Evaluation of atmospheric deposition of nitrogen to the Feitsui Reservoir in Taipei

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Abstract This research studied how the air pollutants of urban areas affect a neighboring reservoir and its water quality. Through the atmospheric dispersion process, air pollutants move from the Taipei metropolitan to the Feitsui reservoir and enter the water body through dry and wet depositions. ISCST3 (Industrial Source Complex Short Term Model), an air quality model, was used to simulate dispersion, dry deposition and wet deposition of the air pollutants. Then the nitrogen loadings to the Feitsui Reservoir were evaluated. The results indicate that wet deposition places a greater burden than dry deposition does on the water body. Wet and dry deposition of NH_4^+ together make up a rather large proportion of the total pollution. The ratio ranged from 21.9 to 25.2%. Those of nitrate make up a smaller proportion, ranged from 2.0 to 2.3%. If we take indirect deposition into account and calculate the NO_3^- and NH_4^+ together, the proportion is 15.9–17.6%.

Keywords Atmospheric deposition; dry deposition; nitrogen loading; wet deposition

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Introduction

Although the average annual rainfall in Taiwan (2,500 mm/yr) is approximately 2.5 times that of the global average, the precipitation index per capita per year is one-sixth lower than that of the world average because of a heavy population density. Natural factors that make water management in Taiwan difficult include steep river slopes, fragile topsoil in watersheds, and significantly uneven temporal and spatial distribution of precipitation. According to hydrological statistics, the rainfall from May to October accounts for 78% of the total annual precipitation. The precipitation from November to April, which is the so-called dry season, accounts for 22% only. In southern Taiwan, the rainfall during the wet season is as high as 90% of the total annual precipitation. Such an uneven rainfall distribution pattern creates difficulties in efforts to utilize water resources.

Since population and economic activity are mostly concentrated in the northern and southern ends of western Taiwan, water shortages occur in these areas when the supply cannot meet the demand. During the dry season, nearly all of the water in the rivers is utilized, and the rivers in the southwest are almost dry except during the typhoon season. Thus, the construction of reservoirs along river systems has long been considered an important approach to fulfill the demands of fresh water supply. Many reservoirs in Taiwan have been found either to have eutrophication problems or are in danger of becoming eutrophic. Extensive highland farming, road construction, and community development destroy the vegetation cover of watershed areas. Excessive use of pesticides and fertilizers and the seasonal use of river banks or beds as cultivating grounds bring nutrients and other pollutants to the streams and reservoirs. In addition, air pollutants can be transported to the water body of the reservoir through the atmospheric dispersion process, and dry and wet depositions (Wu *et al.*, 1992; Leeuw *et al.*, 2003). Most of the reservoirs in Taiwan are public water supply sources. Protecting the quality of these

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water bodies is very important to maintain a sufficient drinking water supply as well as to ensure continuing social and economic development.

Trophic status of the Feitsui Reservoir

Lush vegetation, a high concentration of salts, and high turbidity are the defining characteristics of eutrophication. When reservoirs are polluted with large amounts of nitrogen and phosphorus, however, rapid growth of algae and eutrophication occur, thereby causing the water quality to deteriorate and increasing the cost of water treatment. The trophic state index is often based on total phosphorus (TP) concentration, total nitrogen (TN) concentration, chlorophyll *a* (chl *a*) concentration, and Secchi disk depth (SD). Since eutrophication involves complex changes in the water, the results obtained from using only one parameter may easily mislead or bias the user. For this reason, the multivariable trophic state indexing methods were developed. The most commonly used multivariable indices are the Carlson (1977) and Morihiro *et al*. (1981) indices. The Environmental Protection Administration (EPA, Chinese Taiwan) uses the Carlson trophic state index (CTSI) to conduct an overall assessment of water quality in all reservoirs, but also emphasizes that both algae cell density and TN are two other important parameters which must be monitored.

The Feitsui Reservoir (Figure 1) is the main water supply source in Taipei. Its watershed area covers a total area of 30,300 hectares. Based on a survey carried out by the EPA recently, land use areas that have a larger environmental impact within this watershed include farmland, market space, and exposed ground, comprising a total of 2,018 hectares. According to the Taipei Feitsui Reservoir Administration, monitoring data from 1987 to 2002 show that CTSI values rose from 40.8 in 1993 to 46.3 in 1998 (Table 1). Thereafter, from 1999 to 2002, CTSI remained around 46.0. A CTSI of 50 or more indicates that the water body has reached a state of eutrophication. Based on monthly measurements of water quality over the last five years (Figure 2), CTSI has already exceeded 50 on nine occasions.

Recently, Taipei County's Pinglin Township residents held a local referendum vote in favor of building a highway interchange in Pinglin. The issue has raised people's concerns about the water quality within this water quality protection area. The area of Pinglin Township is over 17,000 hectares, or 59% of the total watershed area of the Feitsui reservoir. The EPA therefore warns against further development and construction within

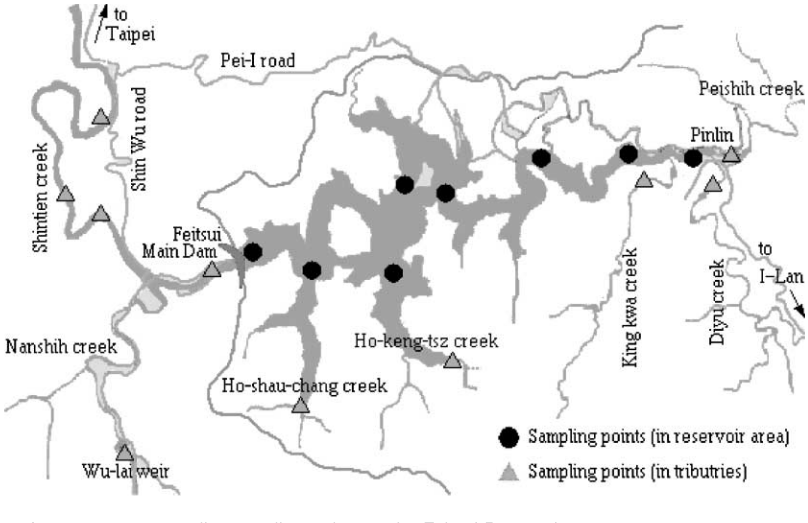

Figure 1 Layout of water quality sampling points of the Feitsui Reservoir

Table 1 Water quality and Carlson trophic state index of the Feitsui Reservoir (by average)

Year	Total P (μg/L)	Chl *a* (μg/L)	SD (m)	CTSI	Algae No. (cells/mL)	TN (mg/L)
1987	20.57	2.07	3.0	42.84	1,687	1.05
1988	20.16	7.28	3.2	45.00	15,189	1.12
1989	12.12	4.99	3.5	41.63	2,171	0.94
1990	10.53	4.85	2.9	42.92	3,303	0.88
1991	9.07	5.00	3.1	41.63	4,525	0.80
1992	8.88	7.00	3.3	41.97	7,887	0.86
1993	8.03	4.40	3.1	40.83	8,155	0.90
1994	9.93	4.80	3.4	41.70	4,889	0.98
1995	11.67	4.10	3.8	41.31	39,705	0.78
1996	16.84	5.16	2.8	44.41	37,218	0.87
1997	13.88	3.67	2.5	43.40	20,082	1.18
1998	14.89	6.18	2.2	46.32	28,520	1.31
1999	20.13	4.53	2.3	45.99	26,977	1.19
2000	21.91	3.70	2.9	45.53	55,085	1.00
2001	27.97	2.16	2.4	46.37	42,844	1.01
2002	33.61	1.27	2.0	46.11	51,680	1.08

the vicinity of the Feitsui Reservoir watershed area in order to prevent further pollution damage to the water source quality.

There are two main types of pollution that affect the water quality of reservoir watersheds. As for point source pollution, sewage systems are available to only 40% of residential and recreational areas due to the rural and mountainous characteristics of this region, and therefore such systems are unable to effectively solve point source pollution. As for non-point source pollution from farmland and forestland, if easy access was provided for motor vehicles, it can be foreseen that the level of traffic to Pinglin would greatly increase, followed by an increasing demand for recreational orchards, villas, and campgrounds. If such a situation is not appropriately managed, human activities would lead to increased levels of nitrogen and phosphorus and cause even more severe eutrophication. At the same time, alterations to the surrounding terrain and lay of the land would result in more exposed ground and overuse of the land. Heavy rainfalls would wash away soil and in severe instances would lead to severe soil erosion. The EPA therefore advises that any development should be preceded by the presentation of a complete set of

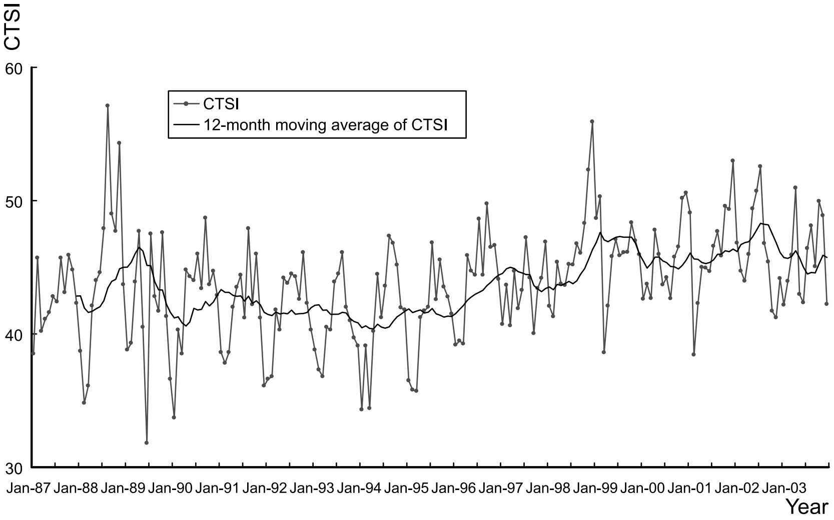

Figure 2 The CTSI of the Feitsui Reservoir from 1987 to 2003

management measures, including aspects of land use so as to ensure that water source areas have a safe quality and quantity of water.

Methods

The ISCST3 (Industrial Source Complex Short Term) model was used in this study. The effects of air pollutants of the Taipei metropolitan (including Taipei City, Taipei County and Keelung City) on the water quality of the Feitsui Reservoir were estimated through the atmospheric dispersion process, dry and wet depositions. Basic data needed in the ISCST3 model include: pollutant sources data (point, area and volume sources of SO_x, NO_x, Pb and TSP), meteorological data (wind velocity, wind direction, temperature, stability, friction velocity and Monin–Obukov length), receptor data (2 km × 2 km receptor grid points, 28 sensitive receptors), and topographical data (grid size 1 km × 1 km). The geocoding function of Arc View was used to input the topographical data.

The dry deposition of particulates was calculated by the Acid Deposition and Oxidant Model (ADOM, Pleim *et al.*, 1984).

$$F(x,y)_{\mathrm{d}} = C(x,y) \times V_{\mathrm{d}} \tag{1}$$

where $F(x, y)_{\mathrm{d}}$ is the dry deposition flux (g/cm^2.s), $C(x, y)$ is the pollutant concentration (g/cm^3), and V_{d} is the dry deposition velocity of particulates (cm/s). The dry deposition velocity can be calculated from the gravitational settling velocity (V_{g}), aerodynamic resistance (R_{a}) and deposition-layer resistance (R_{d}).

$$V_{\mathrm{d}} = V_{\mathrm{g}} + 1/(R_{\mathrm{a}} + R_{\mathrm{d}} + R_{\mathrm{a}}R_{\mathrm{d}}V_{\mathrm{g}}) \tag{2}$$

The gravitational settling velocity (V_{g}) is the function of the diameter of particulate (μm), shape of particulate and its density (g/cm^3). The aerodynamic resistance (R_{a}) is the function of wind velocity, stability and surface roughness length (cm). All influence factors mentioned above must be input into the ISCST3 model to calculate the dry deposition.

The wet deposition of gases and particulates can also be estimated by the ISCST3 model. The scavenging coefficient approach is used in the ISCST3 model to estimate the wet deposition.

$$F(x,y)_{\mathrm{w}} = \int_0^{\infty} \Lambda C(x,y,z)dz \tag{3}$$

where $F(x, y)_{\mathrm{w}}$ is the wet deposition flux (g/cm^2.s), Λ is the scavenging coefficient, and $C(x, y, z)$ is the pollutant concentration (g/cm^3). The scavenging coefficients of particulates with different diameters must be input into the ISCST3 model. The scavenging coefficient is the function of the particulate radius (Jindal and Heinold, 1991).

There are five major input parts of model parameters in ISCST3: CO (job control), SO (source), RE (receptor), ME (meteorology) and OU (output). The options of the CO input file includes default values, pollutants (SO_2, NO_x, PM10, TSP), urban or rural dispersion model, calculating concentrations, dry deposition (DDEP) or wet deposition (WDEP), dry depletion, wet depletion, flat or elevated topography. The concentrations and dry and wet depositions of particulates can be calculated in the ISCST3 model. But for gases, only concentrations and wet deposition can be obtained. SO is the input file pollution source, including location, elevation, altitude and emission rate of pollution source. The units of point and area pollution sources are g/s and g/s.m^2, respectively. The scavenging coefficient of particulate during rainfall (PARTLIQ) was selected from Jindal and Heinold's results (1991), while it was set as $0.0\,\mathrm{s}^{-1}$ during snowfall (PARTICE). For gases, the scavenging coefficients of SO_2 and NO_x were selected as $1.22 \times 10^{-5}\,\mathrm{s}^{-1}$ (the average value of in-clouds and below-clouds) and 7.95×10^{-11} s^{-1} (the average value of NOs and NO_2s) (Hertel *et al.*, 1995). Schwede and Paumier (1996) studied sensitivity of the ISCST3 model to input deposition parameters. Their results are quite useful to choose the input parameters.

Results and discussion

The mass fraction (%) of suspended particulates with different diameters in northern Taiwan are shown in Table 2 (Chiang, 1997). The average mass fraction data were used to input the MASSFRAC values. Figures 3, 4 and 5 show the comparison results between monitored values and simulated results for total suspended particulate (TSP), SO_2 and NO_2, respectively, in 1994 and 1996. Excluding the extreme values of the ratio of monitored value to simulated results for each group, the average ratios for TSP, SO_2 and NO_x are 1.6, 1.2 and 0.56 in 1994, and 1.58, 0.86 and 1.02 in 1996, respectively. The modeling errors are acceptable. Because Xindian (station 4) is the nearby station to the watershed of the Feitsui Reservoir, its ratios of TSP, SO_2 and NO_2 (Table 3) were used as the correcting coefficients for all modeling concentration results of receptors to calculate dry and wet depositions.

Some extreme ratios in Figures 3–5, such as TSP at station 3 (15.47 and 10.59), SO_2 at station 2 (2.40 and 2.69) and NO_2 at station 1 (2.61 and 2.77), result from their locations too near the northern seashore. Lacking in pollution source data from sea area results in the modeling results underestimated at these three monitoring stations.

Dry deposition comes from the settling of TSP. The direct dry deposition means atmospheric pollutants precipitating directly onto the water surface of the Feitsui Reservoir. The precipitation of particulates onto the watershed of reservoir causes the indirect deposition scoured by the surface runoff (assume 20% of pollutants will enter the water body). The average dry depositions of TSP upon the water surface of the Feitsui Reservoir are 8.64 and 6.27 g/m^2.yr (Table 4) calculated by ISCST3 model in 1994 and 1996, respectively.

For the watershed of the Feitsui Reservoir, the average dry depositions of TSP are 6.45 and 5.05 g/m^2.yr. The mass fractions of SO_4^{2-}, NO_3^- and NH_4^+ within particulates are 8.0%, 5.3% and 3.0% by chemical constituent analysis. The total surface area of the Feitsui Reservoir is 10.24 km^2, and the total watershed area is 303 km^2. Thus, the direct and indirect dry depositions of SO_4^{2-}, NO_3^- and NH_4^+ can be obtained by the TSP deposition values, mass fractions, M/S ratios and surface areas (as shown in Table 5).

Wet deposition derives from the scavenging of TSP, SO_2 and NO_x by rainfall. The average wet depositions of TSP, SO_2 and NO_x directly upon the water surface and upon watershed are shown in Table 4. Through a similar calculating procedure, the direct and indirect wet depositions of SO_4^{2-}, NO_3^- and NH_4^+ can be obtained, as shown in Table 5.

Table 2 Mass fraction of suspended particulates in northern Taiwan (%)

Monitoring station	Period	Particulate diameter (μm)		
		≥10	2.5–10	<2.5
Fushing	1994.9–1995.4	69.10	17.24	13.66
	1995.8–1996.3	41.00	31.86	27.14
	1996.9–1997.3	50.00	23.00	27.00
Sanchong	1994.9–1995.4	64.60	18.76	16.64
	1995.8–1996.3	41.00	29.50	29.50
	1996.9–1997.3	64.00	7.92	28.08
Average		54.95	21.38	23.67

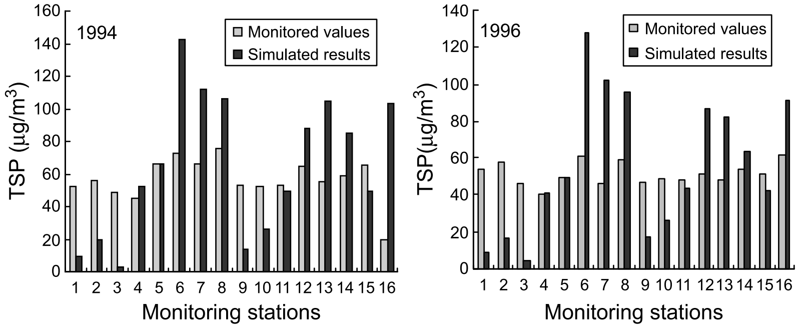

Figure 3 The comparison of monitored values and simulated results for TSP

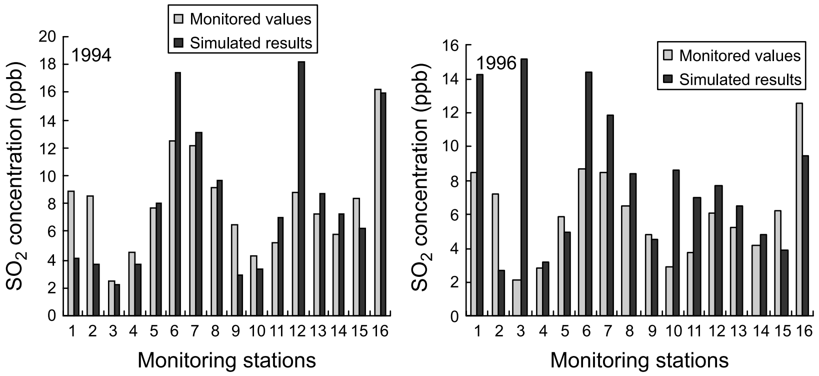

Figure 4 The comparison of monitored values and simulated results for SO_2

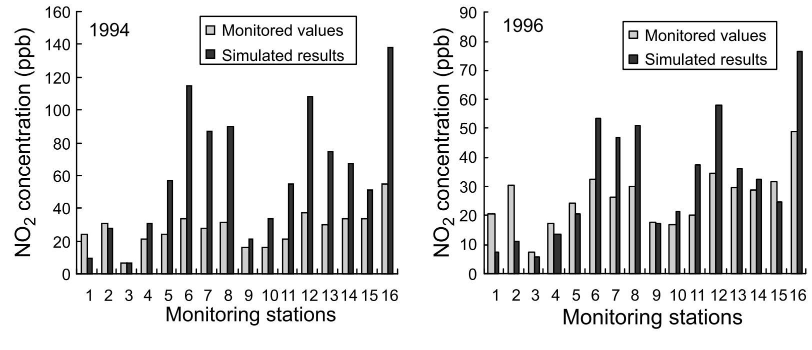

Figure 5 The comparison of monitored values and simulated results for NO_2

Table 3 Monitored and simulated results for Xindian station

Pollutant	Year	Monitored value	Simulated result	M/S ratio
TSP (μg/m^3)	1994	44.84	52.47	0.85
	1996	40.20	41.27	0.97
SO_2 (ppb)	1994	4.46	3.64	1.23
	1996	2.80	3.18	0.88
NO_2 (ppb)	1994	21.66	31.11	0.70
	1996	17.40	13.89	1.25

Table 4 The average dry deposition and wet deposition calculated by ISCST3

Type	Year	Upon water surface (Direct) (g/m^2.yr)	Upon watershed (Indirect) (g/m^2.yr)
Dry deposition			
TSP	1994	8.64	6.45
	1996	6.27	5.05
Wet deposition			
TSP	1994	12.91	8.83
	1996	10.15	7.12
SO_2	1994	0.15	0.13
	1996	0.17	0.22
NO_x	1994	0.00	0.00
	1996	0.00	0.00

Table 5 Dry and wet depositions onto the Feitsui Reservoir

Pollutant	Deposition	Year	Direct deposition (ton/yr)	Indirect deposition (ton/yr)	D/I ratio
SO_4^{2-}	Dry	1994	6.0	26.6	0.23
		1996	5.0	23.7	0.21
	Wet	1994	9.0	36.4	0.25
		1996	8.1	33.5	0.24
	Wet (from SO_2)	1994	2.8	14.8	0.19
		1996	2.3	17.6	0.13
NO_3^-	Dry	1994	4.0	17.6	0.23
		1996	3.3	15.7	0.21
	Wet	1994	6.0	24.1	0.25
		1996	5.3	22.1	0.24
NH_4^+	Dry	1994	2.3	10.0	0.23
		1996	1.9	8.9	0.21
	wet	1994	3.4	13.6	0.25
		1996	3.0	12.6	0.24

The ratios of direct depositions to indirect depositions are near 22%. The wet deposition places a greater burden than dry deposition does on the water body.

According to the report of Taipei Feitsui Reservoir Administration, the annual loadings of SO_4^{2-}, NO_3^- and NH_4^+ are 8,942.4, 436.4 and 22.2 ton/yr, respectively. The results of direct depositions indicate that wet and dry depositions of NH_4^+ together make up a rather large proportion of the total pollution loadings. The ratio is 25.2% in 1994 and 21.9% in 1996. Those of nitrate make up a smaller proportion, 2.3% in 1994 and 2.0% in 1996. Those of sulfate make up a rather low proportion (0.2%). If we take indirect deposition into account and calculate the NO_3^- and NH_4^+ together, the proportion is 15.9–17.6%. Beddig *et al.* (1997) reported that the atmospheric contribution to the nitrogen load of the German Bight during 1989–1992 was estimated to be about 30%.

Conclusions

The water quality of the Feitsui Reservoir is gradually deteriorating. Up to now, only 40% of point source pollution can be controlled by the sewage systems. Consequently, non-point source pollution control within its watershed is urgently needed. This article shows that 15.9–17.6% of NO_3^- and NH_4^+ of the Feitsui Reservoir derives from atmospheric deposition. Efforts should begin as soon as possible for basic data collection and formulating an institutional framework for implementation of control strategies.

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