How do typhoons and dust storms affect rainwater harvesting systems?
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ABSTRACT
This study aimed to investigate the effects of typhoons and dust storms on harvested rainwater quality. Rainwater samples were collected from the rainwater harvesting systems in northern Taiwan between September 2010 and April 2013. There were five typhoons and one dust storm that hit Taiwan during this period. Harvested rainwater was analyzed, including pH, electrical conductivity, turbidity, alkalinity, total organic carbon (TOC), acute biotoxicity test, and concentration of 13 metals and three anions. Results of harvested rainwater of the dust storm showed it had higher pH, turbidity, TOC, Na, Mg, Ca, Cl, NO3, and SO4 than normal rainwater. Conversely, due to strong winds and dilution effect, most of the ion concentrations in harvested rainwater during typhoons were lower than in normal rainwater. In addition, biotoxicity in harvested rainwater during the dust storm and typhoons was not significantly different from that of normal rainwater.

Key words | dust storm, metals, rainwater harvesting, total coliform (TC), typhoon

INTRODUCTION
Rainwater harvesting is a feasible alternative water resource in urban water management, providing water at the point of consumption and greatly reducing operation and maintenance problems compared with the centralized water supply system (Lee et al. 2010). The annual rainfall in Taiwan reaches 2,500 mm, which is nearly 2.5 times the world average; however, the distribution is uneven both spatially and temporally. The wet and dry seasons are distinctive in Taiwan as the amount of precipitation in the wet season accounts for over three-quarters of the total rainfall. Owing to geological as well as morphological factors, the limited storage space of reservoirs also has to provide a considerable amount of water resources for use during the coming dry season (Cheng et al. 2007). Water resource has always been a challenging issue in Taiwan, especially in the face of global climate change which affects the hydrological cycles.

As Taiwan is located in the major typhoon track in the western Pacific Ocean, typhoons are an influential weather phenomenon. The amount of rainfall brought in by typhoons often accounts for over 50% of the rainfall in wet seasons (Cheng et al. 2007). These tropical depressions bring high winds (speeds at the center of up to 17.2 m s⁻¹) and heavy rains and hence are a major source of rainfall in Taiwan (Tsai et al. 2011). However, mudslides and highly turbid water is found as a result of torrential rain during typhoons, and water treatment plants are sometimes forced to shut down or reduce water supply. A typhoon is a tropical storm system, developing with strong wind and moisture circulation near the western tropical Pacific, causing tremendous damage along its migration routes. On average, four typhoon events occur annually in the summer and autumn in Taiwan (Cheng & You 2010).

Dust storm refers to large amounts of sand lifted into the air by strong winds and is a type of weather which deteriorates visibility. Asian dust aerosols can be blown eastward and widely transported to East China, Taiwan, Korea, Japan and even the North Pacific Ocean (Zhang et al. 2010). Dust storms and long-range transport of pollutants are the major environmental concerns of Taiwan during the winter when northeast monsoon prevails following passages of cold fronts (Lin et al. 2004). In recent years with the more readily apparent transportation phenomenon of the
northeast seasonal winds, the pollution from China’s industrialized regions can often drift to Taiwan as stated by the Taiwan Environmental Protection Administration.

Seasonal changes in ion concentrations show that they were significantly influenced by Asian dust storms and typhoons (Minoura et al. 1998). Chemical and microbiological parameters showed seasonal fluctuation as well (Sazakli et al. 2007). Significant difference was observed with all water quality parameters with respect to time (seasonal variation effect) (Despins et al. 2009). Dissolved chemical compositions in rainwater have provided valuable information on pollutant sources in the atmosphere and short-term environmental changes (Cheng & You 2010). However, no systematic study has been carried out on how typhoons and dust storms may affect quality of harvested rainwater.

This study aimed to investigate the rainwater quality as affected by typhoons and a dust storm. General, physicochemical, microbiological parameter and acute biotoxicity tests of harvested rainwater were conducted during the experiment. Rainwater quality during the typhoon period was compared with drinking water standards to assess if it is possible for direct potable use.

**MATERIAL AND METHODS**

The samples were collected from September 2010 to April 2013. A total of 184 rainwater samples were collected from the rainwater harvesting systems (RWHSs) in our campus in northern Taiwan. The detailed information of the RWHSs can be found in the literature (Chiang et al. 2013). There was one dust storm and five typhoons in Taiwan during the period, the dates were 3/24 (dust storm), 6/19–21 (Talim), 8/1–3 (Saola), 8/6–7 (Haikui), 8/21–25 (Tembin\(^1\)), 8/26–28 (Tembin\(^2\)) and 9/27–28 (Jelawat). Typhoon Tembin unusually made landfall in Taiwan twice. After reaching over the southern tip of Taiwan on 23 August, Tembin weakened but regained strength in the South China Sea, looping before making a second landfall on southern Taiwan as a tropical storm on 27 August. According to maximum sustained winds, Jelawat was classified as a strong typhoon, Saola, Haikui and Tembin were classified as a medium typhoon and Talim was classified as a light typhoon. The maximum wind speeds (m/s) were 55, 38, 35, 45\(^1\) (Tembin\(^1\)), 35\(^2\)(Tembin\(^2\)), and 25, respectively, and the cumulative rainfalls (mm) during typhoon were 17.5, 258.5, 8.5, 31.7\(^1\), 21.3\(^2\) and 51.5, respectively. A rainwater sample was defined as the sample collected during 24 hours of each rain event in the pilot-scale RWHS, regardless of number of showers that occurred during collection period. In addition, every 6–8 h samples were collected continuously from when the Saola and Tembin typhoon alerts were announced. All the harvested samples were carried to the laboratory for several on-site analyses, including pH, alkalinity, electrical conductivity (EC), turbidity, and acute toxicity test and multiple-tube fermentation. For further analyses such as metal contents, major anions, and TOC, approximately 200 mL samples were filtered with 0.22 μm membrane filters (mixed cellulose ester, Advantec) and stored in the refrigerator. All the analytical procedures followed Standard Methods (APHA, AWWA & WEF 1995). Total coliform group (TC) analysis of rainwater was conducted following Standard Methods. Lauryl tryptose broth (LST, Difco) was used as the medium of presumptive phase, and a series of 10-time dilution of sample with five tubes each was made. Inoculated tubes were then incubated at 35 °C for 48 ± 4 h. If the tubes contain gas bubbles or convert acidic and turbidly, they are recognized by a positive reaction. Following this, the tubes with positive presumptive reaction proceeded with confirmed phase in which brilliant green bile broth (BGLB, Difco) was the medium. These tubes were then incubated again at 35 °C for 48 ± 4 h. Later, positive tubes with gas bubble were recorded and the presence of coliform bacteria was assessed. Data are shown using box-and-whisker plots. Each box in the figure represents the bounds of the first and third quartile, the median is marked by horizontal line inside the box, and the ends of the ‘whiskers’ represent the minimum and maximum (Despins et al. 2009). Although temperature of rainwater was not measured, the average temperature recorded by the Central Weather Bureau of Taiwan in 2012 was 16.7 °C, 22.6 °C, 29.3 °C, and 24.2 °C in winter, spring, summer, and fall, respectively. The temperature ranged from 27.8 to 29.2 during typhoons. The newborn Daphnia magna (within 24 h) was used in this acute biotoxicity test (NIEA B901.13B). The pH and EC of the original rainwater and culture solution were measured. In addition, the concentration of dissolved oxygen was measured for the rainwater. The rainwater was diluted to six concentrations (100, 80, 60, 40, 20 and 0%) with the culture solution. There
were four containers for each concentration. Five *Daphnia* and 50-mL mixed solution were put into every container. It is unnecessary to feed *Daphnia* during the test. The solution temperature must be controlled at 25 ± 2°C and the illumination time is 16 ± 1 h per day. After 48 h, the number of survived *Daphnia* was recorded and the lethal concentration 50% (LC50) was calculated.

**RESULTS AND DISCUSSION**

In this study, the pH of harvested rainwater ranged from 3.32 to 6.7 and median pH value was 4.3, however, it did not show significant seasonal variations (Figure 1(a)). This implies that acid rain was common in Taipei. Most of the samples exceeded recommended pH for drinking water standard of 6.0–8.5. The pH of harvested rainwater stored in plastic cisterns tended to be slightly acidic (Despins *et al.* 2009). The average pH of the rainwater from the dust storm, and the Talim, Saola, Haikui, Tembin1, Tembin2 and Jelawat typhoons were 5.94, 4.09, 4.96, 4.16, 4.69, 5.28 and 3.82, respectively. The relatively high pH was found during the dust storm, and the Saola, Tembin1 and Tembin2 typhoons. The higher pH value observed in harvested rainwater of the dust storm could be explained by the fact that dust storm aids the neutralization of acid rain because of Ca, Mg and K salts (Lee *et al.* 2010). Acidic deposition is heavily influenced and buffered by natural soil dust from desert and semi-arid areas. The neutralization effects vary by season with the greatest influence in spring, when
pH value increased by 0.1–0.4 in Japan, 0.5–1.5 in Korea, and more than 2 in northern China (Wang 2002). Conversely, strong winds and dilution effect during typhoon period led to less acidic rainwater than in non-typhoon rains (Minoura et al. 1998; Tsai et al. 2011). In our study, harvested rainwater from medium typhoon such as Saola, Tembin1 and Tembin2 were in agreement with this description.

Turbidity of rainwater ranged from 0.69 to 60.23 NTU and the median was 2.54 NTU (Figure 1(b)). The average turbidity of the rainwater from the dust storm, and the Talim, Saola, Haikui, Tembin1, Tembin2 and Jelawat typhoons were 41.43, 0.9, 0.91, 0.88, 2.56, 2.49 and 2.815, respectively. The effect of dust storm on turbidity is obvious and direct, however, the turbidity during Tembin1, Tembin2 and Jelawat typhoon period were slightly higher than other typhoon rainwater. Although turbidity is not necessarily a health hazard, it may constitute a health risk if the suspended particles harbor micro-organisms capable of causing disease in humans, or if the particles have adsorbed toxic organic or inorganic compounds (Kus et al. 2010). Conversely, the disinfection efficiency will be lower if turbidity is high. Turbidity of harvested rainwater showed significant seasonal variation and most of the samples exceeded drinking water standard (2 NTU), except the rainwater samples collected during summer time. Higher turbidity was expected because the metal surface had the smoothest surfaces, which easily washed off particulate matters (Mendez et al. 2011). According to rainwater storage and reuse guideline, turbidity should not exceed 5 NTU (maximum) and 2 NTU (average). Therefore, harvested rainwater collected from pilot-scale should be filtered or undergo precipitation before potable use.

Electrical conductivity, which represents the samples’ total ion content, can be identified as a leading parameter. EC of harvested rainwater ranged from 2.02 to 896 μs/cm and the medium EC value is 38.1 μs/cm (Figure 1(d)). The average of EC of the rainwater from the dust storm, and the Talim,
Saola, Haikui, Tembin¹, Tembin² and Jelawat typhoons were 189.3, 22.18, 9.76, 12.52, 9.76, 33.21 and 67.43 respectively. Besides relatively higher EC of harvested rainwater during dust storm, harvested rainwater during the typhoon did not reveal a difference with normal rainwater. In winter, the weather is mainly influenced by cold high-pressure systems from Mongolia and Siberia. The prevailing northeast monsoon moves south through cold fronts to bring occasional rainfalls. A significant amount of natural and anthropogenic pollutants from mainland China and Northeast Asia are contained in the air currents crossing Taiwan during autumn and winter (Tsai et al. 2014). Therefore, in our study, especially in winter time, the ECs of harvested rainwater were relatively higher than other rainwater samples.

Total organic carbon (TOC) of pilot-scale RWHS ranged from 0.073 to 13.2 mg/L and the median value is 1.97 mg/L (Figure 1(c)). The average TOC of the rainwater from the dust storm, and the Talim, Saola, Haikui, Tembin¹, Tembin² and Jelawat typhoons were 5.025, 0.56, 0.83, 1.43, 1.13, 1.4 and 0.98, respectively. Although the TOC of harvested rainwater during the dust storm demonstrated relatively higher values than other rainwater samples, TOC concentration did not show significant seasonal variation. Conversely, the TOC concentrations during typhoon period were relatively lower than normal rainwater due to dilution effect. Even though TOC does not have maximum contaminant level, it is a precursor for regulated disinfection by-products (Mendez et al. 2011).

Among 13 metals and three anions content in rainwater samples, Na, K, Ca, Mg, SO₄²⁻, NO₃⁻ and Cl⁻ showed higher concentration than others metals, which implied that these were the major composition in rainwater. According to our result shown in Figures 2 and 3, sea-salt species, such as Na, Cl and Mg showed higher contribution of these typhoons to rainwater samples, especially during the strong typhoon storm.

![Figure 3](https://iwaponline.com/ws/article-pdf/15/5/1019/414345/ws015051019.pdf)

**Figure 3** | (a) \(\text{Cl}^−\), (b) \(\text{SO}_4^{2−}\) and (c) \(\text{NO}_3^{−}\) of harvested rainwater.
event (Jelawat typhoon). In contrast, crustal species (Ca, K) and non-sea-salt component, such as NO$_3^-$ and SO$_4^{2-}$, concentrations were slightly lower than normal rainwater during typhoon period (Figures 2 and 3). This is in accordance with other studies that the typhoon brings in sea-salt particles from the Pacific Ocean owing to strong wind and dilution effect during typhoon, those of non-sea-salt component concentrations decrease (Minoura et al. 1998; Sakihama & Tokuyama 2005; Tsai et al. 2011). In terms of heavy metals in rainwater samples, there were only Cu and Zn that met drinking water standards which were set at 1 mg/L and 5 mg/L, respectively (Figures 4(a) and 4(b)).

Figure 4 | (a) Cu, (b) Zn, (c) Cd, (d) Pb, (e) Ni and (f) Cr of harvested rainwater.
However, even though Cd, Ni, Cr and Mn concentrations exceeded drinking water standards in pilot-scale RHWS, with values of 12% ($n = 22$), 2.2% ($n = 4$), 0.5% ($n = 1$) and 14.7% ($n = 27$), respectively, those of higher concentration were only found in the initial stage. It can be conjectured that stainless steel might contain these elements and the top of the oxide surface was in unstable form at the beginning (Chiang et al. 2013). In addition, acid rain in Taipei may promote leaching of various substances (metals) from the collection surface and deteriorate the quality of harvested rainwater (Sazakli et al. 2007). The result indicated that Pb concentration frequently exceeded drinking water standard 18.5% ($n = 34$) except in summer time 1.1% ($n = 2$) (Figure 4(d)). We also found Al in harvested rainwater although it is not regulated in the drinking water standards.

Our study demonstrated that most of the ion concentrations in harvested rainwater were lower than normal rainwater during typhoon event possibly due to dilution effect, with the exception of sea-salt species, Cu, and Fe. Harvested rainwater during dust events showed high pH, turbidity and EC, and the concentration of Na, Mg, Ca, \(\text{Cl}^-\), \(\text{NO}_3^-\) and \(\text{SO}_4^{2-}\) were more than five times higher than normal rainwater. Besides, most of chemical and physical-chemical parameters revealed significant seasonal variation, with the exception of sea-salt species, and this implied different rainfall-types in different seasons. According to our study, harvested rainwater collected in summer time showed better quality while harvested rainwater during winter time was the worst.

Microbiological quality of harvested rainwater was assessed by examining TC which is one of the common microbial indicators. Multiple-tube fermentation was conducted on 74 harvested rainwater samples from pilot-scale RWHS to assess microbiological quality. In this study, the TC of harvested rainwater ranged from <2 to 220 and median TC counts was 7 as shown in Figure 5. Total of 22 out of 74 samples exceeded drinking water standard, however, only one sample that was collected during typhoon exceeded drink water standard (Table 1). During typhoons, TC was low probably because of dilution effect. It was noted that TC of rainwater during the dust storm was low (<2), which was unusual considering its high turbidity. This may be due to experimental error, or the limited number of samples. More observation is needed in the future.

Acute biotoxicity test was conducted to evaluated lethal concentration 50% (LC$_{50}$) by examining the effect of toxics on \textit{Daphnia} survival. The LC$_{50}$ of harvested rainwater from pilot-scale RWHS is shown in Table 2. According to the criteria published by Taiwan Environmental Protection Agency, all of the rainwater samples were categorized into slightly toxic (LC$_{50}$ of 76–100) even during dust storm and typhoon events.

### CONCLUSIONS

Regarding rainwater quality harvested from the RWHS, high turbidity, high concentration of Pb and Fe and acidic pH of harvested rainwater are the major concerns for direct potable use. As a result of TC count and acute biotoxicity test, the harvested rainwater has a great potential as an
alternative water source, however, disinfection treatment is necessary before use.

Chemical, physico-chemical and microbiological parameters showed seasonal fluctuations mainly due to variable seasonal rainfall type and atmospheric conditions. In this study, harvested rainwater during the summer showed better quality while the worst quality was observed during winter. In contrast, higher TC counts were observed during summer and the lowest TC counts during winter.

Harvested rainwater during dust events showed high pH, turbidity and EC, and the concentration of Na, Mg, Ca, Cl⁻, NO₃⁻ and SO₄²⁻ were more than five times than normal rainwater. Conversely, most of the ion concentrations in harvested rainwater were lower than normal rainwater during typhoon events possibly due to dilution effects, with the exception of sea-salt species, Cu and Fe.

**REFERENCES**


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**Table 2** | LC₅₀ of harvested rainwater

<table>
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<th>Date</th>
<th>LC₅₀ (%)</th>
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<tr>
<td>24 April 2012</td>
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<tr>
<td>27 May 2012</td>
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<tr>
<td>02 August 2012 (Saola)</td>
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<tr>
<td>23 August 2012 (Tembin¹)</td>
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<tr>
<td>28 September 2012 (Jelawat)</td>
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