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Early Summer Dissolved Oxygen Characteristics in Restored Streams in Seoul

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서울시 복원하천들의 초여름 용존 산소량 특성 분석

Casey Thoenen · 최운섭 · 최진무

Abstract : This paper presents an evaluation of stream restoration projects in Seoul with a focus on dissolved oxygen. Five test sites across four streams were measured for dissolved oxygen (DO) in late May to early June in 2012 and compared against a set of minimum and maximum thresholds. Only one test site, Hwarang-cheon, showed measurements below 6 mg/l DO. Towards the upper limit, the Hwarang-cheon site was the only tested stream which was not at risk of DO supersaturation. The Danghyeon-cheon site had the highest probability of supersaturation, with DO saturation exceeding 130% expected 86.5% of the time. When measured every hour during daytime, DO levels showed diurnal variations, peaking in the afternoon. However, they showed inconsistent results along transects of the streams. Overall, the streams are rich in DO. To maintain the streams in good standing, nutrient loading should be addressed to prevent potential algal bloom induced hypoxic events down the line.

Key Words : water quality, dissolved oxygen, stream restoration, runoff

1. Introduction

Korea faced rapid urbanization during the latter half of the 20th century, and as a result, urbanization rates went from 35.8% in the 1960s to 90.1% in 2011 (Lee, 2006; Statistics Korea, 2012). Seoul, as a mega city, is home to 10.5 million people and has one of the highest population densities amongst major cities in the world (Seoul, 2012). With a rapid increase of urbanization came dramatic increases in impermeable surfaces, such as the creation of the Cheonggye expressway, which completely covered the Cheonggye-cheon stream with an elevated highway. Once seen as an engineering feat, the expressway epitomized the disregard for watershed management within the urban environment.

In the late 1990s, when the Cheonggye-cheon expressway was due for repairs, the city government decided to remove the expressway and restore the Cheonggye-cheon stream. This stream would serve the purpose of transitioning to the sustainable urban development paradigm and the recovery of eco-friendliness (Cheonggye, 2012). Since the restoration was completed in 2005, other stream restoration projects have been proposed and are in various stages of com-

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pletion. Amongst these are the Bulgwang-cheon, Danghyeon-cheon, Mukdong-cheon, and Hwarang-cheon streams, which share the common goals of providing green space for both recreation use and runoff management. The Danghyeon-cheon, Mukdong-cheon, and Hwarang-cheon projects were completed in 2010, and the Bulgwang-cheon project was completed in 2006.

The effectiveness of the projects can be measured in various ways, and one of them is water quality. There exist many water quality parameters, but oxygen-related parameters such dissolved oxygen (DO) or biological oxygen demand (BOD) are one of the most widely used. Oxygen is a basic requirement for life, and the amount of DO in water is deterministic to the quality of the watershed ecosystem. DO is easily measured in the field and a simple indicator of the watershed pollution (Sanchez et al, 2007; Williams and Boorman, 2012). It is also an important index of an aquatic ecosystem's health (Liu et al, 2007). Low levels of oxygen can have adverse effects on aquatic organisms, both micro and macro, whereas too much oxygen can also be an indicator of algal blooms caused by nutrient enrichment, which may cause hypoxia in the dark hours of the day (O'Boyle et al, 2009). The amount of oxygen that water can hold is determined primarily by water temperature and salinity. When fresh water is concerned, temperature is the primary factor.

The DO level of a stream is a result of influx and outflux of oxygen to and from the stream. The main influx comes from DO from tributaries or other sources, and reaeration from the atmosphere. The outflux results mainly from the DO in the outflow, nitrification, oxidation of carbonaceous material, and oxygen demand from benthal communities in the sediment (Liu et al 2007). Therefore observed measurements of DO reflect such diverse processes, and results may be very location-specific. Seasonally, DO supply tends to be lower in the summer months when high temperatures lead to higher growth and oxygen consumption from aquatic populations (Liu et al 2007). An and Shin (2005) also found a significantly negative correlation between DO and water temperature in a tributary of Geum-gang (river) on a daily scale over a year. The DO level also reveals diurnal cycles. The DO level of Anyang-cheon in Seoul shows an increase in daytime and a decrease at night, which implies that primary production is a major mechanism of oxygen supply (Kim, 2012).

The purpose of this study is to measure water quality, in terms of DO, for the Bulgwang-cheon, Danghyeon-cheon, Mukdong-cheon, and Hwarang-cheon streams. Streams are a vital resource in terms of processing waste material and managing runoff from precipitation events. Water quality parameters include physical properties, such as temperature, dissolved solids, and suspended solids, and chemical properties such as acidity, DO, and biochemical demand (Davie, 2008). In this study, DO and temperature were focused on.

2. Water Data Sampling and Measurement

A total of five sites (Figure 1 (a)) were selected for the primary focus of the study, two for Bulgwang-cheon (Jeungsan and Saejeol sites) and one each for the remaining streams. The Junggye site is on Danghyeon-cheon. Systemic water quality measurement data by a government agency do not exist for these streams. Air temperature, water temperature, and dissolved oxygen were measured on a daily interval over the course of two weeks, from 28 May to 8 June 2012. The measurement period was determined as such due to a couple of reasons. Most importantly, we wanted to avoid the summer monsoon period (*jangmacheol*). The preliminary field measurement period in 2011 included the

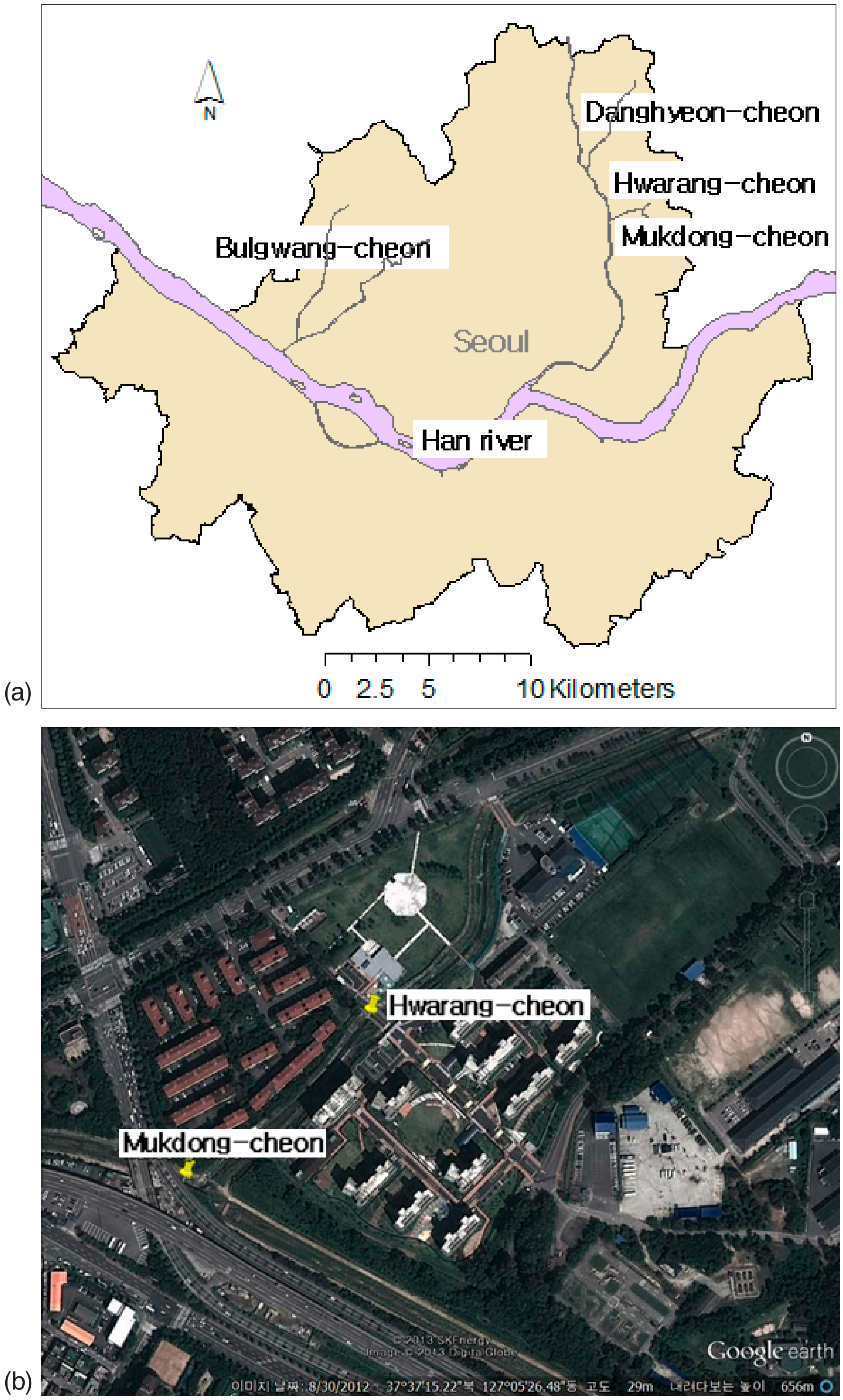

Figure 1. Study Sites

jangmacheol, which disrupted field activity. Measurements could not be taken in late summer of 2012 after the *jangmacheol* due to the investigators' work schedule.

Figure 1 (a) shows an overview of the test site locations within Seoul. It also shows their proximity to the Han River. Detailed measurement sites are shown in Figures 1 (b), 4, and 6. Figure 1 (b) shows the measurement sites on Hwarang-cheon and Mukdong-cheon. Hwarang-cheon flow southwestward right next to Korea Military Academy (upper-right corner in the map) and merges with Mukdong-cheon. Mukdong-cheon flows westward in the figure and merges with Jungnang-cheon downstream. Both of them are in the neighborhood of high-rise apartment buildings with scattered hills and grasslands. There were two regular measurement sites on Bulgwang-cheon, Jeungsan and Saejeol (Figure 4). The stream flows southward, and is underground upstream of Eunggam. The neighborhood features predominantly single-family homes and duplexes, and some high-rise apartment buildings. Junggye, the regular measurement site on Danghyeon-cheon, is shown on Figure 6, and is in the neighborhood of predominantly high-rise apartment complexes.

To measure DO, a hand-held DO-meter (HORIBA OM-14) was used. Two to three measurements were taken each visit. Air and water temperatures were taken with a mercury thermometer. The measurements were mostly taken near the water surface from weirs near the center of the streams. Measurements at the Hwarang-cheon site were taken near the bank, as access was limited.

DO concentration (mg/l) was converted to DO saturation using DOTABLES from the US Geological Survey (2012) using a default atmospheric pressure of 760 mmHg. DO saturation of 100% means that the water is saturated with DO for the given temperature. DO was determined as both a specific (mg/l) and saturation (%); specific values were used for lower limits, while the saturation values were used for upper limits according to Best et al (2007). The 97.5th and 2.5th percentiles were also calculated to identify the middle 95% range of the parameters.

Additional data was collected including both spatial and temporal transects. For the spatial transect, two streams were selected, Bulgwang-cheon and Danghyeon-cheon. For the Bulgwang-cheon stream, data was collected for temperature and DO near the Eungam subway station and measurements were taken

Table 1. Information about measurement sites

Stream	Site name	Latitude / Longitude from Google Earth®	Measured parameters	Temporal transect?	Spatial transect?
Bulgwang-cheon	Jeungsan	37° 35' 5.04" N / 126° 54' 40.33" E	DO, air temperature, water temperature	Yes	Yes
Bulgwang-cheon	Saejeol	37° 35' 43.56" N / 126° 54' 55.01" E	DO, air temperature, water temperature	No	Yes
Danghyeon-cheon	Junggye	37° 38' 48.00" N / 127° 3' 49.07" E	DO, air temperature, water temperature	Yes	Yes
Hwarang-cheon	Hwarang-cheon	37°37'16.49"N / 127° 5'23.80"E	DO, air temperature, water temperature	No	No
Mukdong-cheon	Mukdong-cheon	37°37'11.73"N / 127° 5'16.84"E	DO, air temperature, water temperature	No	No

from six successive downstream locations. It started at 09:40 and ended at 10:32 on 06 June 2012. For the Danghyeon-cheon stream, data was collected near the Junggye subway station in addition to three successive upstream locations. It started at 12:28 and ended at 12:50 on 06 June 2012. A GPS was unavailable for measuring precise locations and distance along the streams, thus distances used in regression analysis were determined through Google Earth® software.

For the temporal transects, Bulgwang-cheon and Danghyeon-cheon were also the targeted sites. Measurements for temperature and DO were taken at a constant location, hourly, over the course of a single day, hours 09:30 to 16:30 on 04 June 2012 for Danghyeon-cheon and 09:00 to 15:00 on 05 June 2012 for Bulgwang-cheon at the Jeungsan site.

Table 1 summarizes the information about the measurement sites.

3. Results

1) Summary of DO and temperature measurements

The measurement results are summarized in Table 2. The Mukdong-cheon site had the highest water temperature whereas the Saejeol site had the lowest water temperature. The differences between air and water temperatures were about 2-3 degrees. When it comes to DO, Bulgwang-cheon sites and the Mukdong-cheon site were about saturated with DO. On the other hand, the Junggye site showed extreme oversaturation whereas the Hwarang-cheon site had only about 80% saturation. The Junggye and Mukdong-cheon sites showed the highest water temperatures, but their mean DO values were very different. It seems it is largely due to the unexpectedly high DO level at the Junggye site. Considering that the values are means of all measurements, it is not meaningful to find a correlation between water temperature and DO from Table 2.

Table 2. Mean air temperature (degrees C), water temperature (degrees C), DO (mg/l), mean saturation, DO at 2.5th percentile, DO at 97.5th percentile, DO saturation at 2.5th percentile, and DO saturation at 97.5th percentile.

Stream	Site name	Mean Air Temp	Mean Water Temp	Mean DO	Mean DO Saturation	2.5th percentile (mg/l)	97.5th percentile (mg/l)	2.5th percentile DO Saturation	97.5th percentile DO Saturation
Bulgwang-cheon	Jeungsan	26.83	23.41	9.14	108%	5.28	13.00	55%	162%
Bulgwang-cheon	Saejeol	26.37	22.60	9.28	108%	6.82	11.75	77%	138%
Danghyeon-cheon	Junggye	26.24	24.55	12.98	156%	9.04	16.91	106%	206%
Hwarang-cheon	Hwarang-cheon	27.20	22.98	6.87	80%	3.79	9.95	45%	115%
Mukdong-cheon	Mukdong-cheon	27.41	25.70	8.77	108%	6.35	11.20	71%	145%

Table 3. Observed (O) and expected (E) probabilities of the stream being below 6 mg/l DO or above 130% DO saturation

Stream	Site name	Events below 6 mg/l		Events above 130% Saturation	
		O	E	O	E
Bulgwang-cheon	Jeungsan	0.0%	5.6%	25.0%	20.6%
Bulgwang-cheon	Saejeol	0.0%	0.5%	0.0%	7.5%
Danghyeon-cheon	Junggye	0.0%	0.0%	87.5%	86.5%
Hwarang-cheon	Hwarang-cheon	37.5%	29.1%	0.0%	0.3%
Mukdong-cheon	Mukdong-cheon	0.0%	1.2%	0.0%	12.1%

Normal water conditions conductive to marine life should fall between 6 mg/l to 10 mg/l DO, and 95% of the measured DO values should read from 70% to 130% saturation (O'Boyle et al, 2009.) Other proposed minimum limits have been suggested at 9 mg/l and 7 mg/l (Best et al, 2007). Table 3 shows the observed and expected probabilities of the stream being below 6 mg/l DO or above 130% saturation, considering the aforementioned thresholds. The expected values were estimated assuming a normal distribution. At the sites tested, Hwarang-cheon has the highest probability of being below the threshold of 6 mg/l, with an expected probability of 29% and an observed occurrence of 38%. The Jeungsan site was also expected to have DO level below 6 mg/l with a probability of more than 5%.

The other streams were not as likely to see oxygen deficiencies during the day, but the Jeungsan, Junggye and Mukdong-cheon sites were expected to exceed the upper threshold for being supersaturated with DO with probabilities more than 10%. Actually, the Jeungsan and Junggye sites showed super-saturation more than 25% of the measurements. Super-saturation can be caused from algal blooms which create oxygen during the day but cause oxygen deficiencies during the evening due to excessive respiration.

The Saejeol site of Bulgwang-cheon is the only test site to have minimal significant risk of super saturation or oxygen deficiency, albeit super-saturation was expected to exceed the threshold with a probability of 7.5%. The Saejeol site is near the source of the Bulgwang-cheon, with water being pumped in at the Eungam subway station upstream. The distance was too close for environmental factors to make an impact.

2) Temporal transects of DO and temperature measurements

Temporal transects were taken of the Junggye site of Danghyeon-cheon, and the results are presented in Figure 2. Overall, the slope for Mean DO and DO saturation were insignificant. Calculations for slope leading up to the peak at 14:30, however, were significant at the 99% confidence interval. Combined with the fact that DO saturation was in excess of 130% throughout the time measured, it is likely that algal blooms pose a problem within this stream. This is consistent on site visual confirmations of algal blooms.

Figure 3 shows the temporal transect for the Jeungsan site in the Bulgwang-cheon stream. The Jeungsan site of Bulgwang-cheon showed a significantly positive slope until 15:00 for both mean DO and DO saturation. Then the slope became negative after 15:00. This shows quite a bit of temporal variation, likely due to photosynthesis. Mean DO was near the 6 mg/l threshold at 9:00 and began to exceed the 130% DO

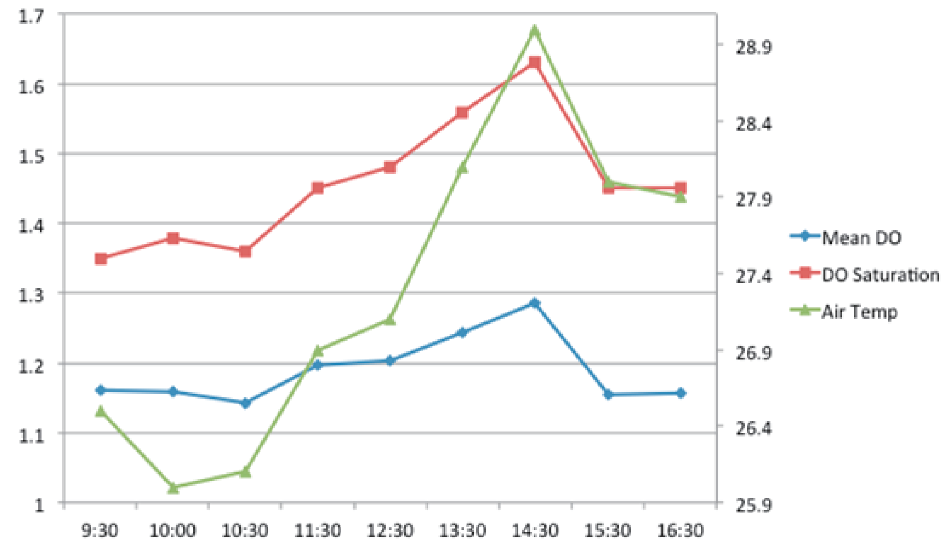

Figure 2. Primary axis: Mean DO (in 10 mg/l) and DO saturation (in 100%); secondary axis: air temperature (degrees C); horizontal axis: time of the day, for the Junggye site of Danghyeon-cheon on 4 June 2012.

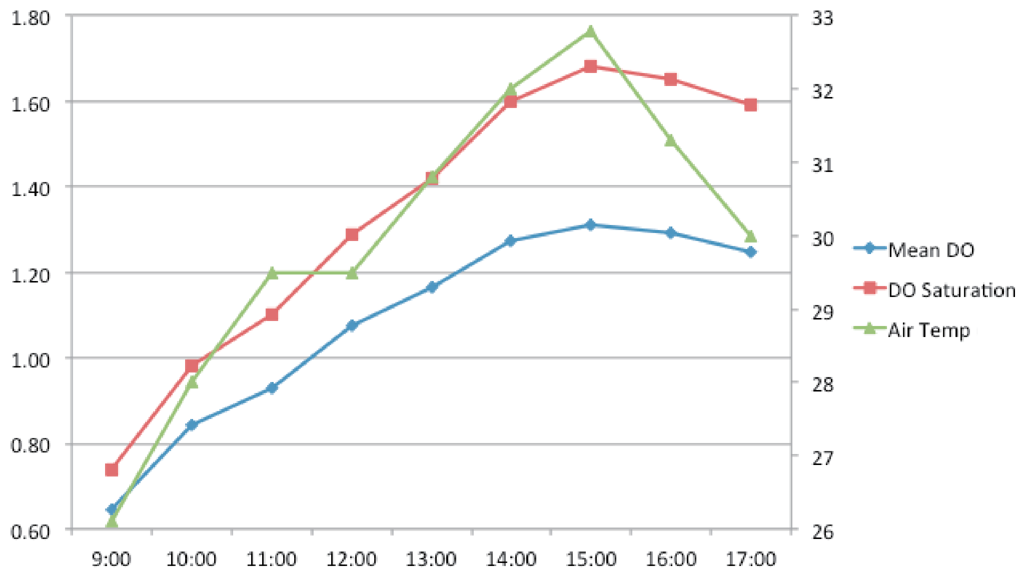

Figure 3. Primary axis: Mean DO (in 10 mg/l) and DO saturation (in 100%); secondary axis: air temperature (degrees C); horizontal axis: time of the day, for the Jeungsan site of Bulgwang-cheon on 5 June 2012.

saturation threshold just after 12:00. The potential for hypoxic conditions in the evening is not an unreasonable assumption.

3) Spatial transects of DO and temperature measurements

Figure 4 shows the spatial transect test points for Bulgwang-cheon, and Figure 5 shows the data collected from the spatial transect. The spatial transect showed minimal variation in DO or DO saturation as measurements were taken down stream. The standard deviations for mean DO and DO Saturation were 8.1 and 10, respectively. The slope of the line had no significance. With the expected super-saturation rate at Jeungsan being about 12.5% greater than at Saejeol, we expected there to be more of a significant slope than was actually calculated.

The spatial transect test points for Danghyeon-cheon are shown in Figure 6, and Figure 7 shows the data collected from the spatial transect of Danghyeon-cheon. The spatial transect showed variation with a standard deviation of 0.9 for DO and 12.5 for DO saturation. Both slopes were significant with a 90% confidence interval. DO and DO saturation both increased downstream.

4. Discussion

Dissolved oxygen is an important chemical property of streams. Oxygen is needed by organisms in order to break down organic wastes that runoff into the stream. In a highly urbanized setting, like Seoul, it is very important to have healthy aquatic ecosystems to process

Figure 4. Locations of spatial transect test sites for the Bulgwang-cheon.

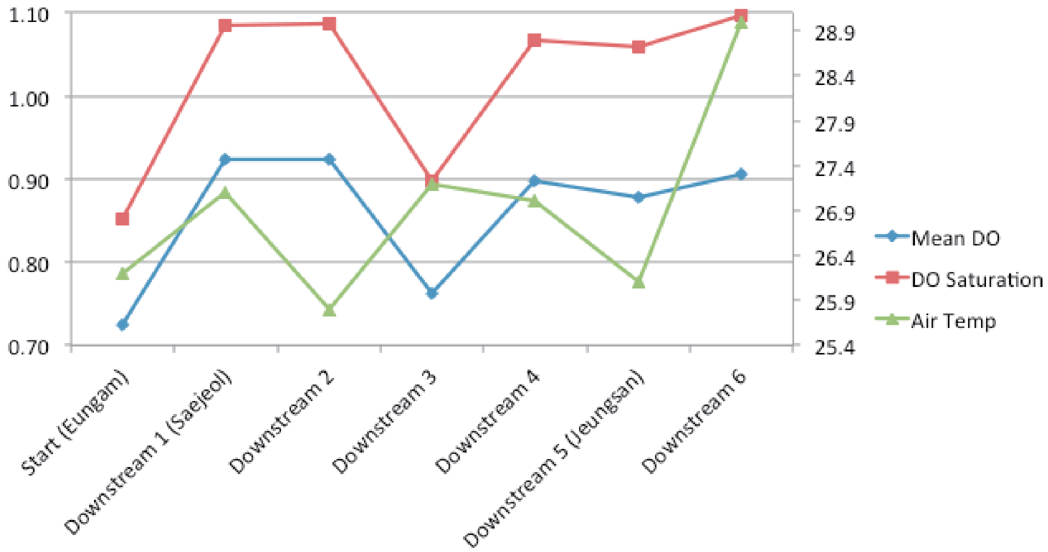

Figure 5. Primary axis: mean DO (in 10 mg/l) and DO Saturation (in 100%); secondary axis: air temperature for Bulgwang-cheon on 6 June 2012.

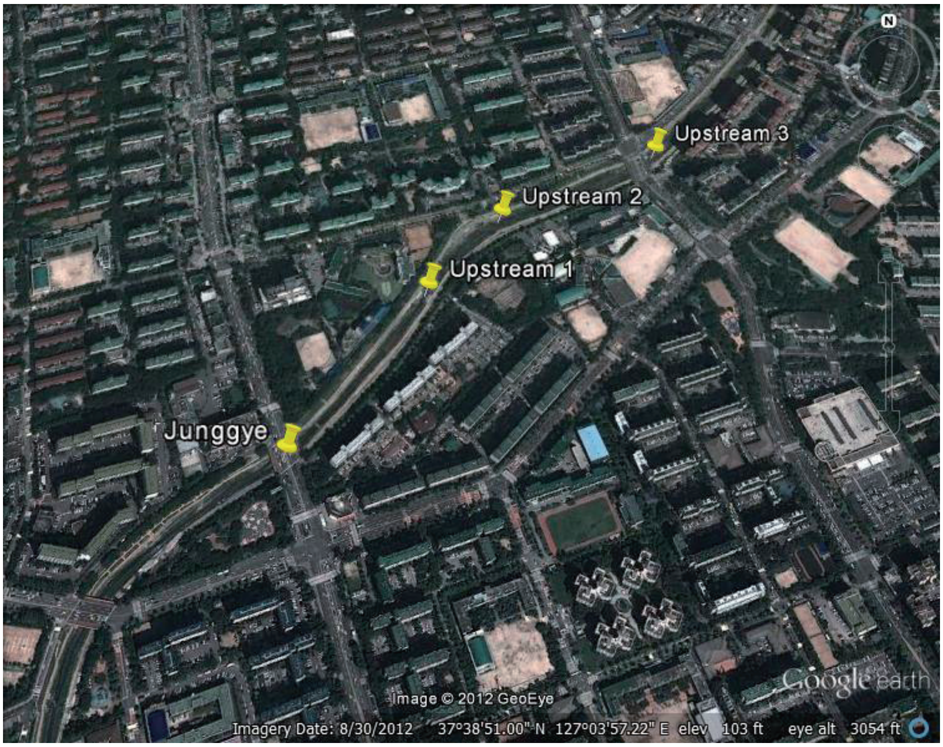

Figure 6. Locations of the spatial transect test sites for the Danghyeon-cheon.

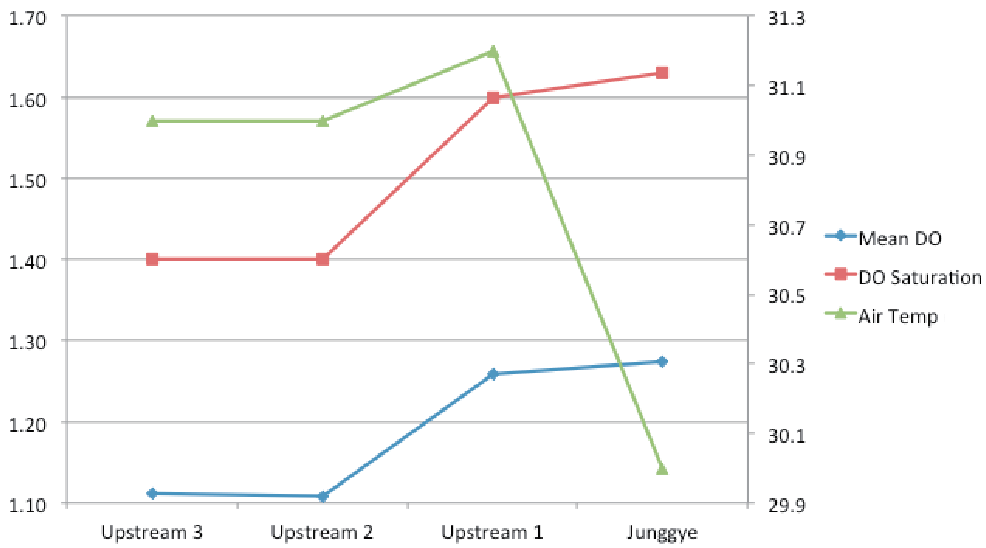

Figure 7. Primary axis: mean DO (in 10 mg/l) and DO Saturation (in 100%); secondary axis: air temperature for Danghyeon-cheon on 6 June 2012.

the additional runoff created by an increased area of impermeable surfaces (Carapeto and Purchase, 2000; Jeon et al, 2010).

DO can be measured as a specific value, or as a percentage of saturation. Both values are important as they relay different information. Specific values of normal water are between 6 and 10 mg/l DO, while values for saturation should be between 70% and 130%. Dissolved oxygen and water temperature are interdependent. Oxygen deficiency (levels below 6 mg/l) can cause negative effects on aquatic fauna, which can hinder the ability of the stream to process waste. Sensitive species can be affected at 5 mg/l DO while hardier fish are not typically affected until 2 mg/l DO (Best et al, 2007). DO super-saturation is typically the result of algal or phytoplankton blooms. While photosynthesis from these blooms provides more oxygen during the day, respiration can cause an oxygen deficit in the darker hours. Blooms can be the result of increased nutrient enrichment (O'Boyle et al, 2009). The temporal transect analysis showed increasing DO levels from morning to afternoon in response to increasing primary production, then falling off late in the afternoon.

Bulgwang-cheon showed various results. The Saejeol site of Bulgwang-cheon showed a combined expected probability of about 8% for being either super-saturated or oxygen deficient. The Jeungsan site, however, showed a risk of about 26%, mostly of being super-saturated. Although the spatial transect showed no significant slope between the sites, the temporal transect found the Jeungsan site had a significant increase in DO as sunlight exposure increased. Temporally, DO started near the lower limit and increased to well above the upper limit for DO saturation. Excessive photosynthesis may be a factor in water quality for Bulgwang-cheon. Further testing for nutrient loading should be conducted.

Danghyeon-cheon was calculated to be outside of the target parameters 86.5% of the time, all above the 130% DO saturation threshold. The temporal transect showed only a small peak in DO, and the spatial transect showed a significant slope, with DO increasing as the stream progressed. The riparian buffer was not as mature as the other sites, and algal blooms were plenty, potentially causing the spatial gradient in DO. Further testing of nutrient loading should be conducted, also more extensive spatial sampling is recommended.

Water quality is evaluated with a range of parameters, and only DO was selected for the study due to limited resources and time. Different water quality parameters are affected by land use and land cover at different spatial scales (Uriarte et al, 2011; Pratt and Chang 2012). The current study is one of the first attempts to examine water quality of restored small streams in Seoul, but has severely limited scope of research. First, measurements were taken during a very dry period in early summer when there was no measurable rainfall. Results are likely to be different during *jangmacheol*, hot and humid summer after *jangmacheol*, or in a cold season. Although the measurement period is quite limited, the study revealed diurnal patterns of DO comparable to other streams in Seoul (e.g. Anyang-cheon). Second, land use and land cover of the catchments were not rigorously analyzed. Since DO is known to be correlated with land use and land cover in the literature (e.g. Amiri and Nakane, 2009; Figueiredo et al, 2010; Uriarte et al, 2011), more DO measurements need to be made and analyzed with land use and land cover. However, because the stream water is not entirely naturally supplied, weak or no correlation is anticipated. For example, water in Danghyeon-cheon is mostly supplied from a treatment facility downstream (Nowon-gu, 2012), making its quality virtually irrelevant to the land cover in the watershed. Hwarang-cheon is in the most natural condition of the studied streams, but showed the lowest DO.

5. Conclusions

The objective of this study was to measure the water quality in a number of restored streams in Seoul, in terms of dissolved oxygen in order to show the effectiveness of stream restoration. Major findings from the study include the following: (1) Danghyeon-cheon showed a very high risk of DO super-saturation; (2) Hwarang-cheon showed a highest risk of oxygen deficiency among the sites; and (3) DO level showed a similar temporal trend to air temperature at a sub-daily scale.

Overall, it appears that the stream restoration projects resulted in or maintain good water quality in terms of DO. However, DO super-saturation does appear to be a problem. The water flowing downstream mostly comes from pumping stations removing water from Seoul's extensive subway system. This water pours directly into the stream itself, causing nutrients to bypass the installed wetland buffer. Having the water filter through installed wetlands would help remove some of the nutrients that allow for algal blooms (Carapeto and Purchase, 2000; Jing et al 2001).

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