ORIGINAL ARTICLE

Wet deposition of inorganic nitrogen compounds associated with rainfall in Phnom Penh, Cambodia

Simorn May[1], Amnat Chidthaisong[2], Sirintornthep Towprayoon[3] and Winai Somboon[4]

Abstract

May, S., Chidthaisong, A., Towprayoon, S. and Somboon, W.
Wet deposition of inorganic nitrogen compounds associated with rainfall in Phnom Penh, Cambodia
Songklanakarin J. Sci. Technol., 2007, 29(2) : 543-552

To estimate wet deposition of nitrogen in Phnom Penh city, Cambodia, rainwater samples at four locations in the center and suburb areas were collected and analyzed during 24 June 2005 to 21 July 2005. The results showed that concentrations of NO_2^- were lower than that of NO_3^- and NH_4^+ at all investigated sites. The NO_2^- concentration range was 0.18-0.33 mg L^{-1} (average ± S.D., 0.23±0.05 mg L^{-1}). The major inorganic nitrogen species in rainwater were NO_3^- and NH_4^+. The NO_3^- concentrations ranged from 1.43 to 1.98 mg L^{-1} (average 1.71±0.18 mg L^{-1}) while that of NH_4^+ ranged from 0.49 to 0.75 mg L^{-1} (average 0.61± 0.07 mg L^{-1}). Statistically, both the average NO_3^- and NH_4^+ concentrations were not significantly different among the sampling sites ($p<0.05$). The amount of wet deposition during study period was then estimated by multiplying these concentrations with the amount of rainfall. It was found that wet deposition depended mainly on the rainfall amount. The average ± S.D wet depositions of NO_2^-, NO_3^- and NH_4^+ during the one-month study period were 110±30, 610±230, and 740±260 g N ha^{-1}, respectively. During the study period, NO_2^-, NO_3^-, and NH_4^+ contributed 8, 42, and 50% to the total wet deposition of inorganic nitrogen compounds in Phnom Penh city.

Key words : nitrite, nitrate, ammonium, wet deposition, Phnom Penh

[1]M.Sc. (Student in Environmental Technology), [2]Ph.D. (Aplied Biotechnology), Asst Prof., [3]Ph.D. (Agriculture), Asso. Prof., [4]Ph.D. (Chemistry), Asso. Prof., King Mongkut's University of Technology Thonburi, Thungkru, Bangkok, 10140 Thailand.
Corresponding e-mail: amnat_c@jgsee.kmutt.ac.th
Received, 26 April 2006 Accepted, 1 October 2006

บทคัดย่อ

สิมอร์น เมย์[1] อำนาจ ชิดไธสง[1] สิรินทรเทพ เต้าประยูร[1] และ วินัย สมบูรณ์[1]

การตกสะสมของสารอนินทรีย์ไนโตรเจนในน้ำฝนในเขตเมืองพนมเปญ ประเทศกัมพูชา

ว. สงขลานครินทร์ วทท. 2550 29(2) : 543-552

การประมาณการตกสะสมของไนโตรเจนในน้ำฝนในเมืองพนมเปญ ประเทศกัมพูชา ได้ศึกษาโดยการเก็บตัวอย่างและวิเคราะห์สมบัติน้ำฝนจากจุดเก็บทั้งหมด 4 แห่ง ระหว่างวันที่ 24 มิถุนายน 2548 ถึง 21 กรกฎาคม 2548 ครอบคลุมพื้นที่ใจกลางเมืองและเขตชานเมือง ผลการศึกษาพบว่า ความเข้มข้นของ NO_2^- ในน้ำฝนโดยทั่วไปต่ำกว่าความเข้มข้นของ NO_3^- และ NH_4^+ ระดับความเข้มข้นของ NO_2^- ที่พบอยู่ระหว่าง 0.18 - 0.33 มก./ลิตร (ค่าเฉลี่ย± ค่าเบี่ยงเบนมาตรฐาน เท่ากับ 0.25 ± 0.05 มก./ลิตร) ความเข้มข้นของ NO_3^- อยู่ระหว่าง 1.43 - 1.98 มก./ลิตร (1.71 ± 0.18มก./ลิตร) ส่วนความเข้มข้นของ NH_4^+ อยู่ระหว่าง 0.49 - 0.75 มก./ลิตร (0.61 ± 0.07มก./ลิตร) ซึ่งเมื่อเปรียบเทียบความเข้มข้น NH_4^+ และ NO_3^- ระหว่างจุดเก็บตัวอย่างทั้ง 4 แห่งพบว่าไม่มีความแตกต่างกันอย่างมีนัยทางสถิติ ($p<0.05$) ปริมาณการตกสะสมไนโตรเจนคำนวณจากข้อมูลความเข้มข้นคูณด้วยปริมาณน้ำฝน พบว่าการตกสะสมขึ้นอยู่กับปริมาณน้ำฝนเป็นหลัก โดยปริมาณการตกสะสม NO_2^-, NO_3^- และ NH_4^+ เป็น 110 ± 30, 610 ± 230 และ 740 ± 260 กรัมไนโตรเจน/เฮกเตอร์ ตามลำดับ หรือคิดเป็น 8%, 42% และ 50% ของการตกสะสมไนโตรเจนรวมทั้งหมด

[1]**บัณฑิตวิทยาลัยร่วมด้านพลังงานและสิ่งแวดล้อม มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี ทุ่งครุ กรุงเทพฯ 10140**

Wet deposition is one of the important processes governing the transfer of beneficial and toxic chemicals from the atmosphere onto surface by wet processes such as rain, snow, and fog (Krupa, 2002). Wet deposition of nitrogen can be beneficial to the ecosystem where nitrogen is deficit (Padgett *et al*., 1999). On the other hand, it can also be harmful to the ecosystem where excess amount of nitrogen exists. For example, the deposition of nitrogen in the forms of NO_3^- and NH_4^+ to the already nitrogen-saturated forests can result in export of nitrogen and subsequent eutrophication in aquatic environments (Bowen and Valiela, 2001). Several studies show that high NO_3^- wet depositions are found in the areas where a large emission of NO_x emission occurs, such as in big cities and industrial areas. The high NH_3 emission associated with NH_4^+ deposition occurs in the area where the cultivated land and animal farms are located (Zapletal, 1998; Park *et al*., 2002). Excess amount of NO_3^- and NH_4^+ in the atmosphere can also lead to acid deposition and the subsequent damages to the ecosystem (Zhao *et al*., 1988). Irwin *et al*. (2002) reported that NO_3^- accounts for at least one-third of the acidifying effect of the combined wet deposition of non-sea salt SO_4^{2-} and NO_3^- over all parts of the United Kingdom. The similar results were also found in Japan and Korea by Bashkin and Park (1998). Therefore, the wet deposition of nitrogen is one of the important aspects considered in air pollution control stretagy.

While there are numerous studies on wet deposition around the world, to our knowledge there has been no investigation in Cambodia. Cambodia is the fifth largest products-imported country amongst Asian country. Two-third of the products is petroleum, transport vehicles, motorcycles, lorries and trucks, and machineries (Keo, 2002). The increase use of these products and of second-hand products (motorcycles, vehicles, and out of dated industrial processes) have mostly concentrated in Phnom Penh city (Cotter, 2000). Meanwhile, urban expansion and economic activities have led to an increased demand for power generation, transportation and industrial production. As a result, waste generation has also significantly increased. It was estimated that about 73% of NH_3 emission to the atmosphere in Phnom Penh came from such urban wastes (Cotter, 2000;

Japan International Cooperation Agency, 1999).

As a consequence of such developments, various environmental problems are emerging. The acid deposition of nitrogen species is among one of the concerns. Therefore, the current research study aims primarily to estimate and know the relative contribution of inorganic nitrogen species (NO_2^-, NO_3^-, and HH_4^+) to wet deposition in the city.

Materials and methods

Study area

Phnom Penh city is located at the intersection of the Mekong, Tonle Sap, and Bassac rivers at latitude 11.33 N and longitude 104.55 E and is the capital city of Cambodia. These rivers provide fresh water and river ecosystem as main sources for sustainable environment condition. Municipality of Phnom Penh consists of 7 districts, 76 communes, and 685 villages. It occupies the area of 290 km^2. The total population in 2003 was 1.2 millions, and expected to be 1.65 millions by 2010 (The council for development of Cambodia, 2005). Four different sites in the city center and its suburb were chosen to monitor the wet deposition of nitrogen. Two sites, Daun Penh (Site II) and Porchentong Meteorological Monitoring Station (Site III), were located in the city center. The other two sites were located in the suburb area approximately 10 kilometers away from the city center. One site was within Royal University of Agriculture (Site IV), and another site was in Kean Svay zone (Site I). The approximate locations of these four sampling sites are shown in Figure 1.

Rainwater sampling and analysis

Rainwater samples were collected during 24 June to 21 July 2005 at approximately 2 meters above the roof in order to avoid splashes. All apparatuses were rinsed with 0.5 N HCl before use. Rainwater was collected manually by using a 25-cm diameter plastic funnel opening, connected to a polyethylene collector (30 L). Rainwater

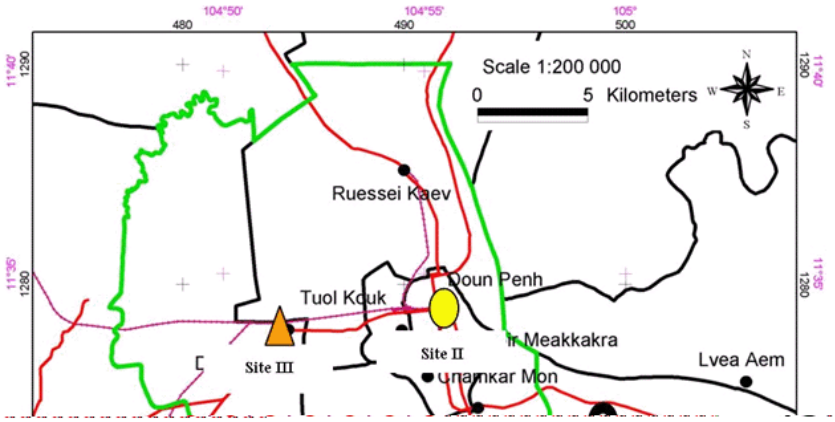

Figure 1. Map of the investigated areas in Phnom Pehn city, Cambodia.

collection was started a few minutes after the rain began and ended immediately when the rain stopped. Each collection period covered 24 hours. Rainfall was measured by using rain guage at all the investigated sites. After collection, pH was measured by a pH meter (HANNA instruments, model # HI 98108, USA). After that, rainwater samples were transferred into four pre-cleaned-plastic bottles with 60 ml content per each and kept in dark place and in a refrigerator at 4°C until analysis. Field blanks with known concentrations of NO_2^- and NH_4^+ were also prepared for quality control. The blanks were treated and handled exactly the same as to those of samples. Analysis results revealed that no contamination or loss during sampling, storage and handling occurred.

Prior to chemical analyses, all the samples were filtered through a glass microfibre filter (0.2 µm pore size; GF/C, Whatman). NO_3^-, NO_2^- and NH_4^+ concentrations were determined with an Ion Chromatograph (Dionex Corporation, DX 600, USA), which consists of a self-regenerating suppressed conductivity detector (Dionex IonPac ED50A), a gradient pump (Dionex IonPac GS50), and automated sample injector (ASI-100). NO_3^- and NO_2^- analysis was measured with a Dionex IonPac® AG11-HC column (2 x 250 mm), while NH_4^+ and other cations were analyzed with a Dionex IonPac® CS12A-5 µM column (3 x 150 mm). The gradient weak base eluent (76.2 mM NaOH + H_2O) was used for anion analysis, and the weak acid eluent (22 mN H_2SO_4) for cation analysis. The concentrations of these compounds in rainwater samples reported here are already corrected by the blank control.

Results and discussion

pH analysis

pH is one of the parameters used as the indicator of rainwater quality. The pH of the un-polluted rainwater in equilibrium with atmospheric CO_2 (365 ppmv) is 5.6. The rainwater in which the pH is less than 5.6 is considered as acid rain, from 5.6 to < 7 is weak acid, and > 7 is regarded as alkaline rain (Tang *et al*., 2005). In Phnom Penh, the pH of individual precipitation events ranged from 5.7 to 7.2 (Figure 2). The average pH at all sites during the monitored period 24 June 2005 to 21 July 2005 was 6.28, corresponding to the hydrogen ion concentration of 0.52 µeq L^{-1}. Thus, rainwater in the city is considered as a weak acid. This relatively high average pH value (relative to clean air atmosphere) was possibly attributed to the relatively high content of alkali elements in rainwater. Ministry of Environment of Cambodia (2002) reported that the level of total suspended particulate in air, which is mainly made up of Ca^{2+}, in the recent past has approximately increased two times (0.844 mg m^{-3}) higher than that of the standard level (0.33 mg m^{-3}). Data on cations analysis in this study agreed well with this inter-pretation. During this period, the average concen-tration of Ca^{2+} at all sampling sites was higest (207.5 µeq L^{-1}). Other ions presented in the rain-water samples were Cl^- (159.7 µeq L^{-1}), Na^+ (68.7 µeq L^{-1}), SO_4^{2-} (71.3 µeq L^{-1}) and K^+ (68.7 µeq L^{-1}). When compared the concentrations of these compounds, it was found that most of them were relatively higher than those reported by other studies (Wang and Wang, 1996; Hara, 1997; Lee *et al*., 2000). In Bangkok, Somboon (1996) also reported the dominant present of Ca^{2+} in rainwater and it was suggested that Ca^{2+} was the main component in buffering the rainwater pH. Its sources included dust and soil particles generated from road traffic and constructions (Somboon, 1996). Phnom Pehn may also have the similar Ca^{2+} as those in Bangkok, especially dust from unpaved roads and building constructions. Other acid-neutralization agents frequently illustrated are NH_3 and carbonate materials. As in Mediterranean area, carbonate particles were the most dominant neutralizing agents (Al-Momani *et al*.,1995; Tuncer *et al*., 2001). The neutralization by carbonate materials was usually reported in the region where composition of precipitation was strongly affected by high calcite content of Saharan dust (Losno *et al*., 1991; Al-Momani *et al*., 1995).

NO_2^-, NO_3^-, NH_4^+ concentrations in rainwater

Concentration of NO_2^- was found lower than

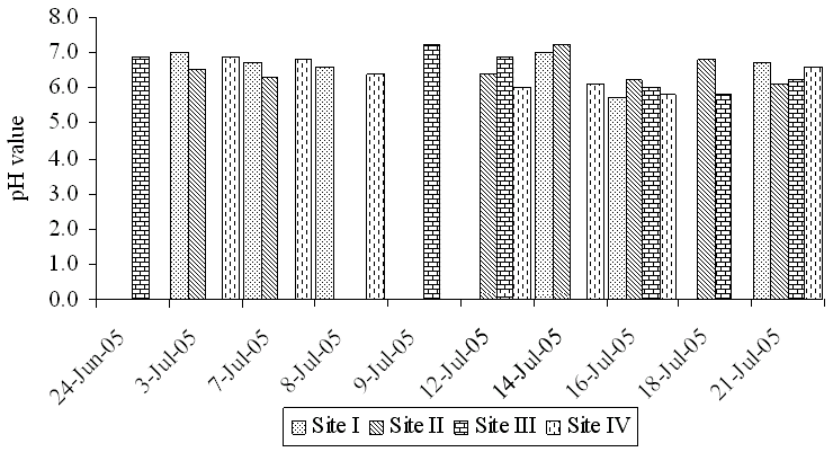

Figure 2. pH of rainwater samples during the study period (24 June 2005 - 21 July 2005).

Table 1. One month weight average (±S.D) concentration of NO_2^-, NO_3^-, and NH_4^+ in rainwater samples and the amount of rainfall at four different sites in the city during 24 June 2005 - 21 July 2005. The values followed by the same letter in the same column indicate no significant difference among them ($p < 0.05$).

Sampling site	NO_2^- (mg L^{-1})	NO_3^- (mg L^{-1})	NH_4^+ (mg L^{-1})	Rainfall (mm)
Site I	0.24±0.02 [a]	1.68±0.18 [b]	0.56±0.05 [c]	149.47 [df]
Site II	0.25±0.05 [a]	1.72±0.18 [b]	0.65±0.07 [c]	117.66 [d]
Site III	0.24±0.06 [a]	1.75±0.22 [b]	0.63±0.08 [c]	109.31 [d]
Site IV	0.21±0.01 [a]	1.69±0.16 [b]	0.58±0.08 [c]	250.57 [ef]
Average	0.23±0.05	1.71±0.18	0.61±0.07	156.75

that of NO_3^- and NH_4^+ at all investigated sites, and it was not detected during the first two weeks of the studied period (Figure 3a). The range of NO_2^- concentration was 0.18-0.33 mg L^{-1} with its average value of 0.23±0.05 mg L^{-1} (Table 1). The major inorganic nitrogen species in wet deposition were NO_3^- and NH_4^+. The NO_3^- concentrations ranged from 1.43 to 1.98 mg L^{-1} with its average value of 1.71±0.18 mg L^{-1}, while the NH_4^+ concentrations ranged from 0.49 to 0.75 mg L^{-1} with its average value of 0.61±0.07 mg L^{-1} (Figure 3b and 3c, Table 1). Statistically, both the average NO_3^- and NH_4^+ concentrations were not significant different among sites ($p<0.05$).

The average NO_3^- concentrations indicated here were in the lower range as those found in other regions. For example, it was 4.37 mg L^{-1} in Bangkok (Somboon, 1996), 2 mg L^{-1} in Chongqing (Larssen *et al*., 1999), and 1.9 mg L^{-1} in Seoul (Lee *et al*., 2000). The average NH_4^+ concentrations were also lower than NH_4^+ found in these cities such as 1.9 mg L^{-1} in Chongqing (Larssen *et al*., 1999), and 1.2 mg L^{-1} in Seoul (Lee *et al*., 2000), respectively. This may reflect the local source inputs of both NO_3^- and NH_4^+, which mainly comes from agricultural and domestic activities in Phnom Penh was lower than those in other cities. As mentioned earlier, the main sources of NO_3^- are emissions from traffics and industrial activities, while that of NH_3 are emissions from agricultural activities including application of nitrogen fertilizer and animal farms. Therefore, the relatively

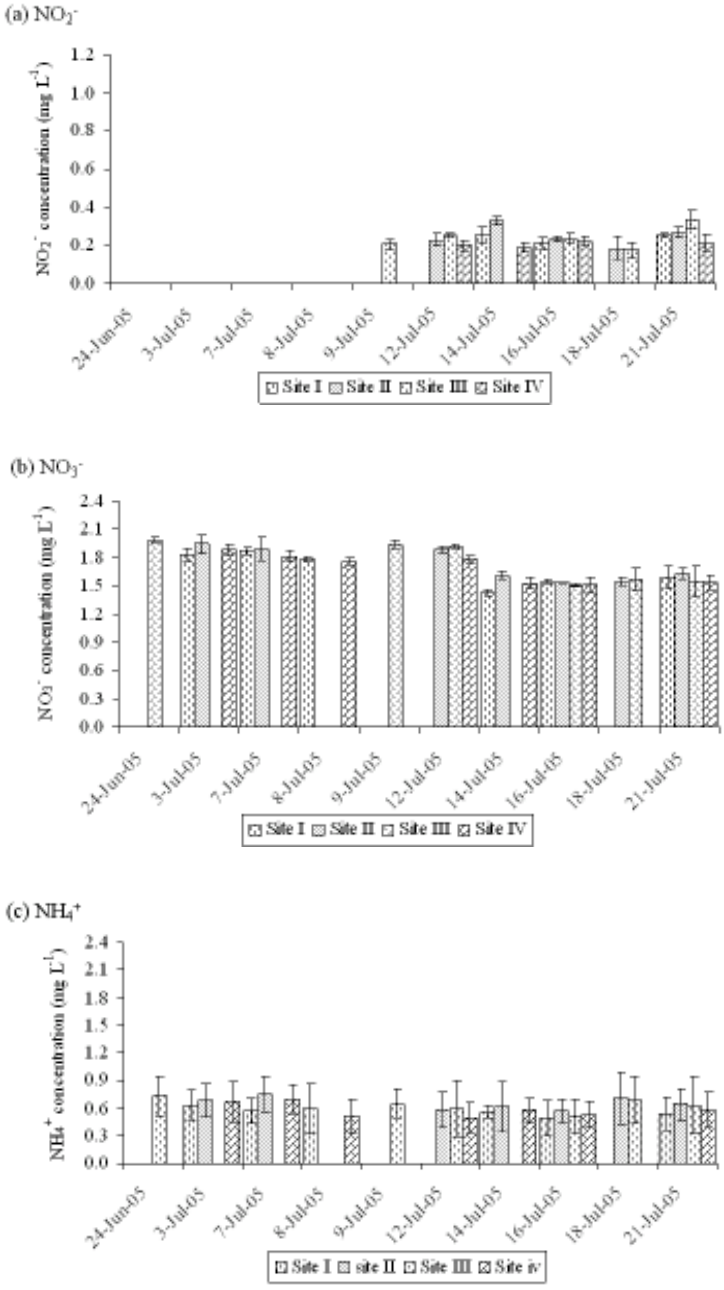

Figure 3. (a) NO_2^-, (b) NO_3^- and (c) NH_4^+ concentrations in rainwater samples at all sites.

low NO_3^- and NH_4^+ concentrations found in the current study indicate the small contribution from its sources compared to that of the others. However, since there has been no data in tha past on deposition of nitrogen, the annual trends over the long time period is not known. As the effects of human activity on emission sources is expected to increase rapidly in the future, it is important to maintain the monitoring activity on deposition of nitrogen and other related compounds. Such monitoring will be useful for air quality control and management in the future.

From this preliminary survey results, it is noticed that the concentrations (NO_2^-, NO_3^-, and NH_4^+) of the two sites (Site II and Site III) located in the center of the city were relatively higher than the other two sites (Site I and Site IV) even though they were statistically not significantly different ($p < 0.05$). This may indicate the relatively higher anthropogenic influences on atmospheric concentration of nitrogen species than at Site I and Site IV.

Wet deposition of nitrogen

In Phnom Penh, rainfall generally concentrates during rainy season (May to October) when southwest monsoon dominates. The amount of rainfall at all the investigated sites during the monitoring period is illustrated in Figure 4. Total amount of rainfall for the monitoring period (24 June 2005 - 21 July 2005) were 149.47, 117.66, 109.31, and 250.57 mm at Site I, Site II, Site III, and Site IV, respectively. Statistically, the accumulated amount of rainfall at Site IV was significantly higher than at Site III and Site II ($p<0.05$).

The total amount of wet deposition of NO_2^-, NO_3^-, and NH_4^+ associated with these rainfalls was estimated by multiplying the average concentrations with the total amount of rainfall at each site and depicted in Figure 5a, 5b, and 5c, respectively. At all the sampling sites, the amount of wet deposition seemed to depend mainly on rainfall amount. Relatively higher wet deposition (NO_2^-, NO_3^-, and NH_4^+) was usually observed at the higher-rainfall sites (higher at Site IV and Site I than Site II and Site III (Figure 4, Table 1)). Several studies also reported the similar results that the total wet deposition depends mainly on the precipitation amount (Beverland *et al*., 1998; Paramee *et al*., 2005). Throughout the whole period, the amount of wet deposition of NO_2^- at all the sites ranged from 60 to 170 g N ha^{-1} with the average value of 110±30 g N ha^{-1} (Figure 5a, Table 2). The wet deposition of NO_3^- ranged from 430 to 1070 g N ha^{-1} with the average of 610±230 g N ha^{-1}, while the wet deposition of NH_4^+ ranged from 600 to 1130 g N ha^{-1} with the average of 740±260 g N ha^{-1} (Figure 5b and 5c, Table 2). These amounts of wet deposition varied from site to site due to the difference in the amount of rainfall.

Conclusion

In this study, results of rainwater sample analysis during 24 June - 21 July 2005 in Phnom Penh city were presented. It was found that certain elements such as Ca^{2+} were higher than those reported in other studies. Such relatively high Ca^{2+} in rainwater may have resulted in a relative high pH of rainwater (6.28) in the city. The main source of Ca^{2+} may have come from dust. On the other

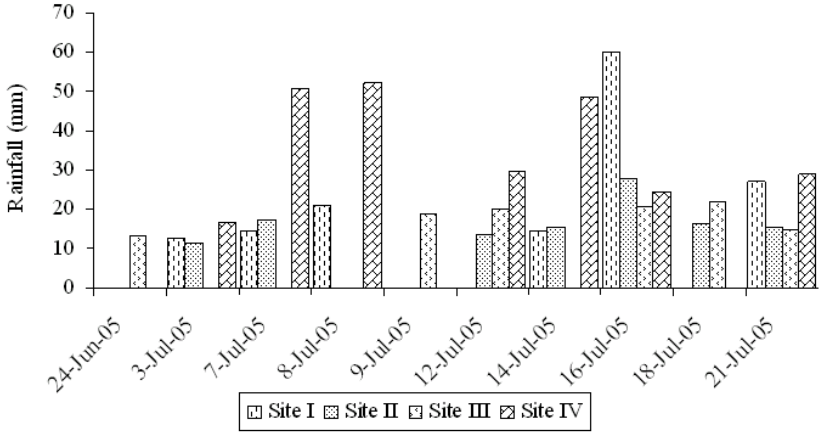

Figure 4. Distribution of rainfall at the study sites.

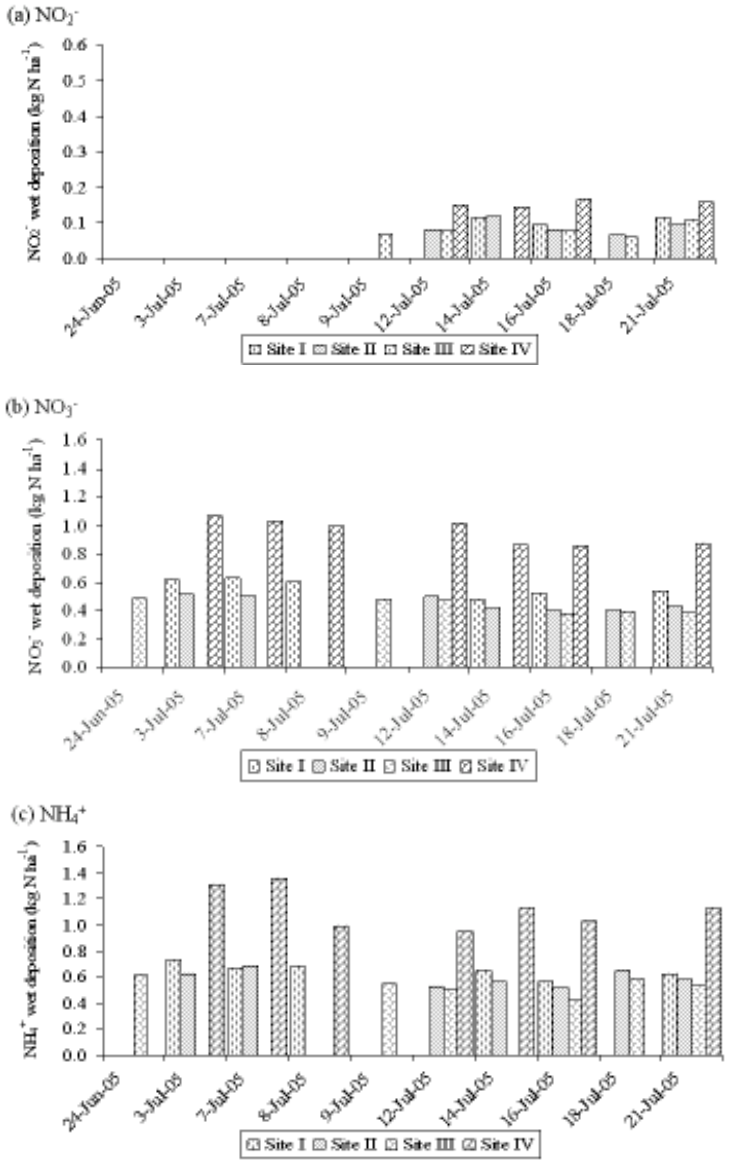

Figure 5. Temporal variations of (a) NO_2^-, (b) NO_3^-, and (c) NH_4^+ wet depositions at the study sites.

hand, the major inorganic nitrogen species in wet deposition were NO_3^- and NH_4^+. The amounts of wet deposition were related to the rainfall amount. The wet deposition of NO_2^-, NO_3^-, and NH_4^+ contributed 8, 42, and 50% to their total wet deposition of inorganic nitrogen compounds, respectively. The results showed that the concentrations of nitrogen species were relatively higher at the sites located in the city center than that at the suburban area. This indicates that the anthropogenic influences on atmospheric concentrations of nitrogen species in Phnom Penh city are emerging. To prevent the harmful effects of acid deposition in the future, measures for controlling emission and management of its possible sources should be considered.

Table 2. The total amounts of wet deposition (NO_2^-, NO_3^-, and NH_4^+) in Phnom Penh city. The values followed by the same letter for each nitrogen species indicate no significant difference ($p< 0.05$).

Sampling sites	NO_2^- (mg L^{-1})	NO_3^- (mg L^{-1})	NH_4^+ (mg L^{-1})
	Average±SD	Average±SD	Average±SD
Site I	110±10 [a]	570±10 [b]	650±50 [c]
Site II	90±20 [a]	460±50 [b]	600±60 [c]
Site III	80±20 [a]	430±50 [b]	540±70 [c]
Site IV	160±10 [a]	960±90 [b]	1130±160 [c]
Average	110±30	610±230	740±260

References

Al-Momani, I.F., Tuncel, S., Eler, U., Ortel, E., Sirin, G. and Tuncel, G. 1995. Major ion composition of wet and dry deposition in the Eastern Mediterranean basin. Sci. of the Tot. Environ., 164: 75-85.

Bashkin, V.N. and Park, S.U. 1998. Acid deposition and ecosystem sensitivity in East Asia. NovaScience Publishers, USA, 427pp.

Beverland, I.J., Crowther, J.M., Srinivas, M.S.N. and Heal, M.R. 1998. The influence of meteorology and atmospheric transport patterns on the chemical composition of rainfall in south-east England. Atmos. Environ., 32: 1039-1048.

Bowen, J.L. and Valiela, I. 2001. Historical changes in atmospheric nitrogen deposition to Cape Cod, Masschusetts, USA. Atmos. Environ., 35: 1039-1051.

Cotter, S. 2000. Air pollution in Phnom Penh city, Charpter 21, 272 pp, Royal University of Phnom Penh, Cambodia.

Hara, H. 1997. Acid deposition chemistry in Asia, Europe and North America. **In** Murano, K. (ed), Proc. of the International Workshop on Unification of Monitoring Protocol of Acid Deposition and Standardization of Emission Inventory, Tsukuba, Japan, pp. 47-52.

Irwin, J.G. and Campbell, G., Vincent, K. 2002. Trends in sulphate and nitrate wet deposition over the United Kingdom: 1986-1999. Atmos. Environ., 36: 2867-2879.

Japan International Cooperation Agency. 1999. A Country Profile on Environment in Cambodia.

Keo, K. 2002. The challenge of the Cambodian economy. CAS Discussion paper No. 38.

Krupa, S.V. and Moncrief, J.F. 2002. An interactive analysis of the role of atmospheric deposition and land management practices on nitrogen in the US agriculture sector. Environ. Pollut., 118: 273-283.

Larssen, T., Seip, H.M., Semb, A., Mulder, J., Muniz, I.P., Vogt, R.D., Lydersen, E., Angell, V., Dagang, T. and Eilertsen, O. 1999. Acid deposition and its effects in China: an overview. Environ. Sci. & Policy., 2: 9-24.

Lee, B.K., Hong, S.H. and Lee, D.S. 2000. Chemical composition of precipitation and wet deposition of major ions on the Korean peninsula. Atmos. Environ., 34: 563-575.

Losno, R., Bergametti, G., Carlier, P. and Mouvier, G. 1991. Major ions in marine rainwater with attention to sources of alkaline and acidic species. Atmos. Environ 25A., (3/4): 763-770.

Padgett, P.E., Allen, E.B., Bytnerowicz, A. and Minich, A. 1999. Changes in soil inorganic nitrogen as related to atmospheric nitrogenous pollutants in southern California, Atmos. Environ., 33: 769-781.

Paramee, S., Chidthaisong, A., Towprayoon, S., Asnachinda, P., Bashkin, V.N. and Tangtham, N. 2005. Three-year monitoring results of nitrate and ammonium wet deposition in Thailand. Environ. Monit. and Asses., 102: 27-40.

Park, S-U. and Lee, Y.H. 2002. Spatial distribution of wet deposition of nitrogen in South Korea. Atmos. Environ., 36: 619-628.

Somboon, W. 1996. Acid and some heavy metals composition of rain in Bangkok, Thailand. Proc. of International Congress of Acid Snow and Rain 1996, Niigata, Japan, Oct. 6-8, 1996.

Tang, A., Zhuang, G., Wang, Y., Yuan, H. and Sun, Y. 2005. The chemistry of precipitation and its relation to aerosol in Beijing. Atmos. Environ., 39: 3397-3406.

The council for development of Cambodia. 2005. Major data base for serving investments in Cambodia.

The Ministry of Environment, 2002. Annual report of office for solid waste and toxic substances management, Phnom Penh, Cambodia.

Tuncer, B., Bayer, B., Yesilyurt, C. and Tuncel, G. 2001. Ionic composition of precipitation at the central Anatolia, Turkey. Atmos. Environ., 35: 5989-6002.

Wand, W. and Wang, T. 1996. On acid rain formation in China. Atmos. Environ., 30: 4091 4093.

Zapletal, M. 1998. Atmospheric deposition of nitrogen compounds in the Czech Republic. Environ. Pollut., 102: 305-311.

Zhao, D., Xiong, J., Xu, Y. and Chan, W.H. 1988. Acid rain in southwestern China. Atmos. Environ., 22: 349-358.