Duration curve analysis for the assessment of pathogen loading from diffuse sources

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Abstract Pathogen level of surface waters has received great attention for protecting public health. In this study, total coliform, fecal coliform and Escherichia coli concentrations were monitored as the pathogen indicator organisms at six monitoring stations in the Geum River, Korea. Rainfall runoff from two agricultural-forestry watersheds was analyzed for their microbial aspect as well. Total coliform concentration of the Geum River showed high correlation with the flow rate. To estimate total coliform loading on the Geum River in probability scale, the duration curve method was applied. In addition, a standard duration curve reflecting the water quality criteria was constructed to determine water quality compliance. Under the assumption of linearity between flow rate and total coliform concentration of the Geum River, total coliform duration curve revealed that total coliform concentrations exceed the desired criteria mainly due to pollutants from diffuse sources.

Keywords Coliform; diffuse pollution; duration curve; indicator organisms; pathogen; rainfall runoff

Introduction

Many concerns are raised about the fecal contamination originated from rainfall runoff (Conboy and Goss, 2000), since pathogens originated from fecal contamination directly impact on the human health (USEPA, 1993). The pathogen levels of water can be assessed by measuring the indicator organism population in the water. The indicator organism should: (i) be easily detected using simple laboratory tests; (ii) generally not be present in unpolluted water; (iii) be present in concentrations that can be correlated with the extent of contamination; (iv) have a die-off rate that is not faster than the die-off rate for the pathogens under consideration (Thomann and Mueller, 1987; USEPA, 2001). Total coliform, fecal coliform, fecal streptococci, and *Escherchia coli* are common indicator organisms to be monitored. The origins of pathogens are various. Potential point pathogen sources are wastewater treatment plants (WWTPs), combined sewer overflows (CSOs), separated sewer overflows (SSOs), slaughterhouses, and animal feedlots (Lipp *et al.*, 2001). For the non-point sources, illicit sewage connections, wildlife, septic systems, livestock, landfills, and pastures would be the potential sources. Stormwater runoff can transport significant loads of pathogens from livestock pastures, livestock and poultry feeding facilities, and feedlots. Indicator organisms are often used as a tool to identify the contaminant sources as well. Maul and Cooper (2000) used enterococci and fecal coliform bacteria concentration to assess the variability of water quality of the agricultural field during wet weather. Whitlock *et al.* (2002) used fecal coliform to identify the sources in an urban watershed.

United Nations Environment Program (UNEP) and World Health Organization (WHO) established water quality criteria of coliform concentration for primary contact recreation purpose. Fecal coliform concentration from a geometric mean of at least five

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samples should be less than 100/100 ml for 50% and less than 1000/100 ml for 90%. USEPA restricts *E. coli* density less than 126/100 ml for fresh water for logarithmic average for a period of 30 days of at least five samples (WHO, 1999). The Korean Government regulates total coliform concentration of surface water by the law, which restricts water concentration to less than 1000 MPN/100 ml for the second grade of source water use and for the first grade of fishery and swimming use.

The research objectives of this study were: (i) to introduce the indicator organism for surface water quality management; (ii) to monitor the concentration range of the indicator organism of the surface water; (iii) to study the relationship between flow rate and indicator organism concentration; and (iv) to estimate indicator organism loadings on a river in probability scale.

Materials and methods

The Geum River is one of the four national rivers in Korea. Six monitoring stations (R1 through R6) are located in the river. The monitoring stations are located about 10 km apart. Figure 1 shows the location of the monitoring stations. Two small watersheds, SW1 and SW2, were selected to monitor the concentrations of rainfall runoff as well. The study watershed SW1 has an area of 3.38 km^2 and mainly constitutes unpolluted forestry. This study watershed is located in the vicinity of the Shindang Reservoir, where designated as a headwater of the Geum River. The study watershed SW2 covers 27.37 km^2. It is mainly comprised of rice paddy (35.9%) and forestry (44.8%).

Ten rainfall events were monitored at study watersheds SW1 and SW2, most in the spring and the summer of 2002. The number of concentration data obtained at each study watershed was about 150, as approximately fifteen samples were taken for each rainfall event. Meteorological information was obtained from the regional office of Korean Meteorological Administration. Rain gauges were located within 2 km of each monitoring station. Runoff volumes were measured using a velocity meter probe, (Global Water® FP-101 of Plano molding company, USA). Flow rates and concentration of base flow were monitored periodically at each site. More frequent sampling was undertaken for high flow condition. The number of samples taken at each rainfall event was adjusted from 12 to 18, by observing hydrographs for adequately depicting shapes of pollutographs.

At the six monitoring stations in the Geum River, water samples were taken on a weekly basis during drought season from October 2002 to April 2003. Flow rate of the

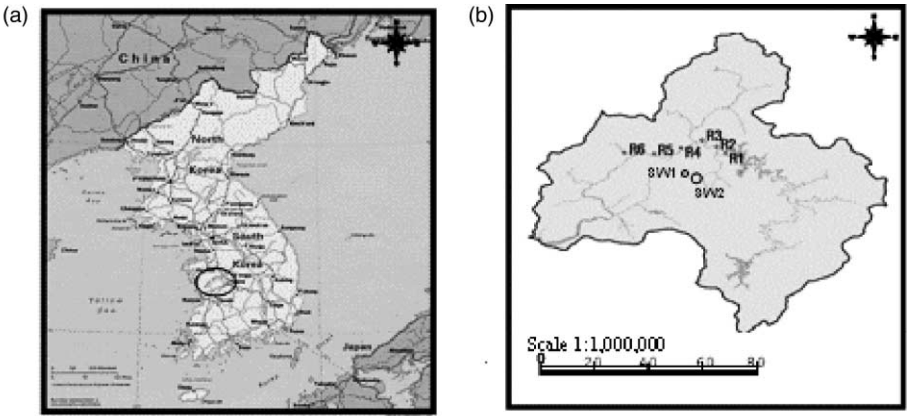

Figure 1 Location of water quality monitoring stations: (a) the Geum River basin; (b) two small watersheds (SW1, SW2) and six monitoring stations (R1–R6) in the basin

monitoring points were estimated using the rating curves provided by the Korean Water Resources Corporation. Rating curves were issued by the company quarterly at different sites of the river. Concentration data of suspended solid (SS), biochemical oxygen demand (BOD), and total coliform (TC) measured by Korean ministry of Environment (KMOE) were also used for analysis of long-term concentration variation of the Geum River. Water level data at monitoring station R5 named Gongju was obtained from the Korean Ministry of Construction and Transportation and converted to flow rate.

Water samples were manually taken and refrigerated prior to analyses. All samples were analyzed within eight hours after collection. For the microbial analysis, water samples were aseptically taken in sterilized, separate container. Water samples were brought to the laboratory in a refrigerated condition, and analyzed using aseptic techniques. Total coliform and *E. coli* concentrations were analyzed using Petrifilm™ of 3 M corp. for QA/QC of data. Petrifilm™ is a variation of the heterotrophic plate count method and thus enumeration is expressed as colony-forming units (CFU/100 ml). A few of the water samples were also analyzed by the multiple tube fermentation (Standard Methods, 1998) for comparison with the monitoring data measured by KMOE. Fecal coliform concentrations were analyzed by the membrane filtration technique (Standard Methods, 1998). The technique is effective for low-to-medium samples and inexpensive (Lisle, 1993). Petrifilm™ and membrane filtration techniques used in this study are fast (24 h ± 2 h for presumptive) and provide direct colony count. A few water samples were measure by either method for data comparison.

SPSS versus 12k was used to compute the descriptive statistics, and the Pearson correlation matrices. The relationship between monitoring data was examined using the Pearson correlation analysis.

Results and discussion

Coliform concentration of rainfall runoff

Table 1 is the descriptive statistics of indicator organism concentration from each watershed during wet weather. The average concentration of fecal coliform from SW1 and SW2 during wet weather is 628 CFU/100 ml and 21,285 CFU/100 ml, respectively. Higher concentration from SW2 was consistent. Agricultural activity of SW2 may have an affect on the magnitude of concentration. Land use effects on the diffuse pollution were reported by many researches (Gardi, 2001; Brezonik and Stadelmann, 2002). Crowther *et al.* (2002) showed the relationship between land use and fecal indicator

Table 1 Concentration range of coliforms from SW1 and SW2 during wet weather

	Site	*n* [a]	Average[b]	SD[d]	SE[e]	Min.	Max.
Total coliform	SW1	147	4,225	6,211	512	nd[f]	32,000
	SW2	143	30,250	25,187	2,106	400	146,000
		Average	16,863	18,879	778	200	89,000
Fecal coliform	SW1	80	628	1,339	150	nd	8,250
	SW2	63	21,285	24,420	3,101	500	97,500
		Average	10,956	12,879	1,625	250	52,875
E. coli	SW1	147	156	389	32	nd	3,200
	SW2	143	11,278	12,952	1,083	nd	70,500
		Average	4,622	8,892	366	nd	36,850

[a] number of samples taken at the designated watershed
[b] average of the designated watershed (CFU/100 ml)
[c] average of all four study watershed (CFU/100 ml)
[d] standard deviation
[e] standard error
[f] not detected

concentration. Higher fecal coliform bacteria concentration was measured during high flow condition in their study. This is due to attachment of microorganisms on suspended solids during runoff (Schillinger and Garner, 1985; Borst and Selvakumar, 2003). The fecal coliform concentration from SW1 and SW2 is much higher than the criteria established by UNEP/WHO.

The coliform concentrations show an increasing tendency from R1 to R3, and decreasing to R6 (Table 2). The Ghap Stream inflows in to the Geum River before R2. A wastewater treatment plant with a capacity of 900,000 m^3/d (= 10.4 m^3/s) without disinfection processes is located on the Ghap Stream. The average drought flow of the Ghap Stream is about 15 m^3/s for the year of 2000. As no significant point sources exist after R5, coliform concentration show a decreasing tendency.

Duration curve analysis for assessing total coliform loading on a monitoring station in the Geum River

The flow duration curve can be constructed by using the daily flow rate data in the following steps:

(1) Daily flow rate during a desired period was compiled and sorted in ascending order to calculate the not-exceeding probability by using the following plotting position formula.

$$F_Q(q_{(i)}) = i/(365 \times n + 1) \tag{1}$$

where, $F_Q(q_{(i)})$ =not-exceeding probability for i th daily flow rate in ascending order and n = number of years.

(2) Exceeding probability can be calculated by Equation 2, and flow duration curve can be drawn with probability for the x-axis and log-scale for the y-axis.

$$EP_Q(q) = 1 - F_Q(q) \tag{2}$$

where $EP_Q(q)$ =exceeding probability corresponding to daily flow rate q.

Figure 2 shows the flow duration curves for the same period. Exceeding probability of a certain flow rate can be easily identified by using Figure 2. For instance, the drought flow of Gongju, which is 50.3 m^3/s, corresponds to 40% of the exceedance probability, implying that the flow rate was higher than the drought flow for 146 (= 365 × 0.4) days. For better understanding of the flow rate change, time series variation of flow for the same period and same location was plotted in a graph.

Figure 3 is the time series variation of total coliform concentration for the same period at Gongju. TC concentration was over the water quality criteria required for Gongju by KMOE (<1000 MPN TC /100 ml, class II) for the extended duration. For

Table 2 Concentration range of coliform bacteria during drought season at two small watersheds and monitoring stations in the Geum River.(unit: $\times 10^2$ CFU/100 ml)

Site	Total coliform			Fecal coliform			*E. coli*		
	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.
SW 1	0.95	48.0	nd	0.84	5.88	nd	0.18	2.00	nd
SW 2	111	800	3.00	105.0	966	31.1	17.6	67.0	nd
R1	17.2	144	nd	2.5	29.4	nd	0.17	2.00	nd
R2	56.4	150	17.0	26.0	99.12	10.9	4.60	23.0	nd
R3	85.1	177	35.0	44.5	159.6	33.6	7.00	21.0	nd
R4	69.8	160	19.0	26.0	117.6	16.8	6.20	58.0	nd
R5	50.2	164	20.0	22.7	134.4	6.7	3.30	52.0	nd
R6	16.7	55.0	nd	1.7	27.7	nd	0.30	5.00	nd

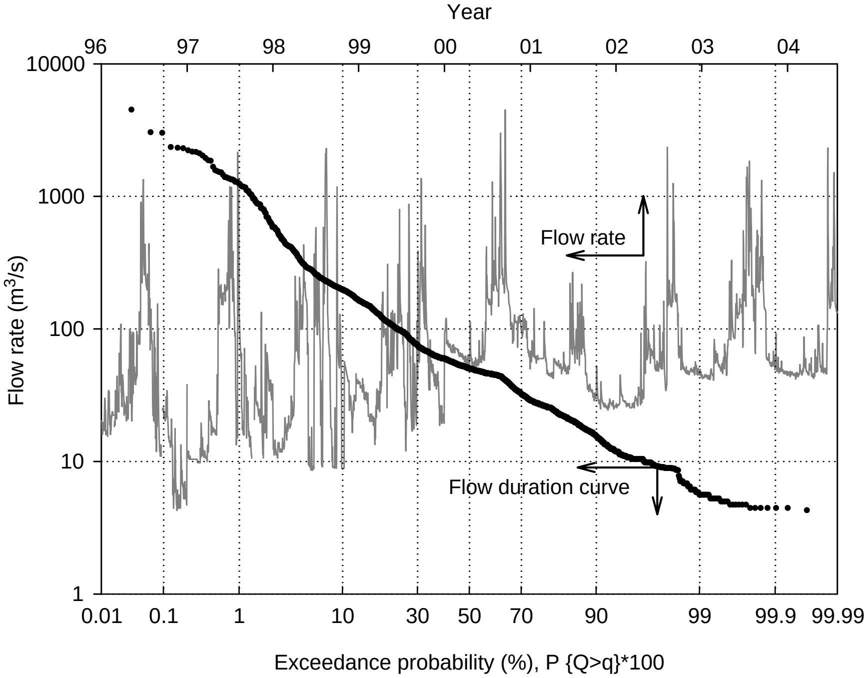

Figure 2 Flow duration curve at Gongju, the Geum River from January 1996–July, 2004

better understanding of the relationship between contaminant concentration and flow rate, time series flow rate variation was plotted in the figure as well.

Figure 3 shows that the flow rate was closely related to coliform concentration. Table 3 is the summary of the Pearson correlation coefficients which varied between +1 for complete linear relationship between two variables and −1 for complete inverse correlation for BOD, SS, and TC concentrations of the monitoring data. The Pearson coefficient between flow rate and BOD was −0.363; this result implied that BOD

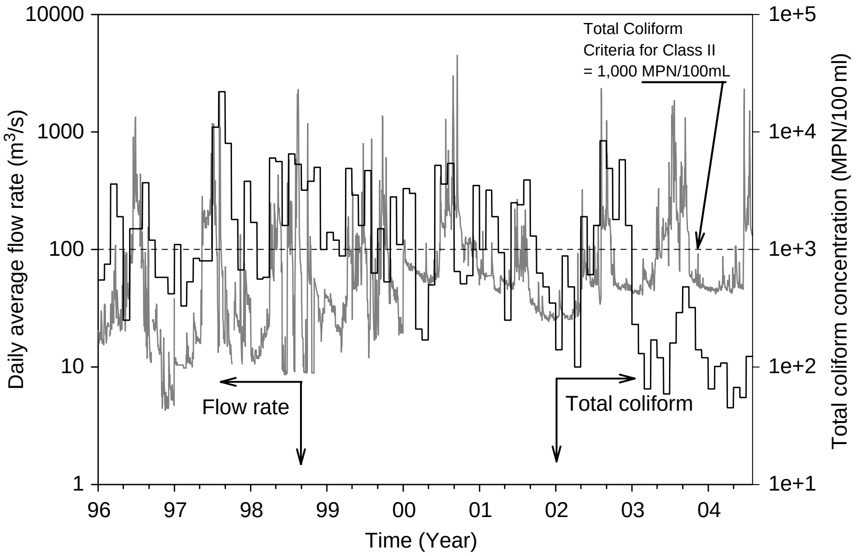

Figure 3 Time series daily flow rate and total coliform concentration at Gongju, the Geum River from January 1996–July 2004

Table 3 Pearson correlation coefficients between water level, biochemical oxygen demand (BOD), suspended solid (SS) and total coliform (TC) concentrations ($n = 108$)

	Level	BOD	SS	TC
Level	1	− 0.363	0.375	0.712**
BOD	− 0.363	1	0.130	− 0.515**
SS	0.375	0.130	1	0.192
TC	0.712**	− 0.515**	0.192	1

**Correlation is significant at the 0.01 level (2-tailed)

concentration was decreasing when flow rate was increasing and that the two variables correlated significantly. However, the Pearson coefficient between flow rate and coliform concentration was 0.712; this result implied a linear relationship between flow rate and coliform concentration.

Load duration curve can be constructed by the following procedure based on flow rate and coliform concentration data shown in Figure 3:

(1) Multiply the monitored concentration and corresponding daily flow rate sorted in ascending order to calculate the daily average load. Then plot the load duration curve in exceeding cumulative probability scale on the x-axis and log-scale on the y-axis. Monthly averaged concentrations were assumed for the daily contaminant load calculation.

(2) Standard load duration curve can be constructed by multiplying daily average flow rate and desired water quality criteria and then plotting the exceeding cumulative probability scale on the x-axis and log-scale on the y-axis.

Plotting the load duration curve and standard duration curve on the same graph enables analysis of the contaminant load exceeding the desired criteria and corresponding flow rate. Figure 4 shows a load duration curve for TC along with a standard duration curve for class II. To meet the water quality criteria for Gongju, which is class II, TC coliform concentration should be less than 1000 MPN/100 ml. Using this water quality criteria and daily flow rate, standard duration curves can be constructed. If the load duration curve

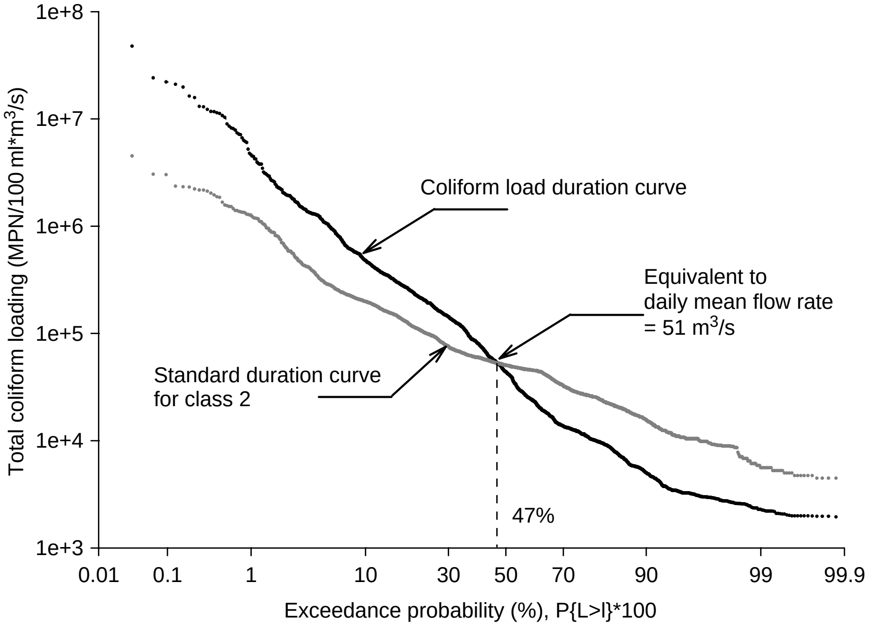

Figure 4 Coliform load duration curve and standard load duration curve at Gongju

exceeds the standard duration curve, it means that the water quality does not meet the water quality criteria for class II at the monitoring point. That is Figure 4 implies that the TC concentration from January 1996 to July 2004 did not meet water quality. Flow rates on the intersection points between coliform duration curve and standard duration curve correspond to 47% of the exceeding cumulative probability and are identified as 51 m^3/s. Considering the high linear relationship between coliform concentration and flow rate of the river, TC concentration exceeding the water quality criteria when flow rate was exceeding 51 m^3/s. When coliform concentration exceeds the water quality criteria at high flow rate, pathogens from diffuse sources need to be reduced to lower the coliform concentration in the receiving water.

Conclusions

This study aimed to characterize the coliform concentrations as pathogen indicator organisms of the Geum River, Korea and to understand the relationship between flow rate and coliform concentrations by using duration curve analysis. Rainfall runoff was identified as one of the main pollutant sources to degrade the surface water in microbial aspect. From the water quality monitoring of the river, it could be understood that rainfall runoff from a watershed with more agricultural activities showed higher coliform concentrations. The correlation analysis between water level, BOD, SS, and total coliform of the river revealed that the total coliform concentration was highly correlated with the flow rate while BOD concentration has a weak inverse correlation with the flow rate. High correlation between flow rate and coliforms occurred because the majority of microorganisms attached on suspended particles, and can be transported to downstream when high mobility occurs during wet weather. The duration curve method was applied to analyze the exceedance probability of total coliform loading exceeding the water quality criteria at a monitoring station located in the Geum River. Flow duration curve were constructed based on daily flow rate from January 1996 to July 2004. The plot of the total coliform load duration curve and a standard load duration curve based on the required water criteria for recreational use, which is 1000 MPN/100 ml, showed that water quality at Gongju did not meet the water quality criteria for coliform constituents of 47% for the duration of the collected data. By using the load duration curve method, water quality compliance can be easily assessed based on the probability scale.

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