed by the Viet Nam National Meteorological and Hydrological Administration (VNMHA) and operated under the technical guidelines of the meteorological and hydrological sector. Historically, the EANET network in Viet Nam has primarily focused on monitoring acid deposition, including wet deposition and dry deposition, as well as assessing their impacts on inland aquatic environment. Monitoring data has been submitted to Network Center of EANET helping and used as the scientific information for the evaluation of both acid depositions and its impacts on ecosystems in East Asia. The location and profile of EANET sites in Vietnam are shown in the Figures 1.1 - 1.8 and Table 1.



Figure 3. Location of EANET monitoring stations in Vietnam.

Table 1. EANET acid deposition monitoring sites in Vietnam

Deposition type	Site category	Location	Sampler	Starting year	Laboratory
Wet deposition	Urban sites (3 sites)	Ha Noi	Wet only sampler	1999	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE
		Da Nang	Wet sampler with pH, EC automatic measurement for each mm of rainfall	2008	Environmental laboratory area II- Mid-central regional Hydro-meteorological Center – Vietnam National Meteorology Hydrology Administration (VNMHA) – MAE
		Ho Chi Minh city	Wet only sampler	2014	Environmental Laboratory - Sub-Institute of Hydro-Meteorology, Environment and Marine Sciences (SIHYMEMS) –IMHEMS-MAE
	Rural sites (3 sites)	Hoa Binh	Wet only sampler	1999	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE

		Can Tho*	Wet only sampler	2014	Environmental Laboratory - Sub-Institute of Hydro-Meteorology, Environment and Marine Sciences (SIHYMEMS) –IMHEMS-MAE
		Yen Bai	Wet only sampler	2015	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE
	Remote sites (1 site)	Cuc Phuong	Wet sampler with pH, EC automatic measurement for each mm of rainfall	2008	Environmental laboratory area I- Mid-central regional Hydro-meteorological Center – Vietnam National Meteorology Hydrology Administration (VNMHA) – MAE
Dry deposition	Urban sites (2 sites)	Ha Noi,	Filter Pack	1999	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE
		Ho Chi Minh	Filter Pack	2014	Environmental Laboratory - Sub-Institute of Hydro-Meteorology, Environment and Marine Sciences (SIHYMEMS) –IMHEMS-MAE
	Rural sites (3 sites)	Hoa Binh	Filter Pack	1999	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE
		Can Tho	Filter Pack	2014	Environmental Laboratory - Sub-Institute of Hydro-Meteorology, Environment and Marine Sciences (SIHYMEMS) –IMHEMS-MAE
		Yen Bai	Filter Pack	2015	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE
Inland aquatic environment	Rural sites (1 sites)	Hoa Binh		1999	Environmental Laboratory - Center for Environmental Research - IMHEMS- MAE

a



b

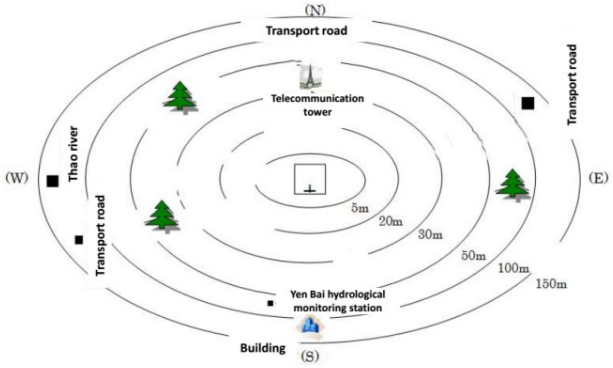


Figure 4. (a) Picture of Yen Bai station and (b) Profile of Yen Bai station: on-site scale (150m).

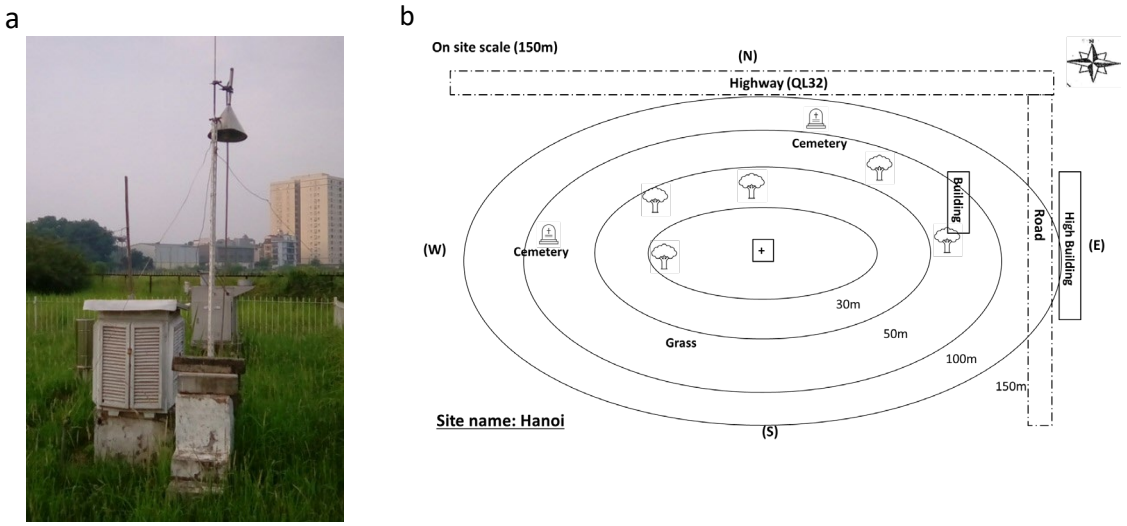


Figure 5. (a) Picture of Ha Noi station and (b) Profile of Hanoi station: on-site scale (150m).

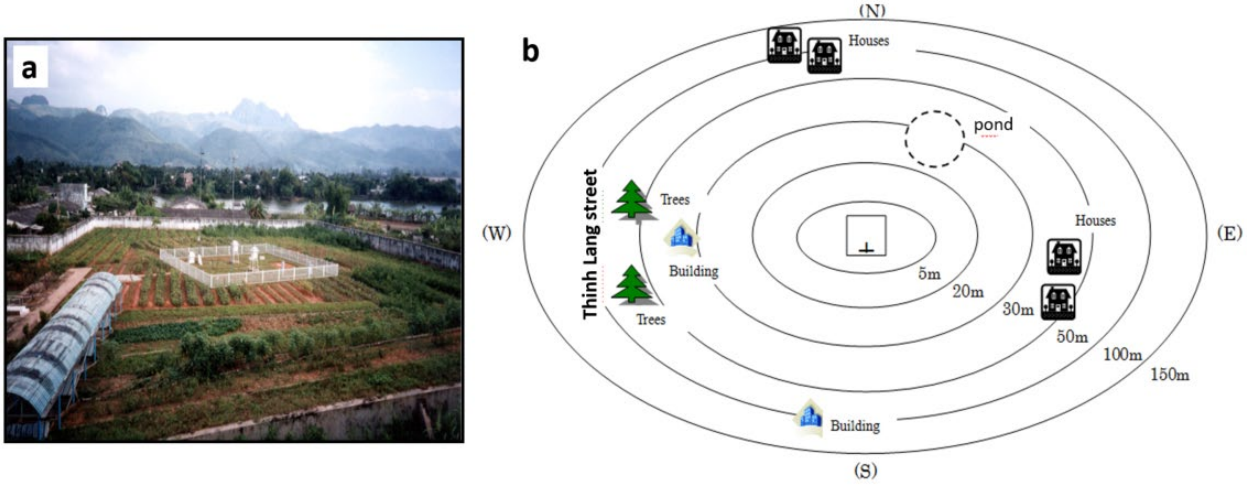


Figure 6. (a) Picture of Hoa Binh station and (b) Profile of Hoa Binh station: on-site scale (150m).

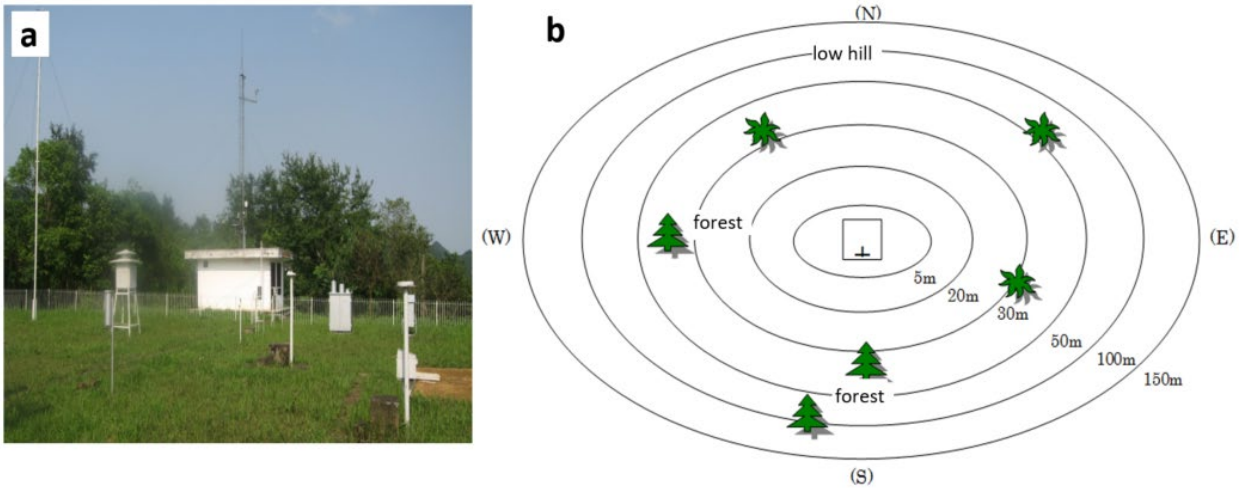


Figure 7. (a) Picture of Cuc Phuong station and (b) Profle of Cuc Phuong station: on-site scale (150m).

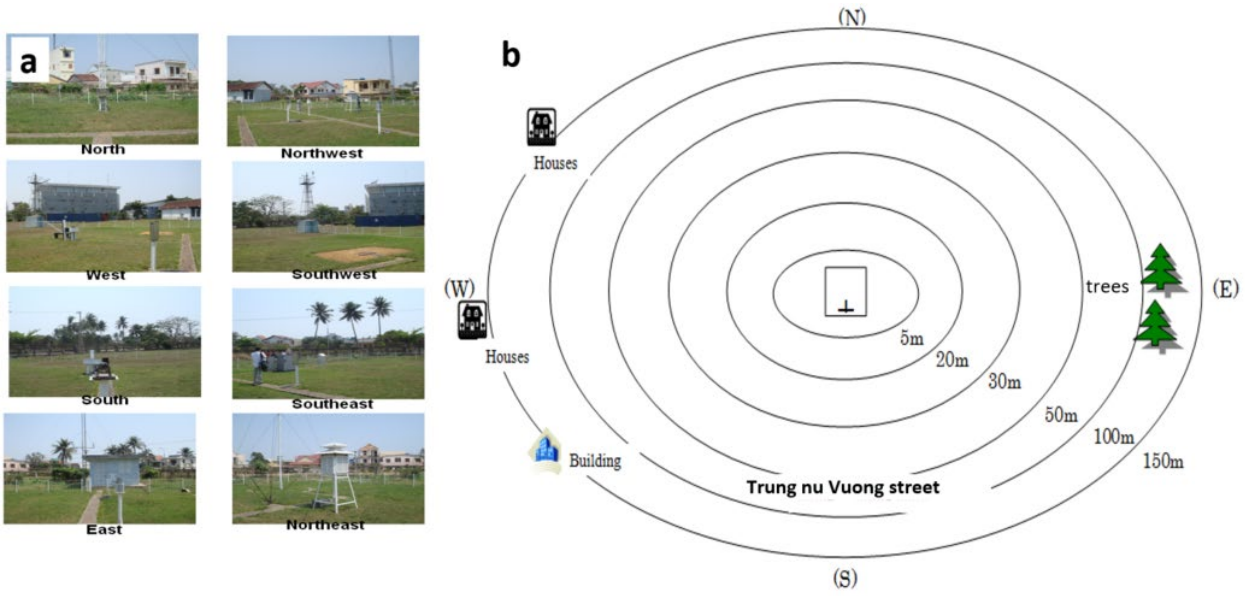


Figure 8. (a) Picture of Da Nang station and (b) Profile of Da Nang station on-site scale (150m).

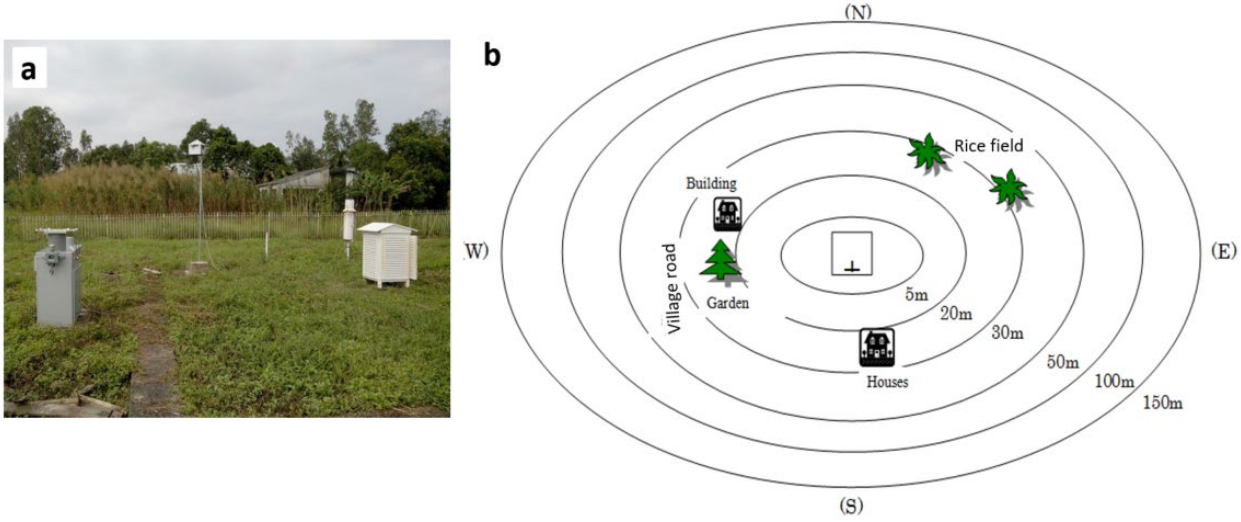


Figure 9. (a) Picture of Can Tho station and (b) Profile of Can Tho station on-site scale (150m).

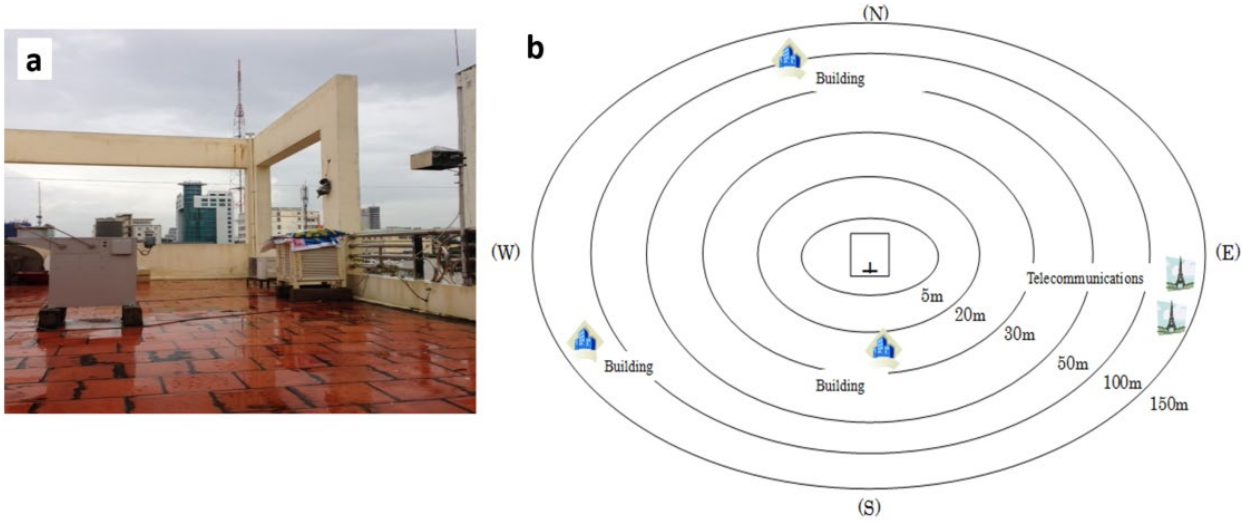


Figure 10. (a) Picture of Ho Chi Minh station and (b) Profile of Ho Chi Minh station on-site scale (150m).

Chapter 2. Acid Deposition and Air Pollution in Vietnam and Their Environmental Impacts

2.1 State of wet acid deposition

a) pH of rain water

The monitoring results for the most recent five-year period (2020–2024) indicate that the annual mean pH of rainwater exhibited distinct spatial variations across different regions of Viet Nam. The northern monitoring sites (Ha Noi, Hoa Binh, Cuc Phuong, and Yen Bai) showed considerable interannual variability in annual mean pH values, in several years annual mean pH values falling below 5.6 (threshold for acid rain). The highest annual mean pH was recorded at the Ha Noi site (6.2 in 2020), whereas the lowest value was observed at the Yen Bai site (4.9 in 2024). In contrast, the monitoring sites in central Viet Nam (Da Nang site) and southern Viet Nam (Ho Chi Minh City and Can Tho site) exhibited relatively stable annual mean pH values throughout this period, ranging from 5.7 to 6.3 (Figure 11).

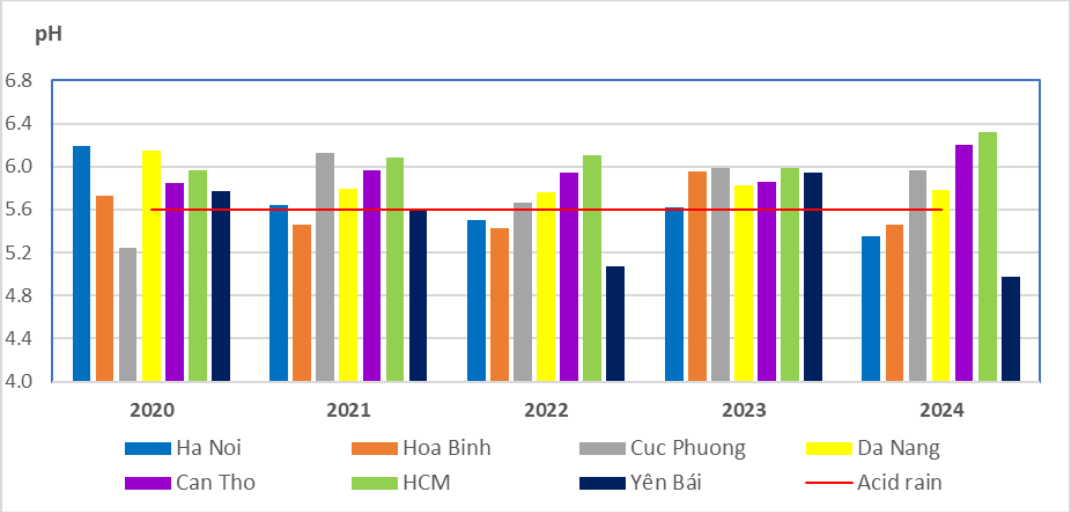


Figure 11. Annual mean pH of rainwater in sites (2020 – 2024)

Overall, the northern monitoring sites consistently exhibited lower rainwater pH values than those in central and southern Viet Nam. These results suggest that acid rain occurs more frequently and with greater severity in northern Viet Nam than in the central and southern regions. The pH of rainwater is influenced by both the level of atmospheric pollution and the amount of rainfall in a given area. Therefore, a comprehensive assessment of acid rain requires not only the measurement of rainwater pH but also the monitoring of meteorological parameters (e.g., air temperature, precipitation, wind speed, and wind direction) and the chemical analysis of ambient air and precipitation samples. Such integrated observations are essential for accurately identifying the cause of acid rain.

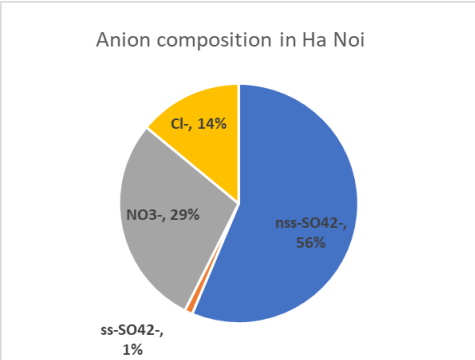
b) Ion composition in rain water

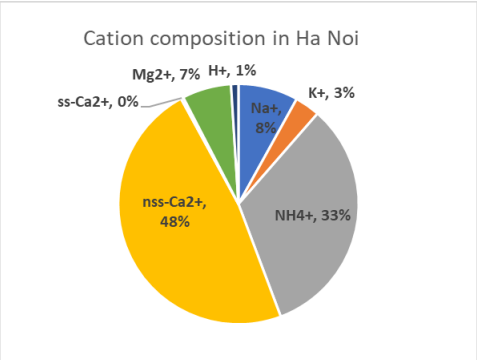
The chemical analysis of rainwater samples revealed distinct regional characteristics in ionic composition. At the northern monitoring sites (Ha Noi, Hoa Binh, and Yen Bai), the ionic composition of rainwater was similar, with the dominant anions being nss-SO_4^{2-} and NO_3^-, and the dominant cations being nss-Ca^{2+} and NH_4^+, accounting for approximately 85% of the total anions and 81% of the total cations, respectively.

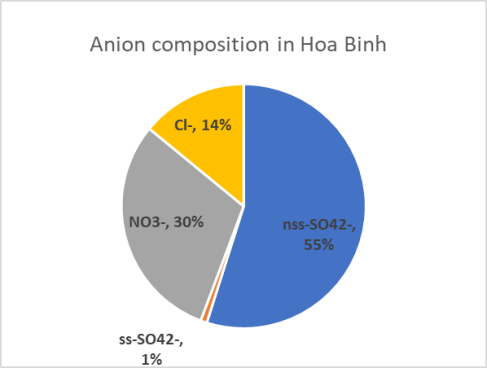
In contrast, the Cuc Phuong site exhibited a distinct ionic composition, where the predominant anions were nss-SO_4^{2-}, NO_3^-, and Cl^-, while the major cations were nss-Ca^{2+}, NH_4^+, Na^+, and Mg^{2+}. These ions accounted for approximately 97% of the total anions and 94% of the total cations, respectively.

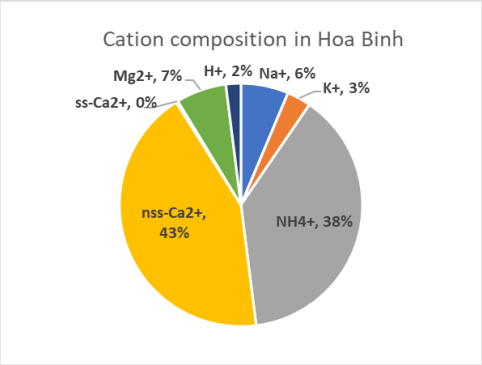
The rainwater chemistry at the southern monitoring sites (Can Tho and Ho Chi Minh City) was also comparable. The dominant anions were nss-SO_4^{2-} and Cl^-, whereas the predominant cations were nss-Ca^{2+}, NH_4^+, Na^+, and Mg^{2+}, representing approximately 87–93% of the total anions and 88–89% of the total cations, respectively.

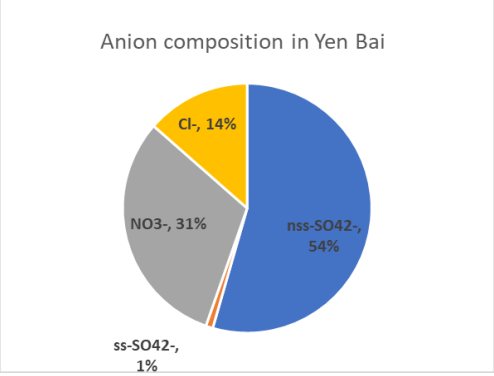
Notably, at the central monitoring site (Da Nang), the ionic composition differed from that of the other regions, with Cl^- being the dominant anion and Na^+, nss-Ca^{2+}, and K^+ being the dominant cations, accounting for approximately 69% of the total anions and 76% of the total cations, respectively (Figure 12).

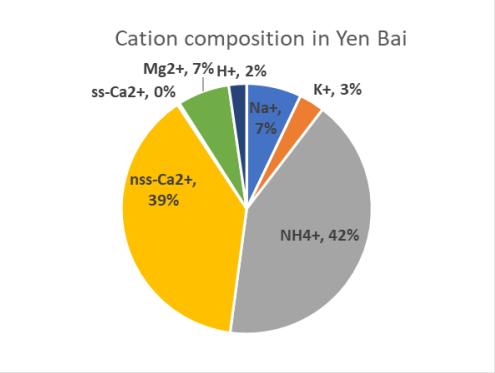

Anion composition in Ha Noi
Cl-, 14%
NO3-, 29%
nss-SO42-, 56%
ss-SO42-, 1%

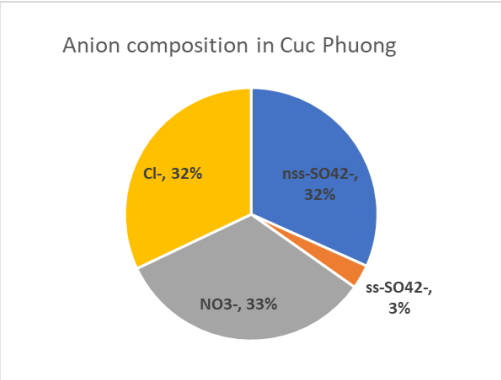

Cation composition in Ha Noi
Mg2+, 7%
H+, 1%
ss-Ca2+, 0%
K+, 3%
Na+, 8%
nss-Ca2+, 48%
NH4+, 33%

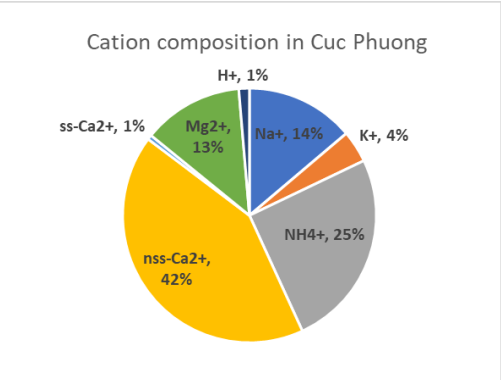

Anion composition in Hoa Binh
Cl-, 14%
NO3-, 30%
nss-SO42-, 55%
ss-SO42-, 1%


Cation composition in Hoa Binh
Mg2+, 7%
H+, 2%
Na+, 6%
ss-Ca2+, 0%
K+, 3%
nss-Ca2+, 43%
NH4+, 38%


Anion composition in Yen Bai
Cl-, 14%
NO3-, 31%
nss-SO42-, 54%
ss-SO42-, 1%


Cation composition in Yen Bai
Mg2+, 7%
H+, 2%
ss-Ca2+, 0%
K+, 3%
Na+, 7%
nss-Ca2+, 39%
NH4+, 42%


Anion composition in Cuc Phuong
Cl-, 32%
nss-SO42-, 32%
NO3-, 33%
ss-SO42-, 3%


Cation composition in Cuc Phuong
H+, 1%
ss-Ca2+, 1%
Mg2+, 13%
Na+, 14%
K+, 4%
NH4+, 25%
nss-Ca2+, 42%

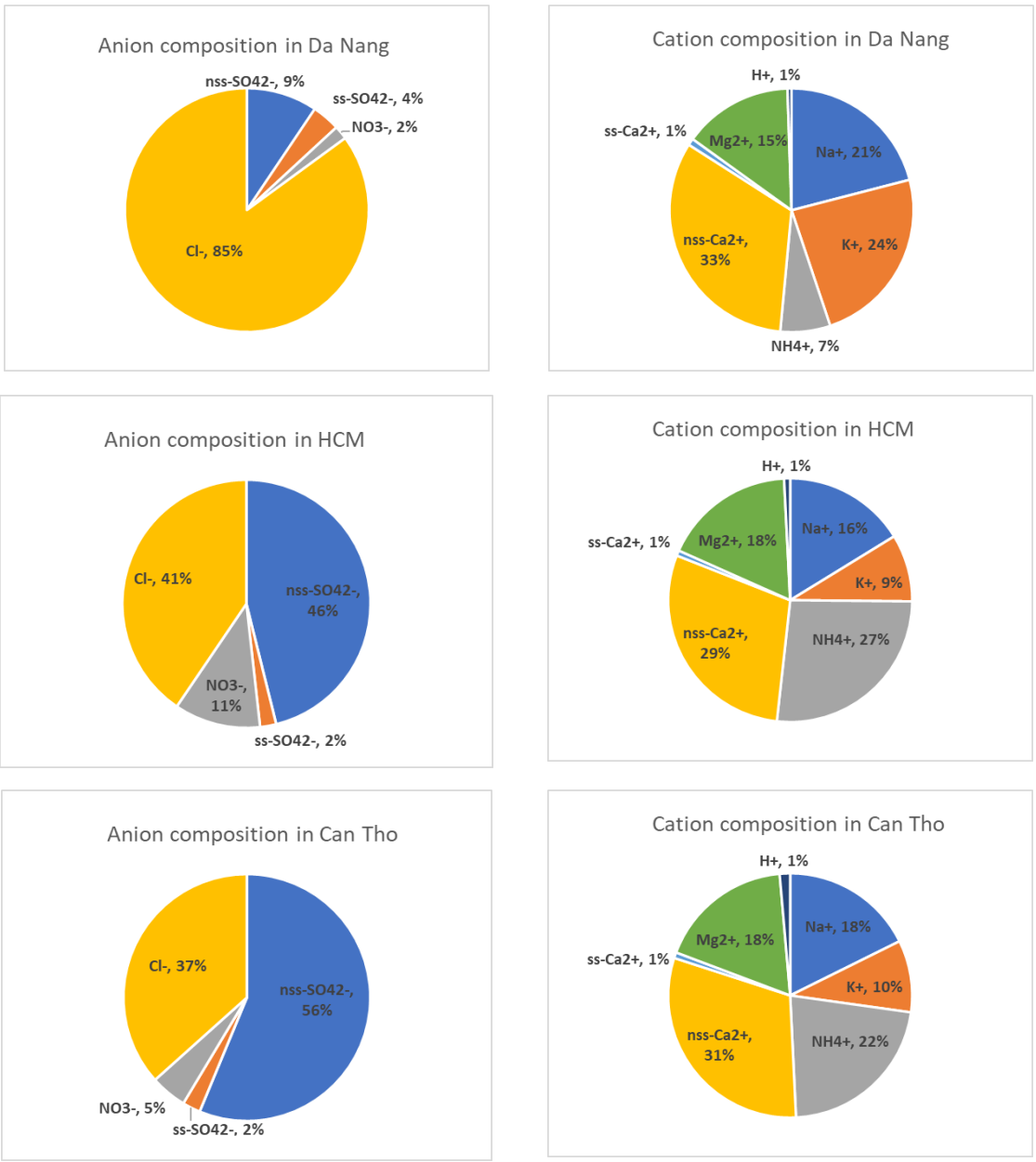


Figure 12. Major ion composition of rainwater in sites.

The results indicate that the ionic composition of rainwater varies considerably among the monitoring sites and exhibits distinct regional characteristics. The northern monitoring sites (Ha Noi, Hoa Binh, and Yen Bai) showed similar ionic compositions and no evident influence of sea-salt aerosols, with the exception of the Cuc Phuong site. In contrast, the monitoring sites in central Viet Nam (Da Nang) and southern Viet Nam (Can Tho and Ho Chi Minh City) exhibited relatively similar ionic compositions and clear evidence of sea-salt influence. This influence was particularly pronounced at the Da Nang site, which is located adjacent to the coastline, as reflected by the elevated concentrations of Cl^-, Na^+, and K^+ ions.

c) State of acid rain

The frequency of acid rain was evaluated based on the proportion of rainwater samples with pH

values below 5.6 (threshold of acid rain), for two monitoring periods: 2015–2019 and 2020–2024. The results showed that during the 2020–2024 period, acid rain occurred predominantly at the northern monitoring sites, whereas it was rarely observed at the central and southern sites. The Yen Bai site recorded the highest acid rain frequency (34%), followed by Hoa Binh (31%), Ha Noi (19%), Cuc Phuong (16%), Can Tho (7%), and Ho Chi Minh City (4%) (Fig. 14). No acid rain events were recorded at the Da Nang site. Overall, the northern monitoring sites exhibited substantially higher acid rain frequencies than those in central and southern Viet Nam.

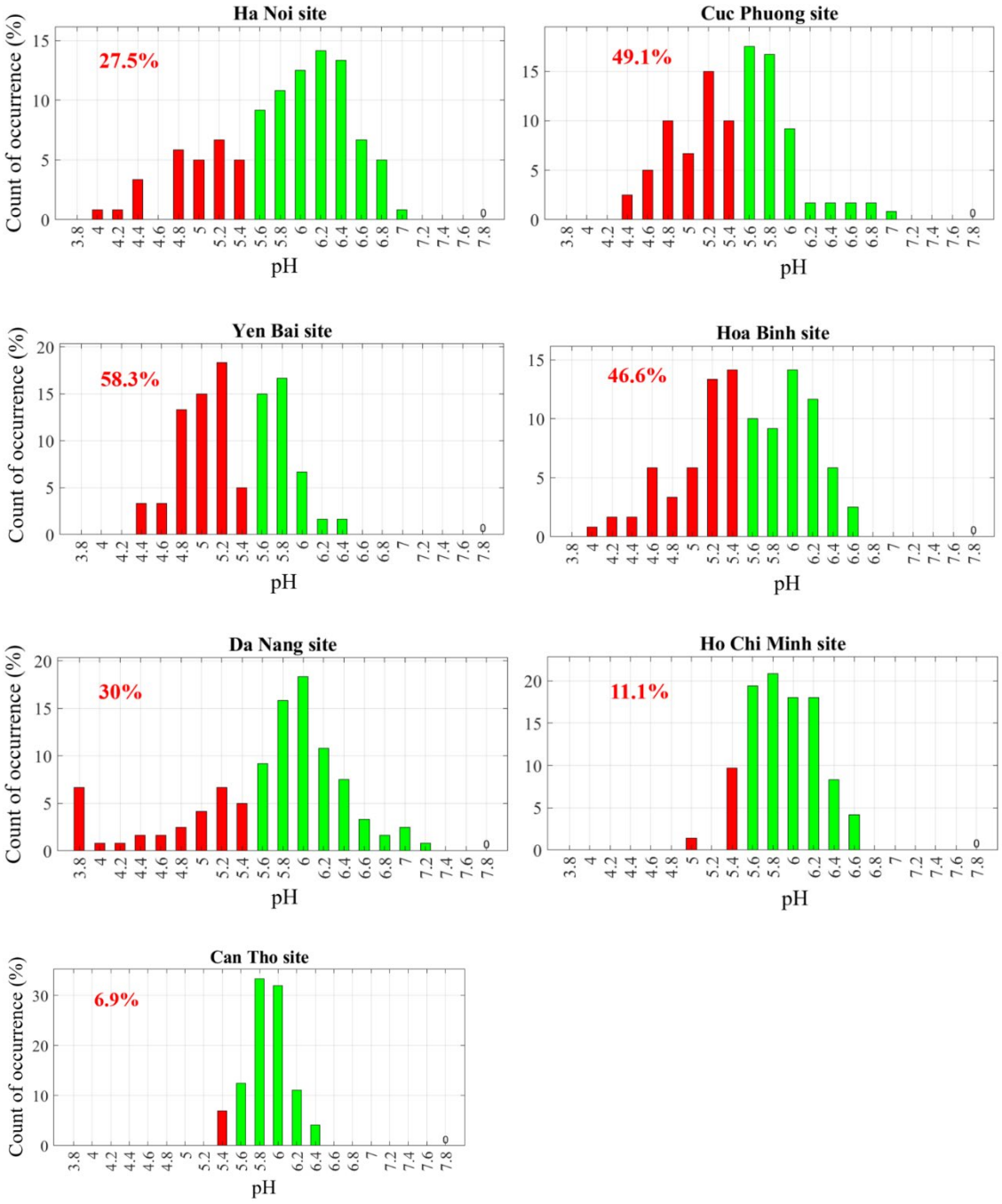


Figure 13. Frequency of acid rain (pH< 5.6) in sites (2015 – 2019)

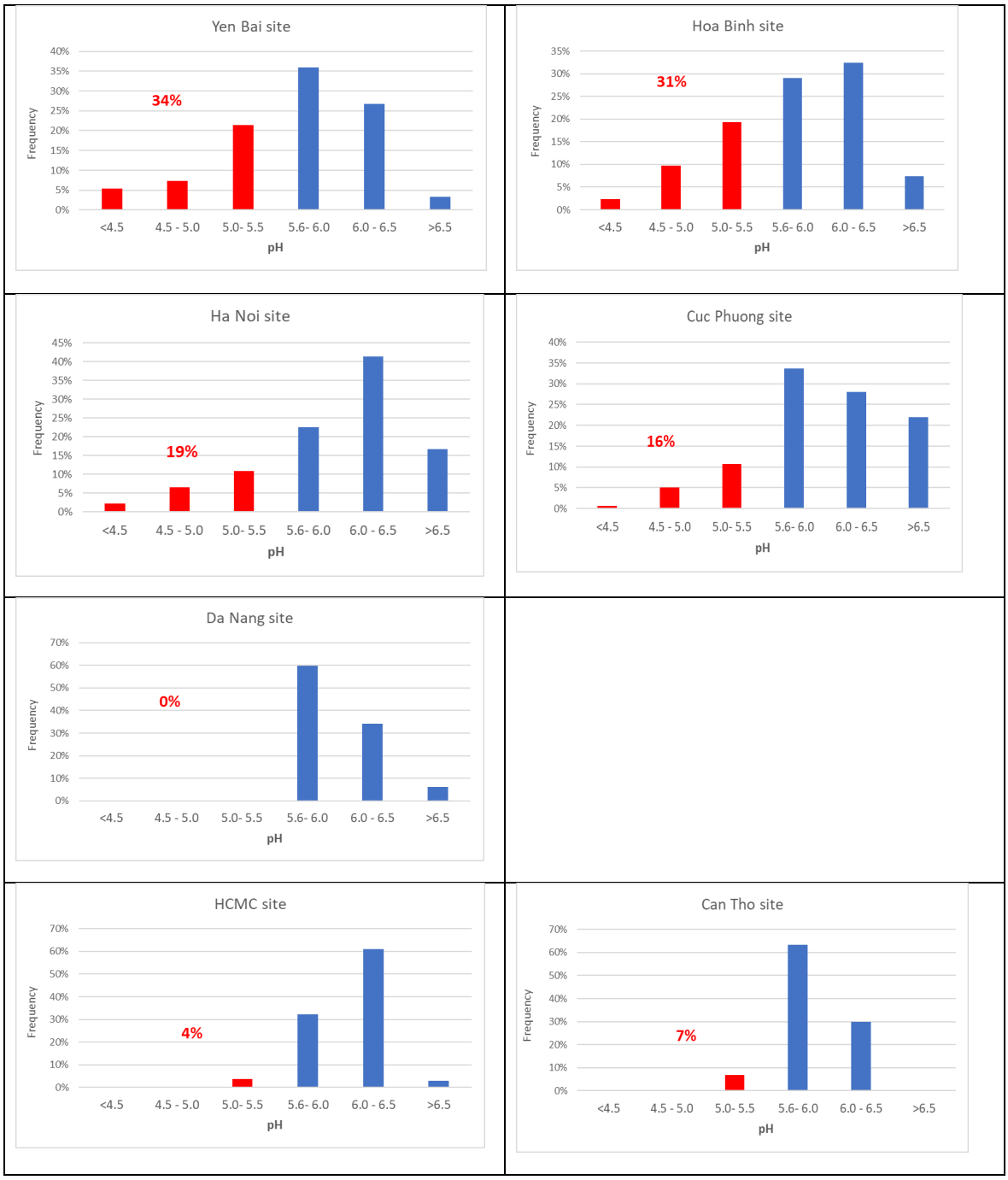


Figure 14. Frequency of acid rain (pH < 5.6) in sites (2020 – 2024)

Notably, acid rain occurred more frequently at the Cuc Phuong ecological site and at the rural sites of Yen Bai and Hoa Binh than at the urban sites of Ha Noi and Ho Chi Minh City. This finding suggests that the occurrence of acid rain is influenced not only by local emission sources but also by regional atmospheric transport and other meteorological factors.

Compared with the 2015–2019 period, the frequency of acid rain declined markedly during 2020–2024, particularly at the northern monitoring sites and at Da Nang site. Specifically, the acid rain frequency decreased from 58% to 34% at Yen Bai, from 46% to 31% at Hoa Binh, from 27% to 19% at Ha Noi, from 49% to 16% at Cuc Phuong, from 11% to 4% at Ho Chi Minh City, and from 30% to 0% at Da Nang (Fig. 13 & 14). These results indicate a substantial reduction in acid rain occurrence across the EANET monitoring network over the past decade.

d) Relationship between pollutant Concentrations, Precipitation Amount, and Wet Deposition Flux

Wet deposition is governed by both the level of atmospheric pollution and the amount of precipitation. Through scavenging processes, atmospheric pollutants are dissolved into precipitation, and their concentrations in precipitation therefore reflect the degree of air pollution. However, pollutant concentrations in precipitation are generally inversely related to precipitation amount because of the dilution; that is, greater precipitation results in lower pollutant concentrations in precipitation. In contrast, wet deposition flux is positively related to both precipitation amount and pollutant concentration.

The characteristics of atmospheric pollution and precipitation vary among monitoring sites, resulting in differences not only in the magnitude of wet deposition but also in the relationships among these variables. During the 2020–2024 period, the annual precipitation recorded at the seven acid deposition monitoring sites varied substantially, ranging from 1,376 to 3,946 mm. The highest mean annual precipitation was observed at the Da Nang site (3,048 mm), whereas the lowest was recorded at the Yen Bai site (1,788 mm).

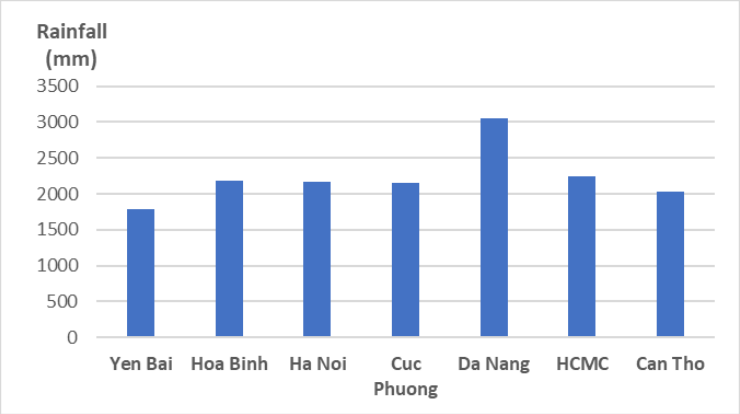


Fig 15. Annual rainfall amount in sites (2020-2024)

The temporal variations in the concentrations and wet deposition fluxes of the three principal acidifying ions (nss-SO_4^{2-}, NO_3^-, and H^+), along with the corresponding precipitation amounts, are shown in Figures 21–24. During 2020–2024, the northern monitoring sites (Ha Noi, Hoa Binh, Yen Bai, and Cuc Phuong) consistently exhibited substantially higher concentrations and wet deposition fluxes of these ions than the central (Da Nang) and southern (Ho Chi Minh City and Can Tho) sites. Furthermore, pronounced interannual fluctuations were observed at the northern sites, whereas no consistent increasing or decreasing trend was evident. By contrast, both ion concentrations and wet deposition fluxes remained relatively stable at the central and southern sites throughout this period.

Among the northern monitoring sites, Ha Noi, Hoa Binh, and Yen Bai consistently exhibited elevated concentrations of all three acidifying ions (nss-SO_4^{2-}, NO_3^-, and H^+) in precipitation. The concentrations of nss-SO_4^{2-} and NO_3^- generally ranged from approximately 30 to 90 µmol L^{-1}, while H^+ concentrations ranged from about 2 to 10 µmol L^{-1}. These elevated ion concentrations indicate a relatively high level of atmospheric pollution in these areas and contribute to the occurrence of acid rain.

In contrast, the Cuc Phuong site, an ecological monitoring site, exhibited a different pattern. Nitrate (NO_3^-) concentrations were relatively high, reaching several tens of µmol L^{-1}, whereas nss-SO_4^{2-} and

H^+ concentrations remained comparatively low relative to those observed at the other northern sites.

At the central site (Da Nang) and the southern sites (Ho Chi Minh City and Can Tho), the concentrations of nss-SO_4^{2-}, NO_3^-, and H^+ were generally lower than those measured at the northern sites, suggesting better regional air quality conditions.

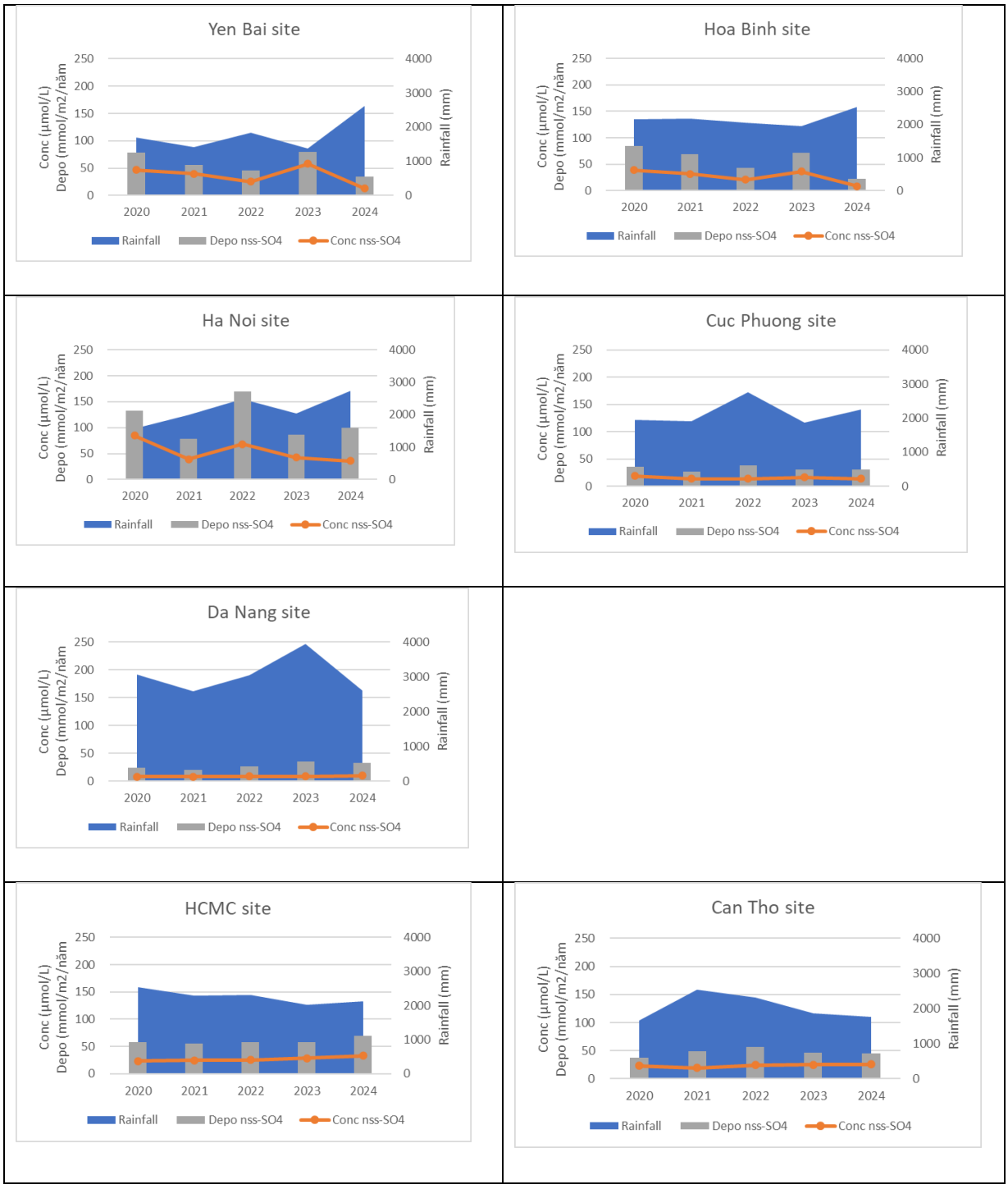


Fig.16. Relationship between nss-SO_4^{2-} Concentrations, Precipitation Amount, and Wet Deposition Flux

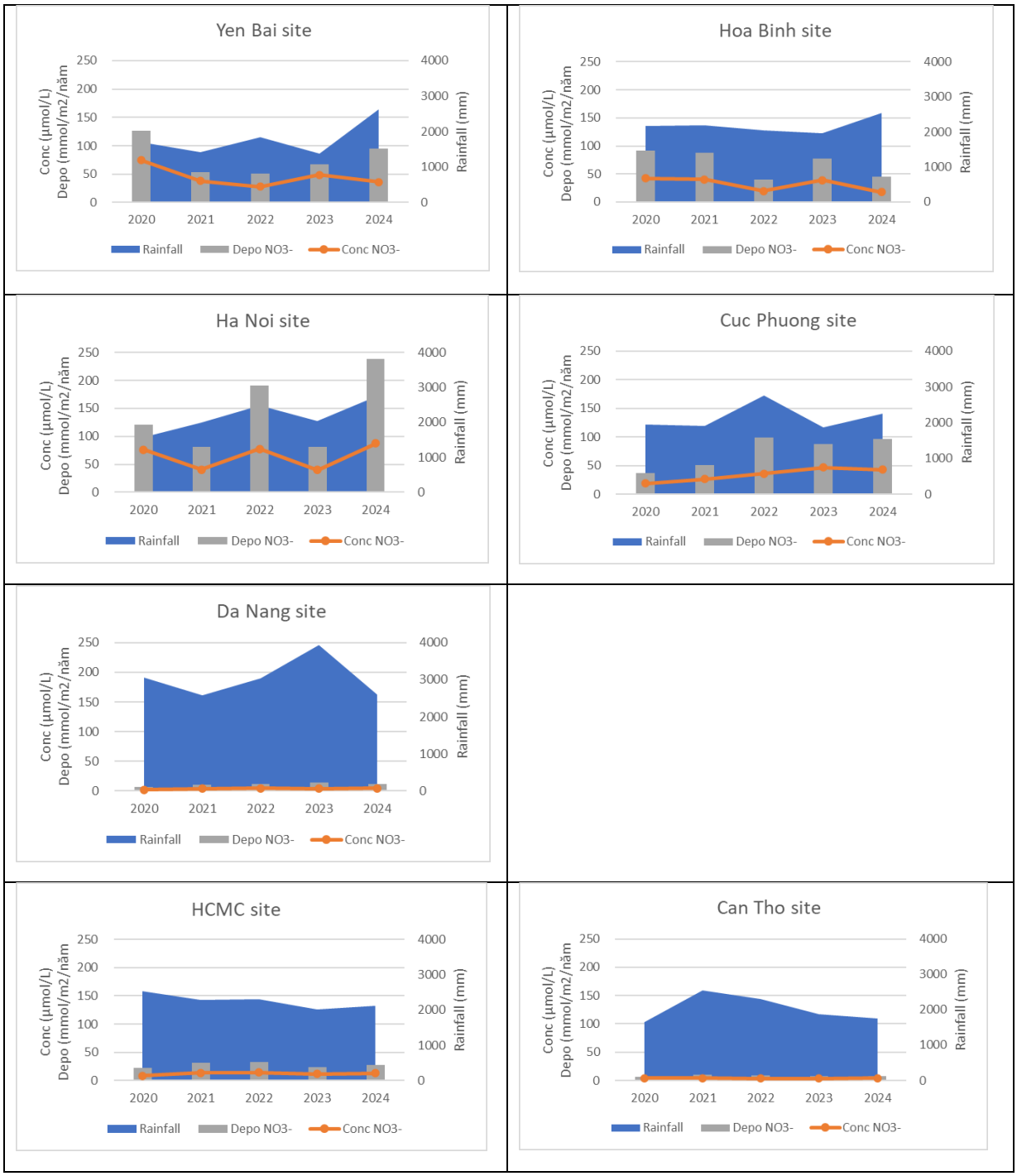


Fig. 17. Relationship between NO_3^- concentrations, Precipitation Amount, and Wet Deposition Flux

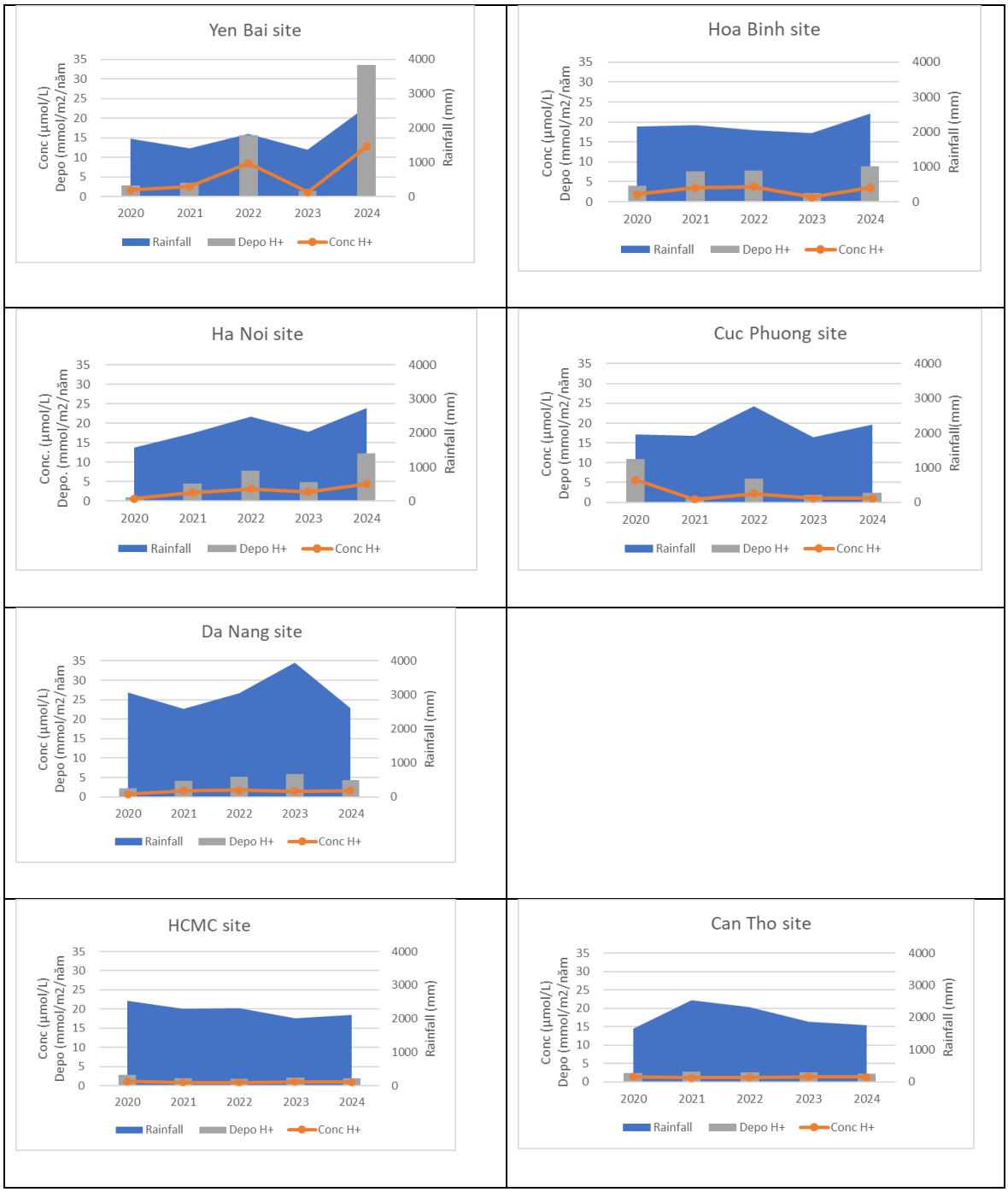


Fig. 18. Relationship between H^+ Concentrations, Precipitation Amount, and Wet Deposition Flux

d) Trend of wet deposition

Using a 25-year monitoring dataset (2000–2024), trends in wet acid deposition at the seven EANET monitoring sites in Vietnam were evaluated using statistical trend analysis. Annual wet deposition data were subjected to linear regression analysis to determine increasing or decreasing trends, and the statistical significance of each trend was assessed using the p-value criterion ($p < 0.05$).

Annual wet deposition fluxes (mmol m^{-2} yr^{-1}) of the three principal ions associated with acid rain formation: H^+, (nss-SO_4^{2-}), and (NO_3^-) were collected from the seven sites of the Viet Nam EANET network for trend assessment. These ions are key indicators of acid deposition because acid rain is

primarily caused by the presence of sulfuric acid (H_2SO_4) and nitric acid (HNO_3) in precipitation. In addition, trends in ammonium (NH_4^+) deposition were also examined because NH_4^+ plays an important role in neutralizing acidity in precipitation.

The results of the wet deposition trend analysis for H^+, nss-SO_4^{2-}, NO_3^-, and NH_4^+ are presented in terms of the slope coefficient derived from linear regression and the corresponding p-value, which indicates the statistical significance of the observed trend (Figures 24–27 and Table 3.3).

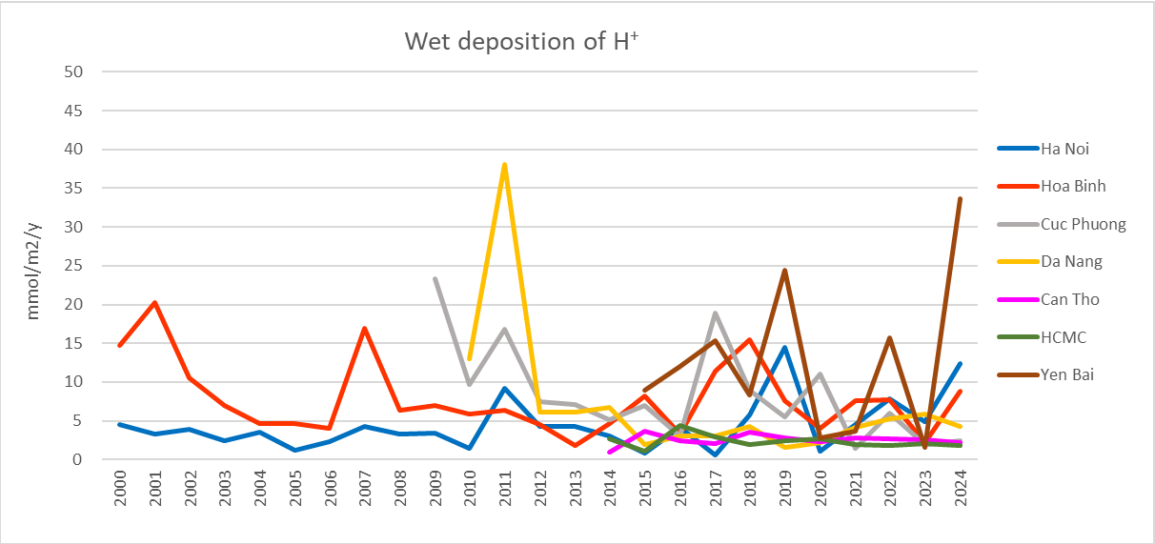


Fig. 19. Temporal Variation of H^+ Wet Deposition (2000–2024)

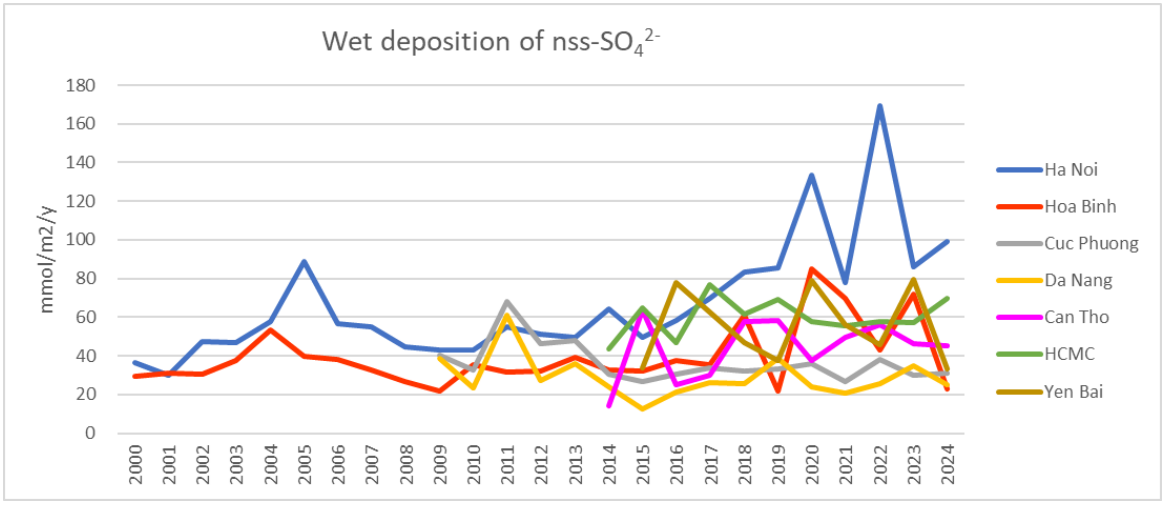


Fig. 20. Temporal variation of nss-SO_4^{2-} Wet deposition (2000–2024)

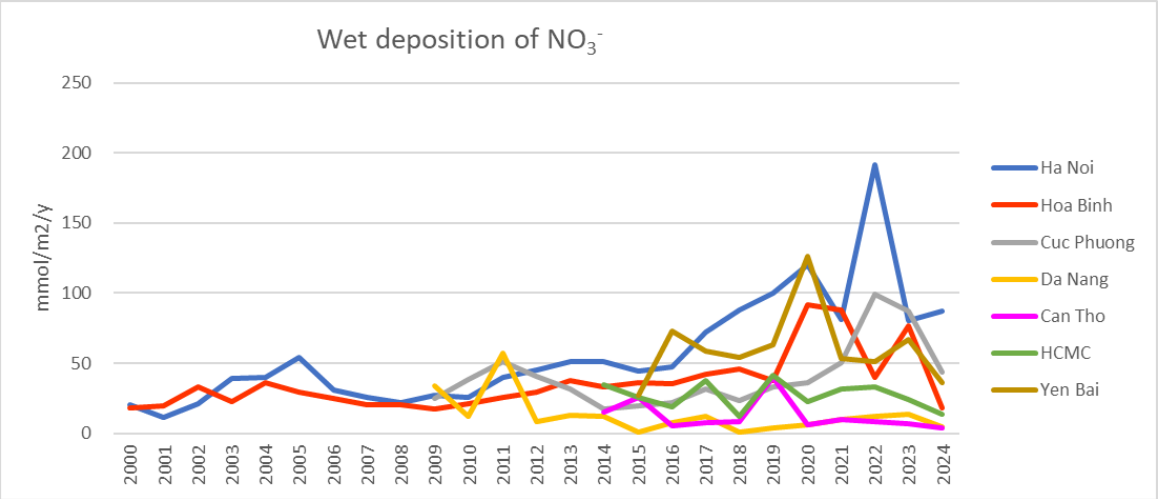


Fig. 21. Temporal variation of NO_3^- Wet deposition (2000–2024)

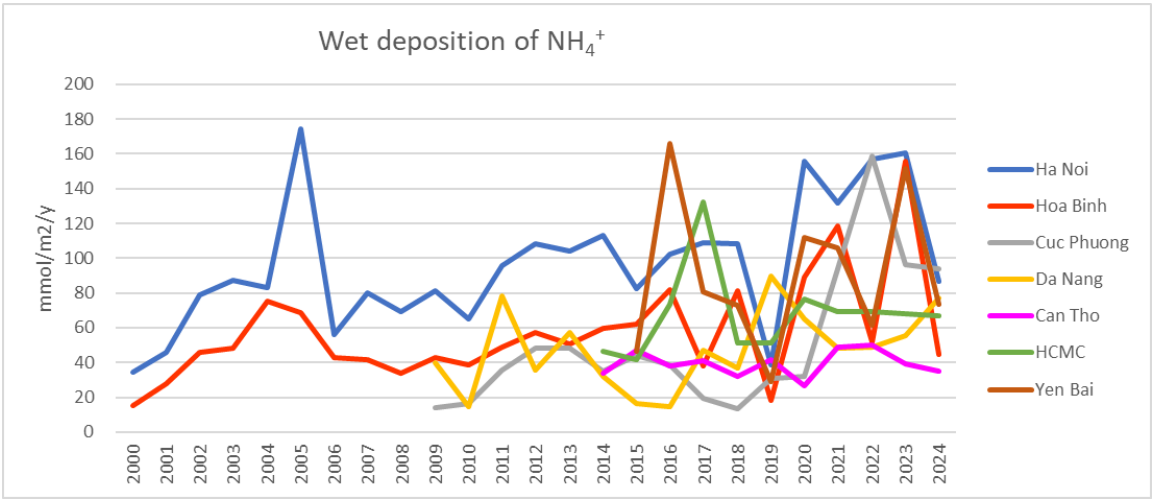


Fig. 22. Temporal variation of NH_4^+ Wet deposition (2000–2024)

Table 2. Trend analysis of Wet deposition in Vietnam EANET sites (2000- 2024)

Sites	Ions	Slope coefficient	p-value	Significant trend (p<0,05)
Yên Bái	H^+	-0.79079	0.443828	-
	nss-SO_4^{2-}	1.780254	0.481639	-
	NO_3^-	2.562866	0.496797	-
	NH_4^+	3.280	0.6169	-
Hà Nội	H^+	0.121537	0.175582	-
	nss-SO_4^{2-}	2.96002	0.000363	Increasing
	NO_3^-	4.361193	1.16E-05	Increasing
	NH_4^+	3.059	0.0040	Increasing
Hòa Bình	H^+	-0.22886	0.107696	-
	nss-SO_4^{2-}	1.171694	0.010673	Increasing
	NO_3^-	2.087444	8.64E-05	Increasing
	NH_4^+	2.504	0.0040	Increasing
Cúc Phương	H^+	-0.78662	0.03103	Decreasing

	nss-SO_4^{2-}	-1.15502	0.069482	-
	NO_3^-	2.901761	0.036305	Increasing
	NH_4^+	5.471	0.0135	Increasing
Đà Nẵng	H^+	-1.9898	0.012538	Decreasing
	nss-SO_4^{2-}	-0.73098	0.301353	-
	NO_3^-	-1.52636	0.073593	-
	NH_4^+	1.492	0.2710	-
Cần Thơ	H^+	0.054114	0.543504	-
	nss-SO_4^{2-}	2.297716	0.223051	-
	NO_3^-	-0.87723	0.503789	-
	NH_4^+	0.551	0.5397	-
Hồ Chí Minh	H^+	-0.08097	0.448489	-
	nss-SO_4^{2-}	0.412494	0.72599	-
	NO_3^-	0.072346	0.946862	-
	NH_4^+	1.183	0.7011	-

The results of the 25-year trend analysis (2000–2024) indicate that acid deposition, as reflected by wet deposition fluxes of nss-SO_4^{2-} and NO_3^-, has increased significantly at northern monitoring sites, including Ha Noi, Hoa Binh, and Cuc Phuong. This increase occurred despite a decline in acid rain occurrence, as evidenced by decreasing H^+ deposition and by decreasing frequency of acid rain, primarily due to increasing NH_3/ NH_4^+ pollution and the associated enhancement of acid neutralization in precipitation.

The Da Nang site (central Viet Nam) showed a statistically significant decreasing trend in H^+ wet deposition, indicating a reduction in acid rain occurrence. In contrast, no significant trends in wet deposition were identified at the southern monitoring sites during the period of 2000- 2024.

2.2 State of dry deposition

a) Gases concentration

Dry acid deposition was assessed based on the atmospheric concentrations of the gaseous species SO_2, HCl, HNO_3, and NH_3, together with the ionic composition of atmospheric aerosols. The spatial and temporal variations in the concentrations of SO_2, HCl, HNO_3, and NH_3 were evaluated using observations from the five Vietnamese EANET monitoring sites for dry deposition (Yen Bai, Hoa Binh, Ha Noi, Ho Chi Minh City, and Can Tho).

During the recent five-year period (2020–2024), the annual mean SO_2 concentrations at the monitoring sites ranged from 0.4 to 1.2 ppb. Overall, the northern monitoring sites (Yen Bai, Hoa Binh, and Ha Noi) exhibited higher SO_2 concentrations and greater variability than the southern sites (Ho Chi Minh City and Can Tho). In contrast, the southern sites showed relatively stable SO_2 concentrations throughout the period, remaining at comparable levels of approximately 0.5–0.6 ppb. No distinct seasonal pattern in SO_2 concentrations was identified across the monitoring sites. Nevertheless, slight increases in SO_2 concentrations were observed at the Ha Noi and Yen Bai sites during September–November, while a slight decline was evident at the Ho Chi Minh City site during November–December.

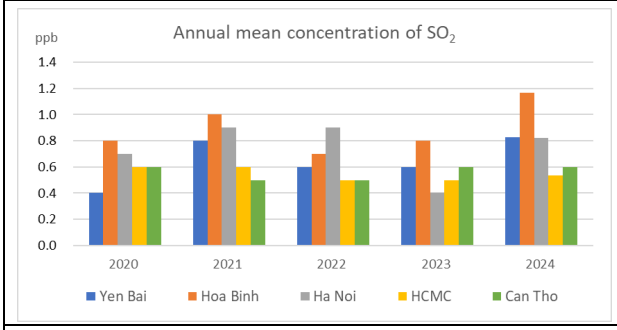


Fig.23. Temporal variation of SO_2 concentrations at Sites (2020-2024)

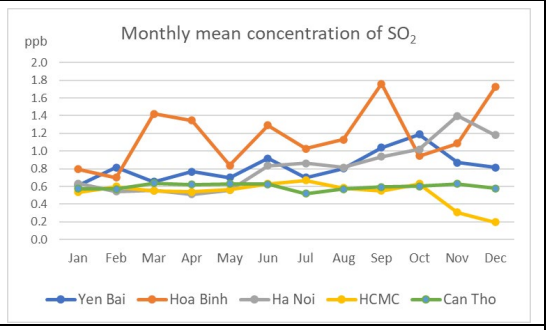


Fig. 24. Monthly variation of SO_2 concentrations at Sites

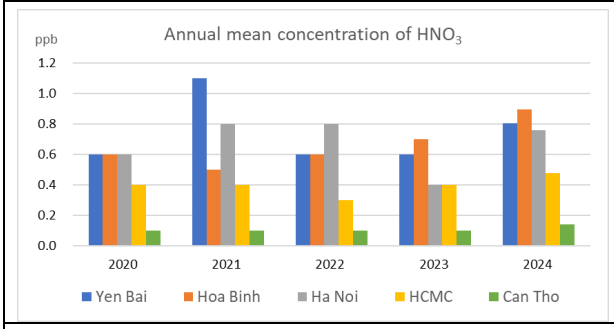


Fig.25. Temporal variation of HNO_3 concentrations at Sites (2020-2024)

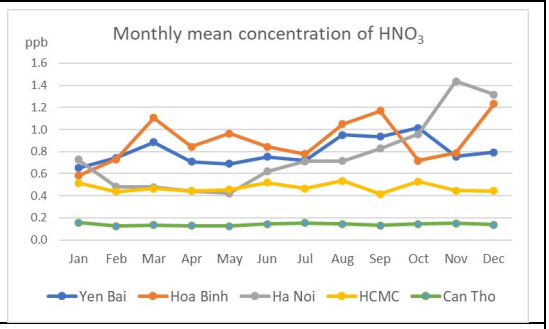


Fig.26. Monthly variation of HNO_3 concentrations at Sites

The annual mean HNO_3 concentrations varied considerably among the monitoring sites, ranging from 0.1 to 1.1 ppb. The northern monitoring sites (Yen Bai, Hoa Binh, and Ha Noi) consistently exhibited substantially higher HNO_3 concentrations than the southern sites, with levels approximately two to three times higher than those at Ho Chi Minh City and five to ten times higher than those at Can Tho. The Can Tho site consistently recorded the lowest HNO_3 concentrations throughout the 2020–2024 period. The highest annual mean HNO_3 concentrations were observed at the Yen Bai site in 2021 and at the Hoa Binh site in 2024. In contrast, the southern sites maintained relatively low and stable HNO_3 concentrations during the study period. No clear seasonal pattern in HNO_3 concentrations was identified across the monitoring sites. However, a slight increase in HNO_3 concentrations was observed at the Ha Noi site during September–December.

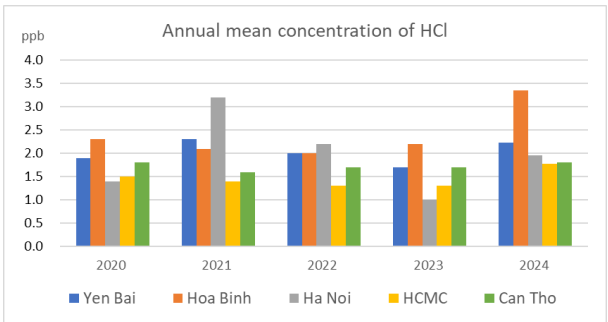


Fig.27. Temporal variation of HCl concentrations at Sites (2020- 2024)

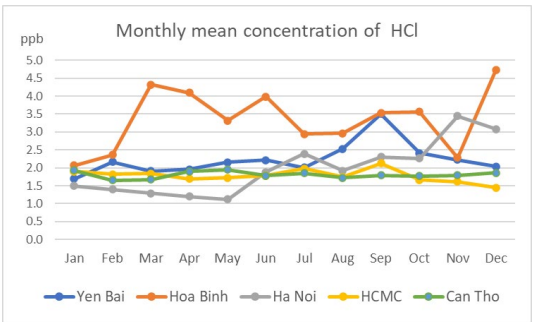


Fig.28. Monthly variation of HCl concentrations at Sites

The annual mean HCl concentrations showed considerable spatial variation among the monitoring sites, ranging from 1.0 to 3.3 ppb. At the northern monitoring sites, HCl concentrations exhibited substantial interannual variability, with the lowest annual mean concentration recorded at the Ha Noi site in 2023 and the highest at the Hoa Binh site in 2024. In contrast, the southern sites maintained relatively stable HCl concentrations, ranging from 1.3 to 1.6 ppb throughout the period of 2020- 2024. No distinct seasonal pattern in HCl concentrations was observed across the monitoring sites.

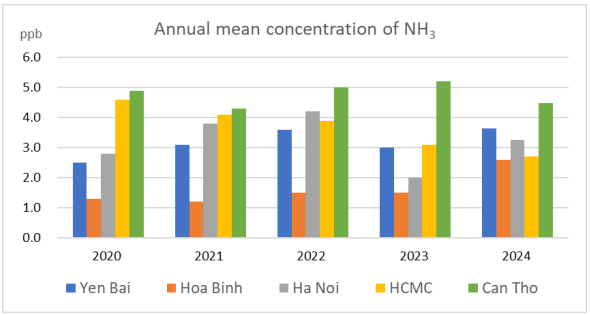


Fig.29. Temporal variation of NH_3 concentrations at Sites (2020- 2024)

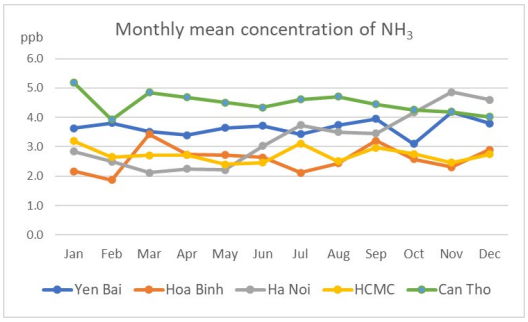


Fig.30. Monthly variation of NH_3 concentrations at Sites

The annual mean NH_3 concentrations varied substantially among the monitoring sites, ranging from 1.2 to 5.2 ppb. In contrast to the acidic gases (SO_2, HNO_3, and HCl), NH_3, an alkaline gas, generally exhibited lower concentrations at the northern monitoring sites (Yen Bai, Hoa Binh, and Ha Noi) than at the southern sites (Ho Chi Minh City and Can Tho). The lowest annual mean NH_3 concentration was recorded at the Hoa Binh site, whereas the highest was observed at the Can Tho site. With respect to seasonal variation, no distinct seasonal pattern in NH_3 concentrations was observed at most monitoring sites.

b) Aerosol composition

The major ionic constituents of atmospheric aerosols were classified into two groups: cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, and NH_4^+) and anions (SO_4^{2-}, NO_3^-, and Cl^-). Analysis of aerosol ionic composition revealed clear differences between urban and rural monitoring sites.

The urban sites (Ha Noi and Ho Chi Minh City) exhibited the highest total ionic concentrations, ranging from 276 to 372 $\mu eq.L^{-1}$, and showed similar ionic composition profiles, with Ca^{2+} and SO_4^{2-} as the dominant ions, accounting for approximately 26–32% and 22–24% of the total ionic concentration, respectively.

The rural sites exhibited lower total ionic concentrations, with annual mean values of 244 $\mu eq.L^{-1}$ at Can Tho, 177 $\mu eq.L^{-1}$ at Yen Bai, and 55 $\mu eq.L^{-1}$ at Hoa Binh. These sites also shared similar ionic composition profiles, in which Ca^{2+}, NH_4^+, and SO_4^{2-} were the dominant species, contributing approximately 14–20%, 15–21%, and 20–29% of the total ionic concentration, respectively.

These results indicate that urban and rural areas differ in both aerosol pollution levels and chemical composition. Aerosol pollution was generally more severe at the urban sites

(Ha Noi and Ho Chi Minh City) than at the rural sites (Yen Bai, Hoa Binh, and Can Tho). Calcium (Ca^{2+}) and sulfate (SO_4^{2-}) were the predominant ionic components at both urban and rural sites. However, NH_4^+ accounted for a substantially larger proportion of the aerosol ionic composition at the rural sites than at the urban sites.

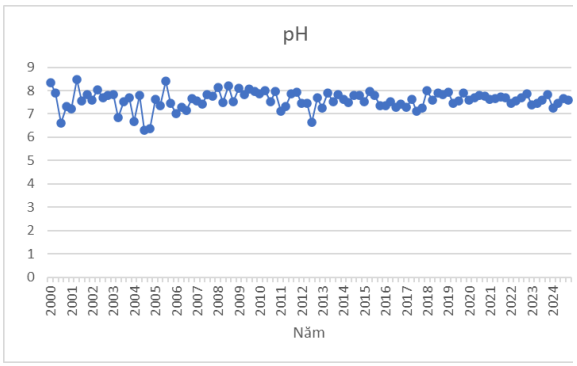


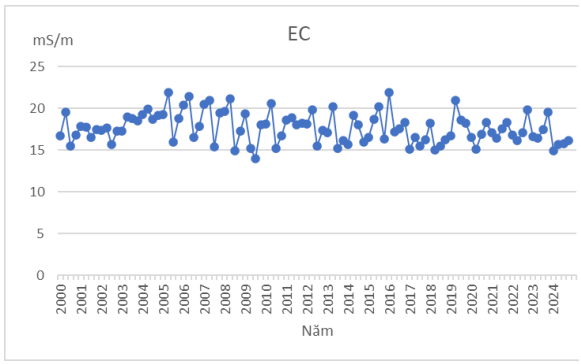
Fig.31. Aerosol ionic composition in sites

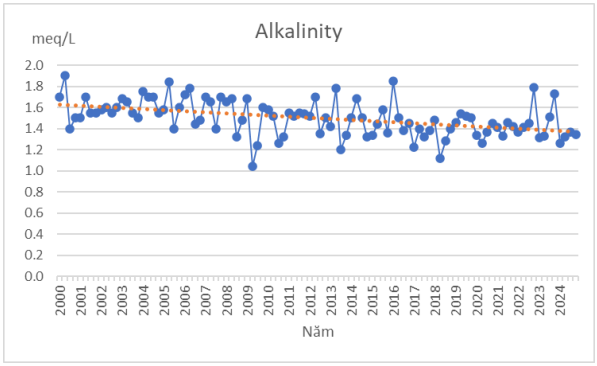
2.3 State of inland aquatic environment

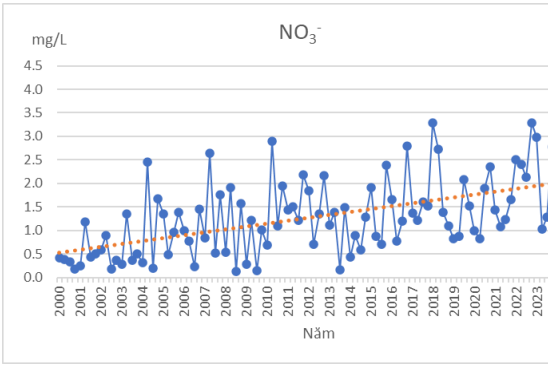
a) *Characteristics and temporal variation of water chemistry in Hoa Binh Reservoir*

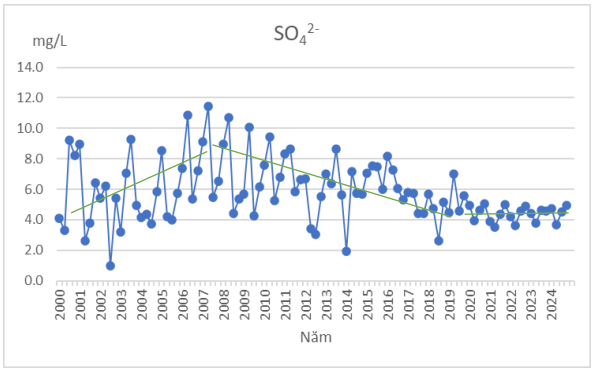
Hoa Binh Reservoir is characterized by relatively high pH (7.59) and alkalinity (1.5 meq L^{-1}), with Ca^{2+} and SO_4^{2-} as the predominant ions. Over the 25-year monitoring period (2000–2024), the chemical composition of the reservoir water exhibited measurable changes, as evidenced by temporal variations in the concentrations of the major ions (Figure 3.1).

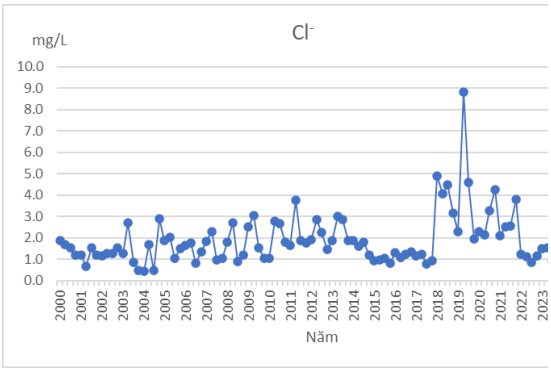

pH
Năm

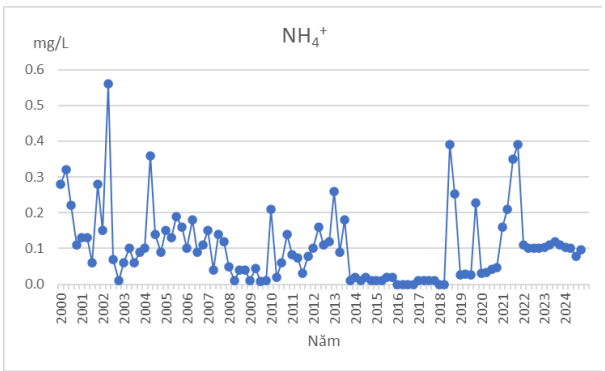

EC
mS/m
Năm


Alkalinity
meq/L
Năm


NO3-
mg/L
Năm


SO4 2-
mg/L
Năm


Cl-
mg/L
Năm


NH4+
mg/L
Năm

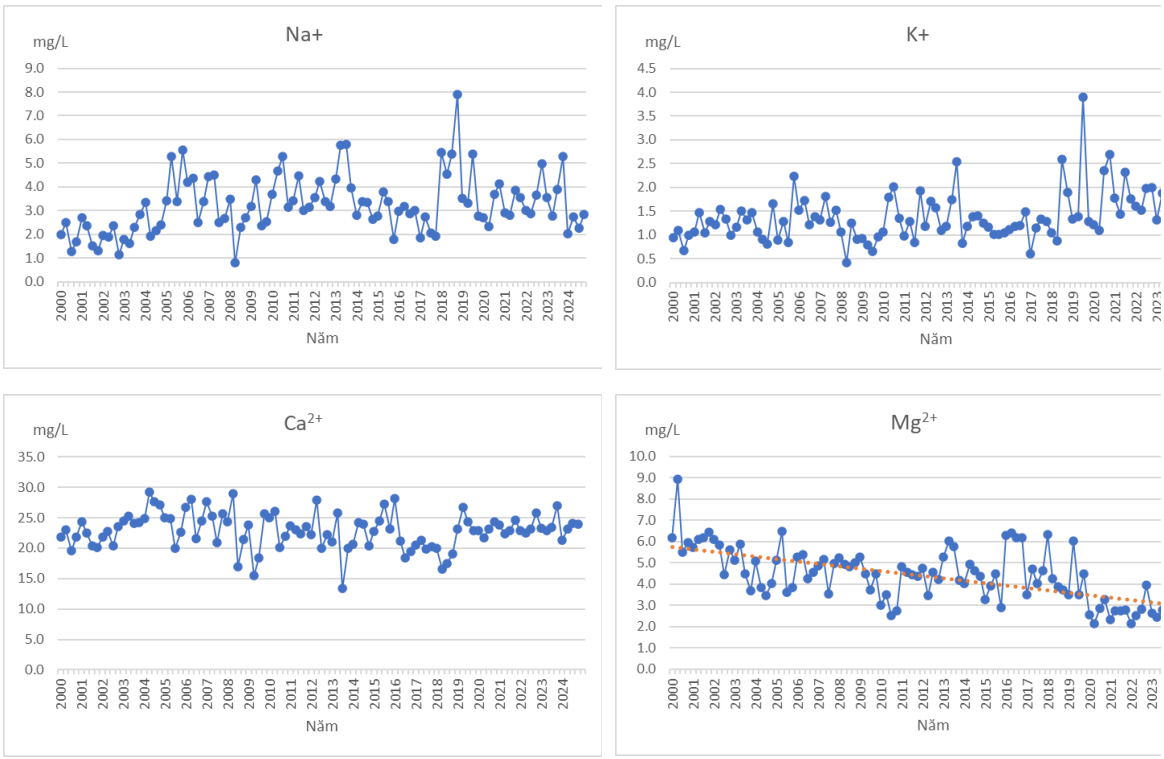


Fig 321. Temporal variation of water chemistry in Hoa Binh Reservoir (2000- 2024)

- The pH values ranged from 6.31 to 8.49.
- Electrical conductivity (EC) exhibited substantial variability, ranging from 14 to 22 mS m^{-1}.
- Alkalinity also varied considerably, ranging from 1.04 to 1.90 meq L^{-1}.
- SO_4^{2-} concentrations showed pronounced variability, ranging from 1.0 to 11.45 mg L^{-1}. Three distinct phases of SO_4^{2-} concentration change were identified over the 25-year monitoring period. During 2000–2007, SO_4^{2-} concentrations increased rapidly from approximately 4 to 8 mg L^{-1}. This was followed by a marked decline from approximately 8 to 4 mgL^{-1} during 2008–2019. From 2020 to 2024, SO_4^{2-} concentrations remained relatively stable at around 4 mg L^{-1}.
- NO_3^- concentrations ranged from 0.13 to 3.91 mg L^{-1}. Despite considerable variability, a clear increasing trend in NO_3^- concentrations was observed over the 2000–2024 period.
- Cl^- concentrations varied widely, ranging from 0.4 to 8.8 mg L^{-1}. However, no distinct seasonal pattern or long-term trend was identified.
- NH_4^+ concentrations ranged from below the detection limit (<0.01 mg L^{-1}) to 0.56 mgL^{-1}. No distinct seasonal pattern or long-term trend was observed.
- Na^+ concentrations exhibited considerable variability, ranging from 0.81 to 7.90 mg L^{-1}.
- K^+ concentrations ranged from 0.42 to 3.90 mg L^{-1}.
- Ca^{2+} concentrations ranged from 13.33 to 29.17 mg L^{-1}.
- Mg^{2+} concentrations ranged from 2.06 to 8.92 mg L^{-1}. A pronounced decreasing trend in Mg^{2+} concentrations was observed over the 2000–2024 monitoring period.

b) Trends in the Chemical Composition of Hoa Binh Reservoir Water

The linear regression analysis indicated that the chemical composition of Hoa Binh Reservoir water has changed over the past 25 years. Among the monitored parameters, NO_3^- exhibited an increasing trend, whereas Mg^{2+} showed a decreasing trend. For the remaining parameters, however, no clear trends were identified by linear regression. Therefore, the Seasonal Mann–Kendall (SMK) test was applied to further evaluate the temporal changes in the major ions of Hoa Binh Reservoir water. The results are presented in terms of the Z statistic, the corresponding p-value indicating the statistical significance of the trend, and Sen's slope for the major water quality parameters, including pH/H^+, EC, alkalinity, SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+} (Table 3).

Table 3. Trends in the chemical composition of Hoa Binh Reservoir Water (2000-2024)

Parameter	n	tau	S	Z	p_value	Sen's slope	Trend (p<0.05)
pH	100	-0.01232	-61	-0.17872	0.858156	-0.0009	No
H^+	100	0.012323	61	0.178722	0.858156	3.64E-08	No
EC	100	-0.15515	-768	-2.28448	**0.022343**	-0.058	Decreasing
Alkalinity	100	-0.33778	-1672	-4.98161	**6.31E-07**	-0.011	Decreasing
SO_4^{2-}	100	-0.19515	-966	-2.87398	**0.004053**	-0.085	Decreasing
NO_3^-	100	0.38	1881	5.599265	**2.15E-08**	0.058	Increasing
Cl^-	100	0.115152	570	1.694794	0.090115	0.019	No
NH_4^+	100	-0.14384	-712	-2.12425	**0.033649**	-0.002	Decreasing
Na^+	100	0.21596	1069	3.180812	**0.001469**	0.046	Increasing
K^+	100	0.270101	1337	3.979488	**6.91E-05**	0.024	Increasing
Ca^{2+}	100	-0.03717	-184	-0.54502	0.585738	-0.020	No
Mg^{2+}	100	-0.4602	-2278	-6.78191	**1.19E-11**	-0.124	Decreasing

Note: Z values +/- reveal ***Increasing/Decreasing trends****, shaded cells indicate statistically significant results (p < 0.05)*

The trend analysis indicated that alkalinity, EC, SO_4^{2-}, Mg^{2+}, and NH_4^+ exhibited statistically significant decreasing trends ($p < 0.05$). In contrast, Na^+, K^+, and NO_3^- showed statistically significant increasing trends ($p< 0.05$). No statistically significant trends were identified for pH/H^+, Ca^{2+}, and Cl^- ($p \geq 0.05$).

Based on the measured pH values and the trend analysis of pH/H^+ over the 25-year monitoring period (2000–2024), there is no evidence that Hoa Binh Reservoir has undergone acidification, despite the relatively high acid rain frequency (25%) in the region (Hoa Binh site) and the substantial acid deposition load of approximately 25–30 kg ha^{-1} yr^{-1} reported in studies [N.T.V. Anh, 2018]. The absence of acidification in Hoa Binh reservoir can be attributed primarily to the high buffering capacity of the reservoir water, as indicated by its relatively high alkalinity (1.5 meq L^{-1}), which is sufficient to neutralize the acidity introduced through atmospheric deposition.

The results also revealed a decreasing trend in SO_4^{2-} concentration and an increasing trend in NO_3^- concentration in the reservoir water. These findings are consistent with previous studies conducted in Viet Nam and across Southeast Asia, which have reported a long-term shift in acid deposition from sulfate-dominated to nitrate-dominated inputs, characterized by declining sulfate deposition and increasing nitrate deposition [EANET, 2021; N.T.K. Anh, 2019; N.T.V. Anh, 2017].

Chapter 3. Review of National Air Quality Management including Acid Deposition

In Viet Nam, the air quality management system is organized into two administrative levels: the central (national) level and the local (provincial/municipal) level.

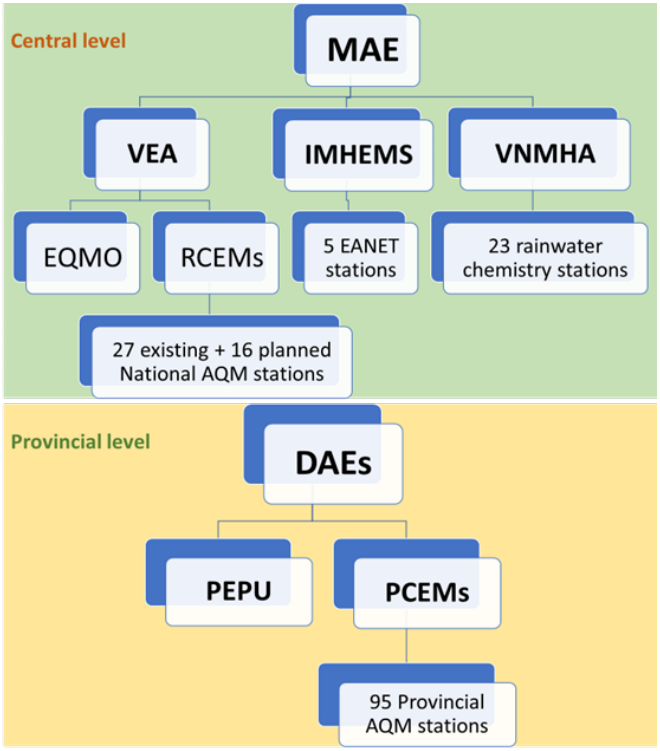


Fig. 33. Institutional structure of Air quality management system including Acid deposition in Vietnam

At the central level, Air quality management is overseen by the Ministry of Agriculture and Environment (MAE). Within the MAE, the Viet Nam Environment Agency (VEA) is responsible for implementing Air quality management through two key units: the Environmental Quality Management Office (EQMO) and the Regional Centers for Environmental Monitoring (RCEMs). The EQMO is responsible for developing policies, regulations, and technical guidelines related to air quality management, while the RCEMs are responsible for the operation and management of the National Air Quality Monitoring Network (National AQM stations).

In addition, MAE has designated the Institute of Meteorology, Hydrology, Environment and Marine Sciences (IMHEMS) as the National Focal Point (NFP) for the East Asian Acid Deposition Monitoring Network (EANET). IMHEMS is responsible for coordinating EANET activities in Viet Nam and for operating and managing the country's EANET acid deposition monitoring network. In addition, MAE has recently assigned IMHEMS to conduct research on atmospheric pollution dispersion and to develop air quality forecasting capabilities for major cities in Viet Nam.

Furthermore, the Viet Nam Meteorological and Hydrological Administration (VNMHA) is responsible for operating the rainwater quality monitoring network, which is integrated with meteorological stations across the country.

At the local level, Air quality management falls under the authority of the provincial or municipal Departments of Agriculture and Environment. Overall environmental management is undertaken by the Provincial Environmental Protection Units (PEPUs), while the Provincial Centers for Environmental Monitoring (PCEMs) are responsible for operating the provincial air quality monitoring networks (Provincial AQM stations).



Note: Red dots represent National AQM stations and green dots represent Provincial AQM stations [Source: VEA, 2021]

Fig.34. Location of automatic and continuous ambient air quality monitoring stations

Chapter 4. Conclusion

Since joining the East Asian Acid Deposition Monitoring Network (EANET) in 1999, Viet Nam has been an active member in the Network's activities. Over the past two decades, the Vietnam EANET network has expanded to seven monitoring sites distributed across the country.

As the National Focal Point (NFP) of Viet Nam, the Institute of Meteorology, Hydrology, Environment and Marine Sciences (IMHEMS) has been responsible for conducting continuous acid deposition monitoring at the seven EANET sites located in Yen Bai, Hoa Binh, Ha Noi, Cuc Phuong, Da Nang, Ho Chi Minh City, and Can Tho. In addition, IMHEMS has actively participated in all major EANET activities, including Inter-Laboratory Comparison, technical training courses, technical workshops, and EANET's research projects such as the Low-Cost Sensor (LCS) project and the Volatile Organic Compounds (VOC) project.

The results of acid deposition monitoring in Viet Nam indicate the following:

- The occurrence of acid rain during the 2020–2024 period decreased markedly compared with the 2015–2019 period, particularly at the northern monitoring sites and the central site (Da Nang).
- Long-term trend analysis (2000–2024) revealed significant increases in the wet deposition fluxes of nss-SO_4^{2-} and NO_3^- at the northern monitoring sites (Ha Noi, Hoa Binh, and Yen Bai). This increase occurred despite a decline of acid rain, as indicated by decreasing H^+ deposition, and is likely associated with increasing atmospheric NH_3/NH_4^+ levels and enhanced acid neutralization.
- The concentrations of the gaseous pollutants SO_2, HNO_3, HCl, and NH_3 were generally higher and exhibited greater variability at the northern monitoring sites (Yen Bai, Hoa Binh, and Ha Noi) than at the southern sites (Ho Chi Minh City and Can Tho).
- Analysis of aerosol ionic composition showed that the urban sites (Ha Noi and Ho Chi Minh City) had the highest total ionic concentrations (276–372 μeq L^{-1}), with Ca^{2+} and SO_4^{2-} as the dominant ionic species.
- The pH of Hoa Binh Reservoir remained stable, approximately 7.5, indicating that the reservoir has not undergone acidification. Acid deposition appears to have only a limited influence on changes in reservoir water quality because the reservoir is affected by various pollution sources, including industrial, agricultural, transportation, and domestic activities. In addition, the naturally high alkalinity of the reservoir water (1.5 meq L^{-1}) provides substantial buffering capacity, enabling effective neutralization of acid deposition.

Overall, these findings indicate that the acid rain situation in Viet Nam has improved considerably compared with previous periods. Nevertheless, air pollution continues to pose a major environmental challenge, with increasing impacts from other pollutants, particularly

fine particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs), especially in large metropolitan areas such as Ha Noi city and Ho Chi Minh City.

Recognizing the importance of this issue, the Government of Viet Nam has introduced a range of legal and regulatory instruments and has invested in technical infrastructure to strengthen air quality management and monitoring. However, under the current institutional framework, air quality management and acid deposition monitoring are administered by different organizations with separate responsibilities.

As EANET continues to expand its scope from acid deposition monitoring toward broader air quality issues, there is a necessary for an integrated management framework. Rather than focusing solely on acid deposition, the network is increasingly addressing wider air pollution challenges and their impacts on ecosystems and human health.

In this context, improving the effectiveness of air pollution control and acid deposition monitoring in Viet Nam will require the Ministry of Agriculture and Environment (MAE) to strengthen institutional coordination and, where appropriate, further align the roles and responsibilities of the agencies responsible for air quality management and the operation of air quality and acid deposition monitoring networks. Such coordination would help enhance the efficiency of monitoring, data sharing, and policy implementation while supporting a more comprehensive approach to air quality management.

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