Journal of Environmental Management 97 (2012) 46–55

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Development of Web-based Load Duration Curve system for analysis of total maximum daily load and water quality characteristics in a waterbody

Jonggun Kim [a], Bernard A. Engel [b], Youn Shik Park [a], Larry Theller [b], Indrajeet Chaubey [b], Dong Soo Kong [c], Kyoung Jae Lim [a,*]

[a] Department of Regional Infrastructure Engineering, Kangwon National University, Chuncheon, Gangwon 200-701, South Korea
[b] Department of Agricultural Engineering, Purdue University, West Lafayette, IN 47907-2093, USA
[c] Department of Life Science, Kyonggi University, Suwon, Gyeonggi-do 443-760, South Korea

ARTICLE INFO

Article history:
Received 24 September 2010
Received in revised form
10 November 2011
Accepted 24 November 2011
Available online 28 December 2011

Keywords:
Flow Duration Curve
Load Duration Curve
Total maximum daily load
Water quality characteristics

ABSTRACT

In many states of the US, the total maximum daily load program has been widely developed for watershed water quality restoration and management. However, the total maximum daily load is often represented as an average daily pollutant load based on average long-term flow conditions, and as such, it does not adequately describe the problems they aim to address. Without an adequate characterization of water quality problems, appropriate solutions cannot be identified and implemented. The total maximum daily load approach should consider adequate water quality characterizations based on overall flow conditions rather than on a single flow event such as average daily flow. The Load Duration Curve, which provides opportunities for enhanced pollutant source and best management practice targeting both in the total maximum daily load development and in water quality restoration efforts, has been used for the determination of appropriate total maximum daily load targets. However, at least 30 min to an hour is needed for unskilled people based on our experiences to generate the Load Duration Curve using a desktop-based spreadsheet computer program. Therefore, in this study, the Web-based Load Duration Curve system (https://engineering.purdue.edu/~ldc/) was developed and applied to a study watershed for an analysis of the total maximum daily load and water quality characteristics in the watershed. This system provides diverse options for Flow Duration Curve and Load Duration Curve analysis of a watershed of interest in a brief time. The Web-based Load Duration Curve system is useful for characterizing the problem according to flow regimes, and for providing a visual representation that enables an easy understanding of the problem and the total maximum daily load targets. In addition, this system will be able to help researchers identify appropriate best management practices within watersheds.

1. Introduction

The health of a stream ecosystem is deteriorated by point and nonpoint source pollution. In most cases, managing the pollution loads and sources could restore stream health. Streamflow characteristics including flow volume, rate, and timing are specific to each watershed. The site specific nature of streamflow requires that nonpoint source pollution, such as from agricultural, mining, and construction activities; saltwater intrusion; and land/subsurface waste disposal, be appropriately managed and controlled to restore the hydrologic and ecological functions of watersheds (Elshorbagy et al., 2005). In many states in the US, the total maximum daily load (TMDL) program has been widely developed and implemented to restore water quality in streams and reduce pollutant loads from both point and nonpoint sources (Mostaghimi et al., 2003). TMDL often represents an average daily pollutant load based on average long-term flow conditions, which limits its effectiveness in terms of describing the problems they are to address. Without an adequate characterization of the problems of a watershed, appropriate solutions cannot be identified and implemented. For this reason, water quality characterizations for various flow conditions, rather than a single flow such as average daily flow value of the stream/watershed, should be considered to restore water quality (Cleland, 2002). For successful development of TMDLs, both current and allowable pollutant loads for a waterbody must be estimated. Thus, many computer models have been developed and applied to

* Corresponding author. Tel.: +82 33 250 6468; fax: +82 33 251 1518.
E-mail address: kjlim@kangwon.ac.kr (K.J. Lim).

0301-4797/$ – see front matter
doi:10.1016/j.jenvman.2011.11.012

watersheds to estimate flow or water quality (e.g. QUAL2E (Enhanced Stream Water Quality Model; EPA, 1995), SWMM (Storm Water Management Model; Lewis, 2004), HSPF (Hydrological Simulation Program – FORTRAN; Bicknell et al., 1997), GWLF (Generalized Watershed Loading Function; Yagow et al., 2006), SWAT (Soil and Water Assessment Tool; Arnold et al., 1993), and ANSWERS (Areal Non point Source Watershed Environment Response Simulation; Aisha, 2007). These models have been successfully validated for a wide variety of spatial and temporal domains, and can be efficiently used to simulate the effects of various BMPs (Benham et al., 2005).

Computer models require sufficient expertise and demand significant time to prepare the model input data, run the model, and interpret the results. Thus, other methods utilizing statistical techniques are often used as alternatives to computer models to estimate current and allowable pollutant loads for TMDLs. One of the techniques frequently used in the development and application of practical TMDLs is the Load Duration Curve (LDC) technique, because of its ease of development and ability to be understood (Cleland, 2003). The LDC shows the percentage of time, or duration interval, for which a given value of a pollutant load is equaled or exceeded within a particular watershed. The LDC has been widely used for determination of appropriate TMDL targets (NDEP, 2003). When the measured load is plotted on the LDC, it can give information about patterns of loading under various flow conditions, impacts of point and nonpoint sources and flow conditions under which target water quality loads are exceeded (Cleland, 2002). The LDC is useful for identifying water quality improvement solutions depending on watershed processes and contributing areas (Cleland, 2006).

Conventional development of duration curves has been done by importing flow and water quality data into spreadsheets and manipulating the data to analyze cumulative frequencies and exceedance probabilities for flow and pollutant load, sort the resultant values, and plot flow and load values against their likelihood of exceedance. This process can, however, be complex and is prone to errors if the developer is not an expert in spreadsheet manipulation and formatting of flow and water quality data. Thus, Johnson et al. (2009) developed an automated LDC spreadsheet tool for Texas with a concept of automating the creation of the duration curves and computing the load reductions needed within each flow regime. Through the Johnson et al. (2009) LDC tool, a user can easily retrieve flow and water quality data provided from USGS gauge stations and get a feedback to meet water quality criteria. In our study, although we utilized the same concept to create load duration curve automatically, we developed a Web-based LDC system connecting with Google Map to visualize the USGS gauge stations. Moreover, the system was integrated with other modules to provide more information from a result.

The objectives of this study were to: 1) develop a Web-based LDC system using Perl/CGI, GNUPLOT, JavaScript, and the Google Maps API for the analysis of TMDL and water quality characteristics in a watershed; and 2) analyze pollutant concentration and load characteristics using the Web-based LDC system for a watershed to target appropriate watershed-specific BMPs.

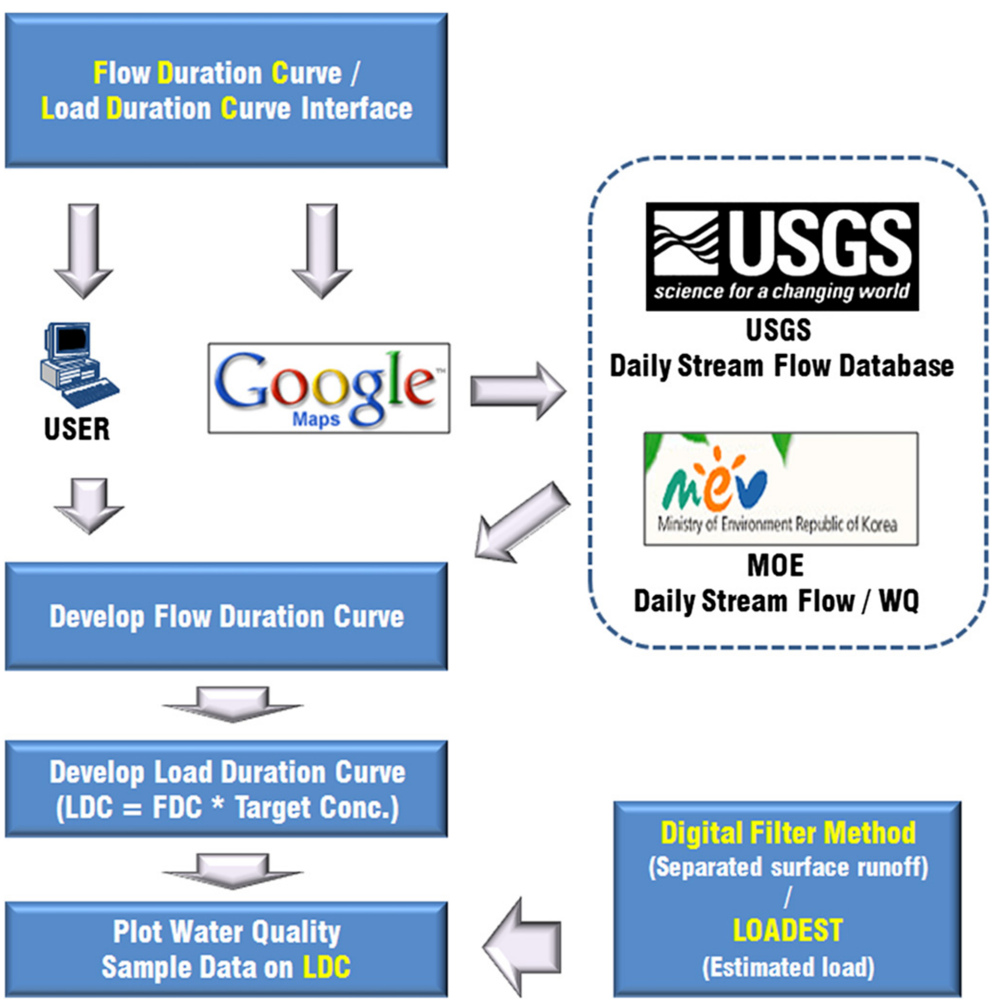

Fig. 1. Overview of the Web-based Load Duration Curve System.

2. Methodology

In this study, a Web-based LDC system was developed to automate the processes for efficiently generating the LDC of streams/rivers/watersheds of interest using a desktop-based spreadsheet computer program to analyze the TMDLs and water quality characteristics of the watershed. The Web-based LDC system first reads the date of measurement, stream flow, and water quality data prepared by users or retrieved from a remote server using Google Maps, then generates the FDC (Flow Duration Curve) and LDC automatically. In addition, the digital filter method and LOADEST (Load Estimator) model were added to the Web-based LDC system to separate surface runoff from streamflow and to calculate daily pollutant loads. Fig. 1 shows an overview of the Web-based LDC system developed in this study. All procedures described in Fig. 1 are automated using Perl/CGI, Javascript, GNUPLOT script, and the Google Maps API. A more detailed description is provided in the next section.

2.1. Development of FDC module

To generate the LDC, the FDC first needs to be generated using streamflow data. Thus, the FDC module of the Web-based LDC system was developed using Perl/CGI, GNUPLOT, and JavaScript programming. The FDC module reads the daily stream flow data, which is either provided by a user or retrieved from a remote server using the Google Maps interface. In this study, the Google Maps-based interface was developed and integrated with the Web-based LDC system for collecting stream flow from USGS gauging stations in the USA (Fig. 2(a)) and the Ministry of Environment (MOE)

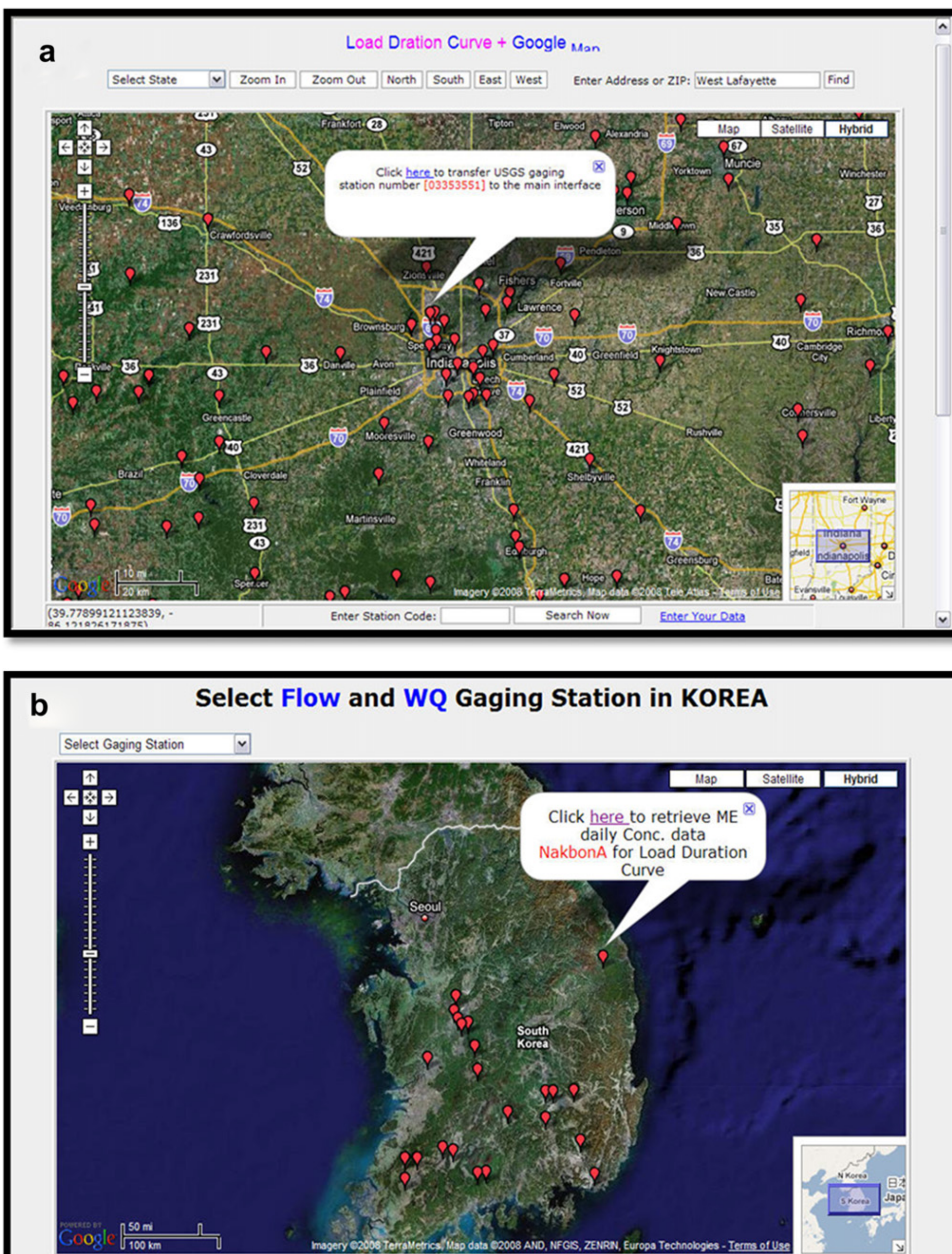

Fig. 2. Google Maps interface for collecting data from (a) USGS gauging stations in the USA and (b) MOE gauging stations in Korea.

gauging stations in Korea (Fig. 2(b)). The Google Maps interface of the Web-based LDC system links the USGS data server and the MOE data stored at remote servers for automatic retrieval of stream flow and water quality data to generate the FDC and the LDC. The USGS gauging stations provide daily stream flow data, and MOE gauging stations provide the 8-day stream flow and water quality data for the Web-based LDC system. The easy-to-use Google Maps interface is efficient for collecting the stream flow and water quality data for the Web-based LDC system. In addition, if there is no gauging station at the location of interest, and the water quality data for a nearby location is available, users can enter the drainage area ratio in the input interface to calculate flow data from a nearby gauging site by multiplying measured flow data by this drainage area ratio value to calculate flow data for the ungauged site. The daily flow data read from the remote server through the Google Maps interface are sorted from highest to lowest flow to calculate the percentage of days that flow is equaled or exceeded and generate the FDC data using Perl/CGI programming. Using this sorted flow data, the FDC module generates the FDC graph using GNUPLOT scripting and CGI programming, as shown in Fig. 3. In addition, the flow data is grouped into 5 zones, which are High Flows, Moist Conditions, Mid-range Flows, Dry Conditions, and Low Flows, reflecting flow duration intervals of 0–10%, 10–40%, 40–60%, 60–90%, and 90–100%, respectively. These 5 zones can be used to explain watershed characteristics and flow patterns according to hydrologic conditions. The FDC can represent the relationship between magnitude and frequency of daily stream flow for a particular watershed. It provides a simple, comprehensive, graphical view of the overall streamflow variability in a watershed (Vogel and Neil, 1994).

2.2. Development of LDC module

Generally, the allowable pollutant load data to generate the LDC are calculated by multiplying the daily stream flow by the water quality standard for a particular pollutant. Thus, the LDC module of the Web-based LDC system was developed to generate the LDC data by multiplying flow data in the FDC by the water quality standard data provided by users in the input interface. The observed pollutant load data were generated by multiplying flow data by concentration data provided by user on the same date. Then, the pollutant loads are plotted on the LDC graph in order to help users compare observed loads with the LDC. Fig. 4 shows a LDC graph generated with the LDC module of the Web-based LDC system. The plotted water quality data explain the exceedance of water quality standards and associated allowable loading. In addition, box–whisker plots were illustrated on the LDC to provide water quality distribution for each flow duration regime, as shown in Fig. 4. The section of box–whisker plots were placed at the center of each of the High-flow, Moist-condition, Mid-range flow, Dry-condition, and Low-flow zones. The box–whisker plot for each FDC zone (10th, 25th, 50th, 75th, and 90th) can be used to help interpret water quality conditions from the watershed.

2.3. Development of surface runoff separation and load estimation modules using the digital filtering technique and LOADEST model

The separation of the surface-runoff component from baseflow is important for interpreting hydrologic conditions and watershed characteristics. Thus, surface-runoff ratio can be utilized to interpret hydrologic conditions and watershed characteristics affecting

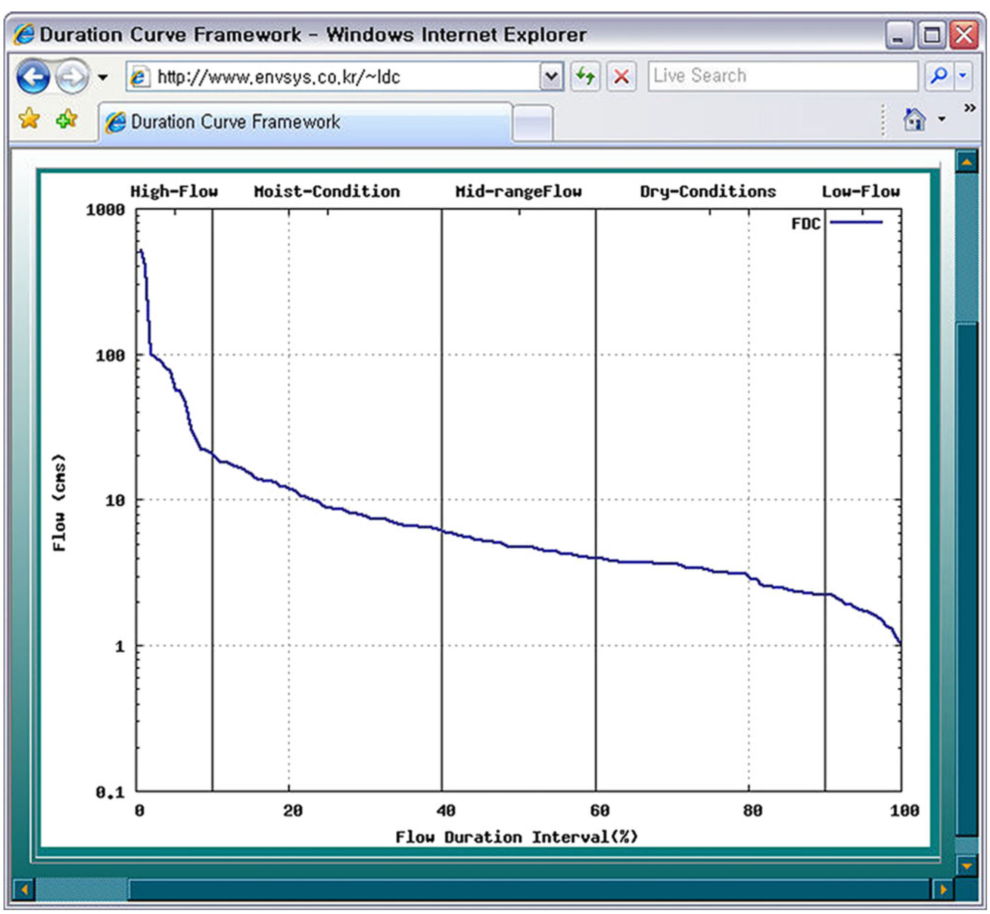

Fig. 3. Flow Duration Curve using the Web-based Load Duration Curve system.

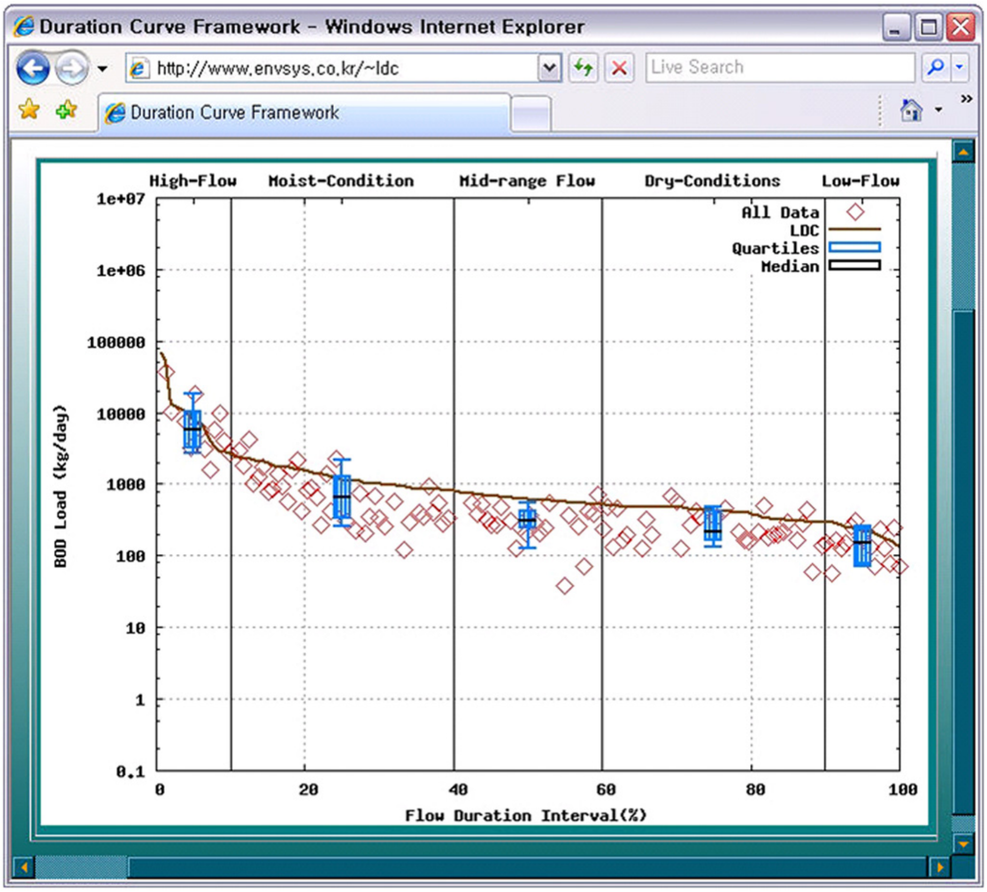

Fig. 4. Load Duration Curve using the Web-based Load Duration Curve system.

NPS pollutant loading during storm events. A module to perform surface-runoff separation, i.e., baseflow separation from stream flow, was developed in this study to provide more information on the FDC and LDC using the Perl/CGI programming and GNU scripting. A digital filter method, developed by Eckhardt (2005) for separating surface-runoff considering a digital filter parameter and BFI_{max} (maximum value of Base Flow Index), was used for the surface-runoff separation module of the Web-based LDC system. Eckhardt (2005) suggested use of BFI_{max} values of 0.80 for perennial streams with porous aquifers, 0.50 for ephemeral streams with porous aquifers, and 0.25 for perennial streams with hard rock aquifers. Thus, this surface runoff separation module also provides 3 BFI_{max} values according to aquifer type, which are 0.80, 0.50 and 0.25, respectively, and the user can select or enter a BFI_{max} value for separating surface-runoff from streamflow. This module uses Equation (1), developed by Eckhardt (2005).

$$b_t = \frac{(1 - BFI_{max}) \times \alpha \times b_{t-1} + (1 - \alpha) \times BFI_{max} \times Q_t}{1 - \alpha \times BFI_{max}} \quad (1)$$

where, b_t is the filtered base flow at the t time step; b_{t-1} is the filtered base flow at the t−1 time step; BFI_{max} is the maximum value of the long-term ratio of base flow to total streamflow; α is the filter parameter; and Q_t is the total stream flow at time step t.

$$S_t = Q_t - b_t \quad (2)$$

where, S_t is surface-runoff at time step t.

The surface-runoff separation module separates the surface runoff component from stream flow using Equations (1) and (2), and determines the surface runoff ratio by dividing the surface runoff by the stream flow data. When the surface runoff exceeds 50% of the total stream flow, the surface runoff separation module plots the load data with a different symbol to provide pollutant load characteristics under various flow conditions. It means that water quality problems could be caused by surface runoff so that management of surface runoff is needed in the given watershed.

In general, obtaining adequate water quality data to match flow data is difficult and costly. The estimated daily pollutant load using the LOADEST model, which has been developed to estimate constituent loads in streams and rivers, can be used as auxiliary data to interpret water quality characteristics (Runkel et al., 2004). Thus, the pollutant load estimation module, using the LOADEST model as a core engine, was also developed and integrated with the Web-based LDC system using Perl/CGI programming and GNUPLOT scripts to provide daily pollutant load for comparison of estimated loads with the observed load. The Daily pollutant load data are plotted over the LDC to provide general pollutant load characteristics over the various flow regimes. In this study, stream flow and water quality data collected to generate the FDC and LDC were utilized for estimating daily load using the LOADEST-based pollutant load estimation module. Then, daily load estimation is plotted on the LDC for comparison with measured pollutant load data plotted on the LDC. Daily load estimation values from LOADEST can be used to evaluate the general water quality status of watersheds compared with water quality standards for pollutants of interest. Also, observed load data collected from April to October are plotted with different symbols to facilitate analysis of seasonal water quality effects, as shown in Fig. 5.

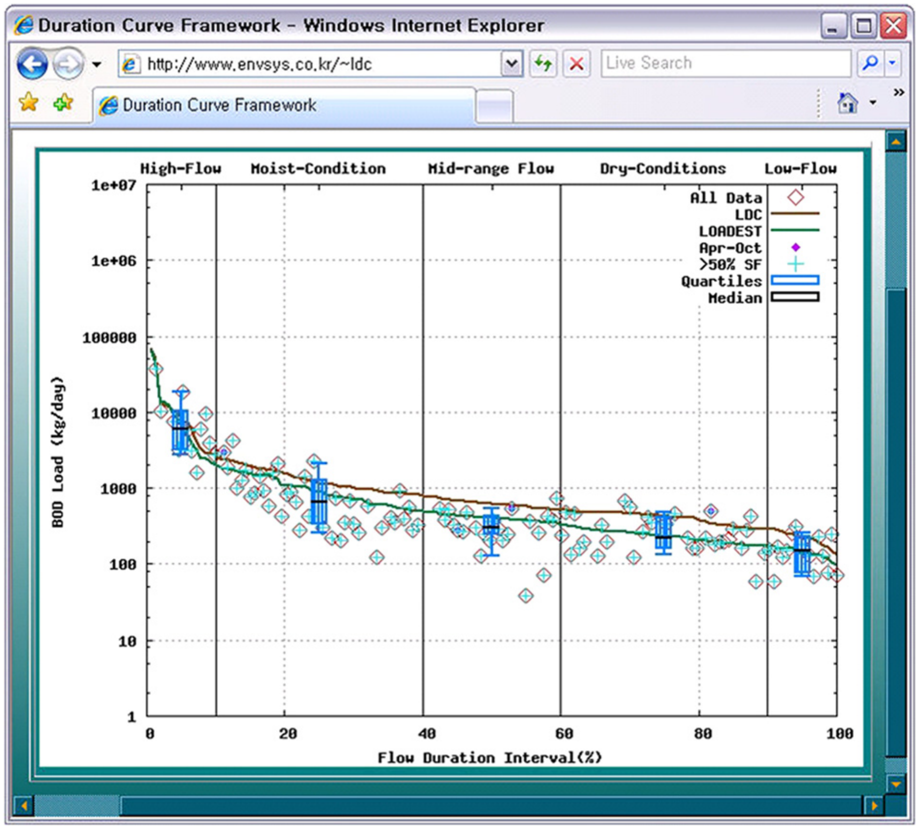

Fig. 5. Load Duration Curve with surface flow, LOADEST estimated daily loads.

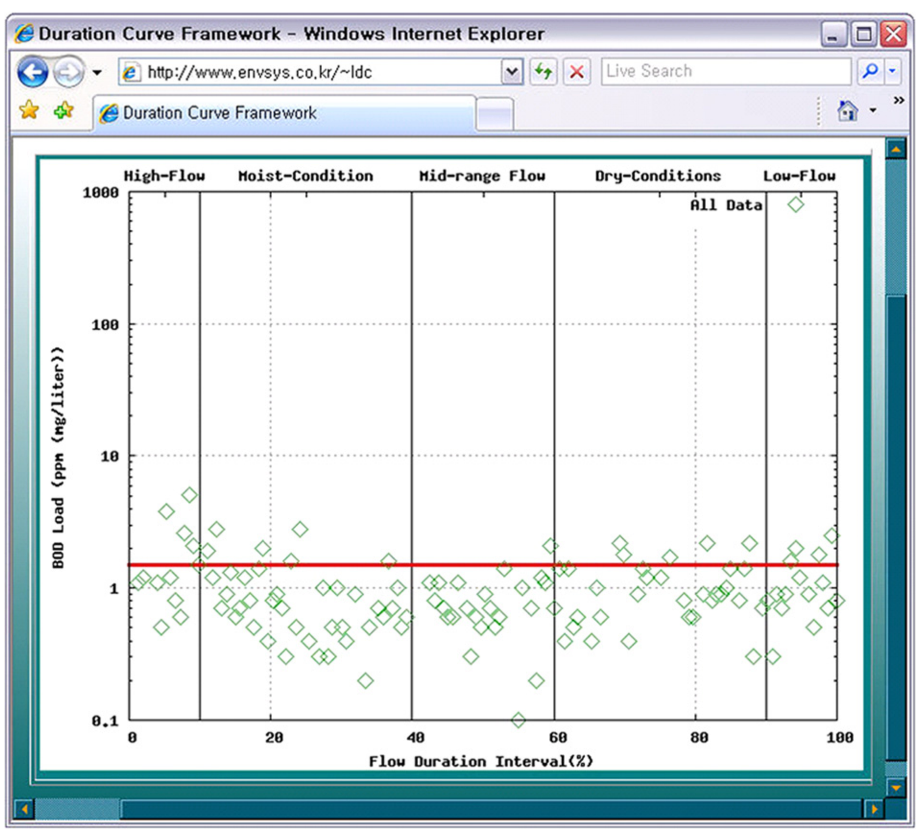

Fig. 6. Comparison of target water quality with all observed concentration data.

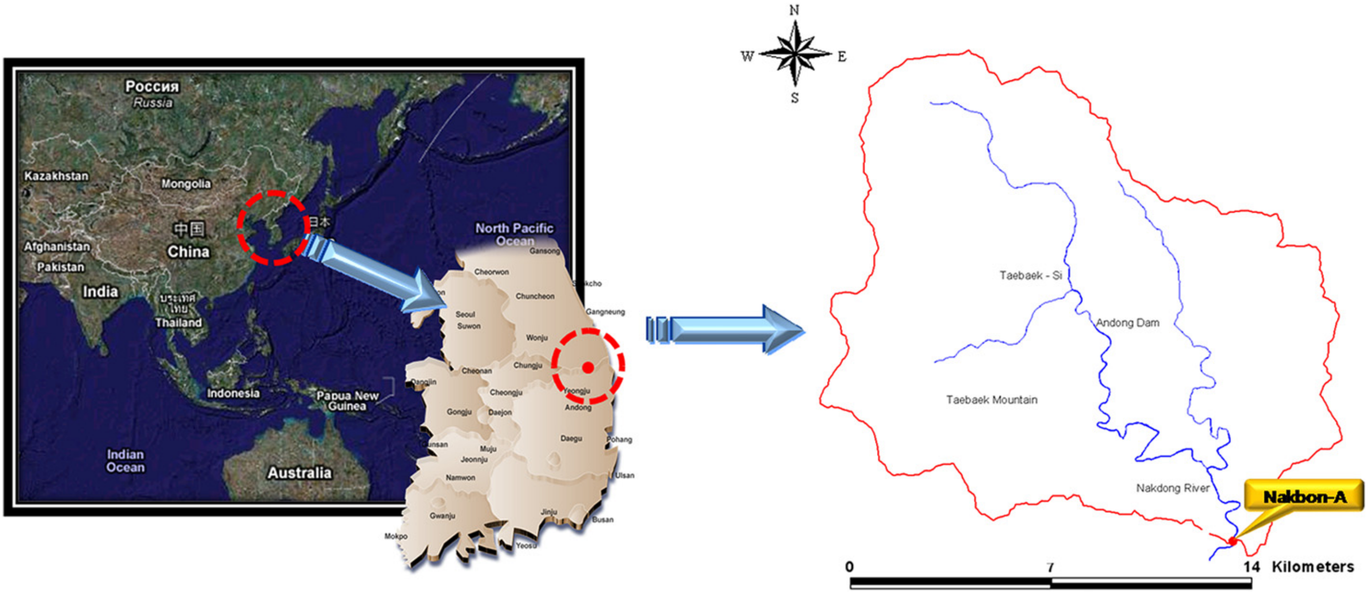

Fig. 7. Location of Nakbon-A watershed.

To provide information regarding water quality violations of observed data under various flow regimes compared with water quality standard concentration values, a straight line graph of the quality of the target water was plotted with the observed water quality data (Fig. 6). The straight line represents the water quality standard concentration value which was used to calculate the allowable pollutant load by multiplying with daily stream flow data. All data points above this line represent exceedance of a water quality standard and need to be reduced to bring water quality concentrations below acceptable limits. A user can download the data generated for the FDC, the LDC, and the Box–Whisker plot for further analysis.

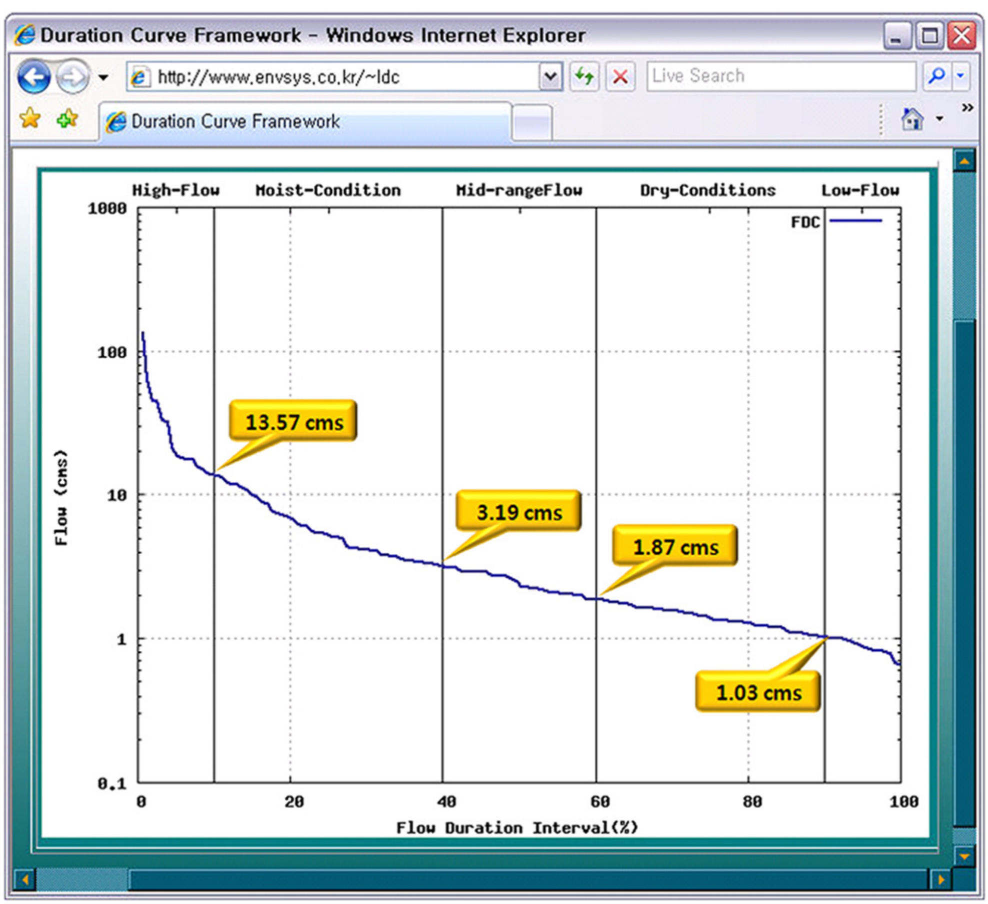

Fig. 8. Flow Duration Curve for Nakbon-A watershed.

3. Application of Web-based LDC system

In this study, the Web-based LDC system was applied to the Nakbon-A watershed in South Korea (Fig. 7) because many efforts have been undertaken by the Korean government to improve water quality for this watershed. Many flow and water quality data were available for this site. The watershed is 20,127 ha in size, and is located at the border between the two contiguous local governments, Gangwon-do and Gyeongsangbuk-do in South Korea (Choi et al., 2008). Primary land use in this watershed is forest (87.62% of the entire watershed) in the upper portion of the watershed, and agriculture, pasture, bare ground, urban land and water each occupy 6.85%, 1.78%, 1.11%, 2.61% and 0.03% of the watershed area, respectively. In addition to nonpoint sources, there are several point sources of pollution including reclaimed land, urban areas and waste disposal in the watershed.

The Web-based LDC system was applied to the Nakbon-A gauging station data. The 8-day stream flow and water quality data from the MOE were retrieved by the automated module of the Web-based LDC system. The FDC module reads the data for the Nakbon-A watershed, sorts the data from the highest to the lowest, and calculates the percentage of days to generate the FDC data. The FDC of the studied watershed shows observed flow values of 10%, 40%, 60%, and 90%, for which the flow duration intervals are 13.57, 3.19, 1.87, and 1.03 cubic meters per second (cms), respectively (Fig. 8).

A LDC was then created for the Nakbon-A watershed with the LDC module of the Web-based LDC system. The LDC for Nakbon-A watershed with a BOD target value of 1.5 mg/L is shown in Fig. 9. Fig. 9 indicates that most observed loads in the Nakbon-A watershed are below the allowable limit, while several observed loads during the flow duration interval of 90–100 (low flow conditions) are above the allowable limit. This implies there may be constant pollutant discharge sources, such as wastewater treatment plants, irrigation return flows, or dry weather flows in the Nakbon-A watershed resulting in violation of water quality standard during low flow conditions.

The Web-based LDC system plots observed BOD load data when the surface runoff exceeds half of the total stream flow collected from April to October for an analysis of seasonal water quality effects. As shown in Fig. 10, pollutant load data above the allowable limit data on the low flow conditions occurred in the winter season (January to April or October to December). In addition, estimated daily load data using LOADEST are also plotted on the LDC. The estimated loads are lower than the observed loads, which were calculated by multiplying the FDC by the BOD water quality standard for the entire period (Fig. 10).

Fig. 11 shows observed water quality concentration data compared with target water quality concentration for the TMDL. Although most observed concentration data were lower than the target concentration value, the water quality standard was violated on several days with dry and low flow conditions. Based on the LDC and water quality concentration graph generated by this Web-based LDC system, water quality criteria are not met during low flow conditions which may be influenced by direct or indirect illicit discharges in this watershed. Actually, industrial and livestock wastewater are discharged into the river and may be a source of water quality impairment during low flow conditions. Thus,

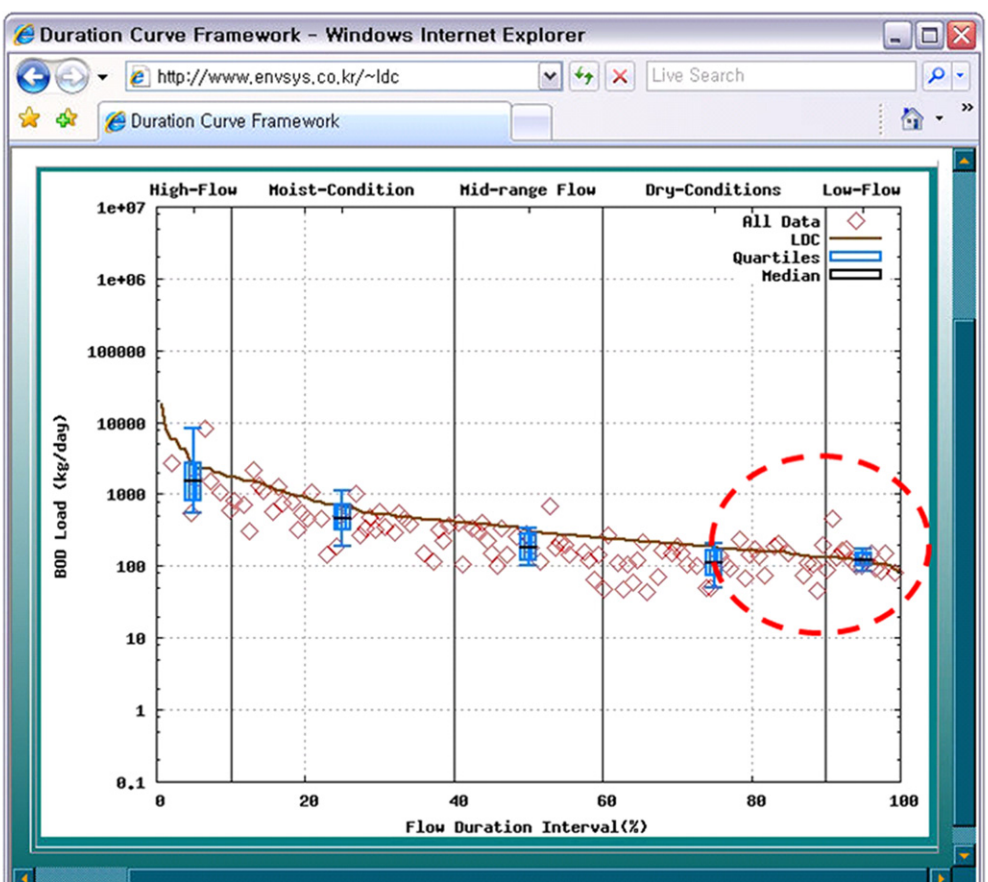

Fig. 9. BOD Load Duration Curve for Nakbon-A watershed.

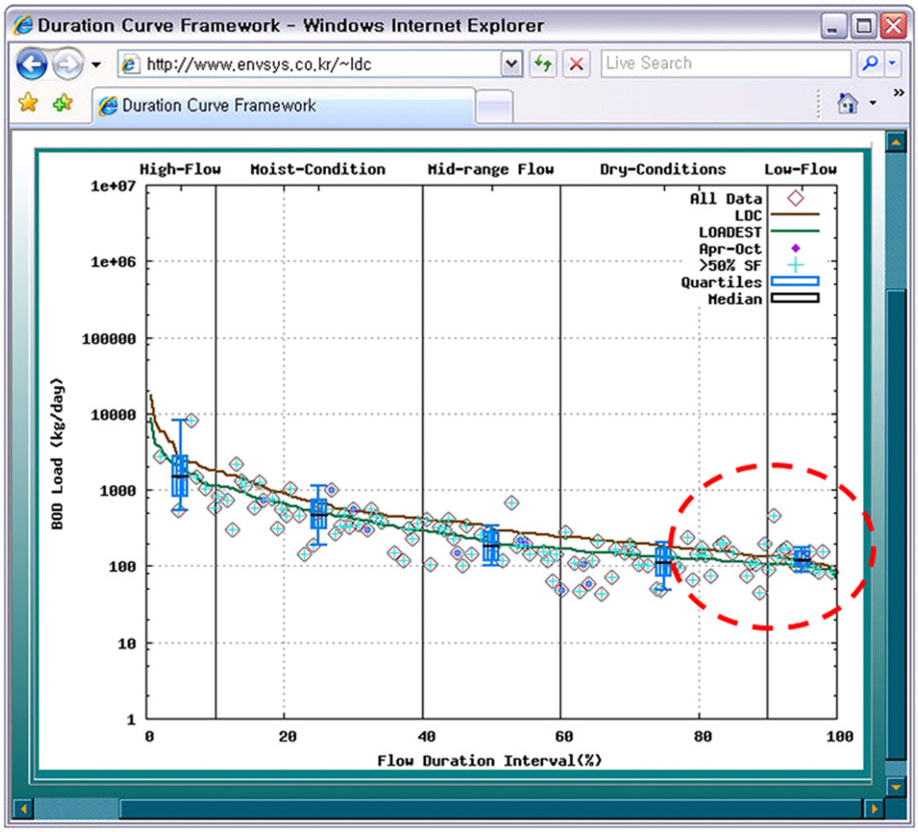

Fig. 10. The Load Duration Curve using separating surface-flow and daily load of LOADEST model for Nakbon-A watershed.

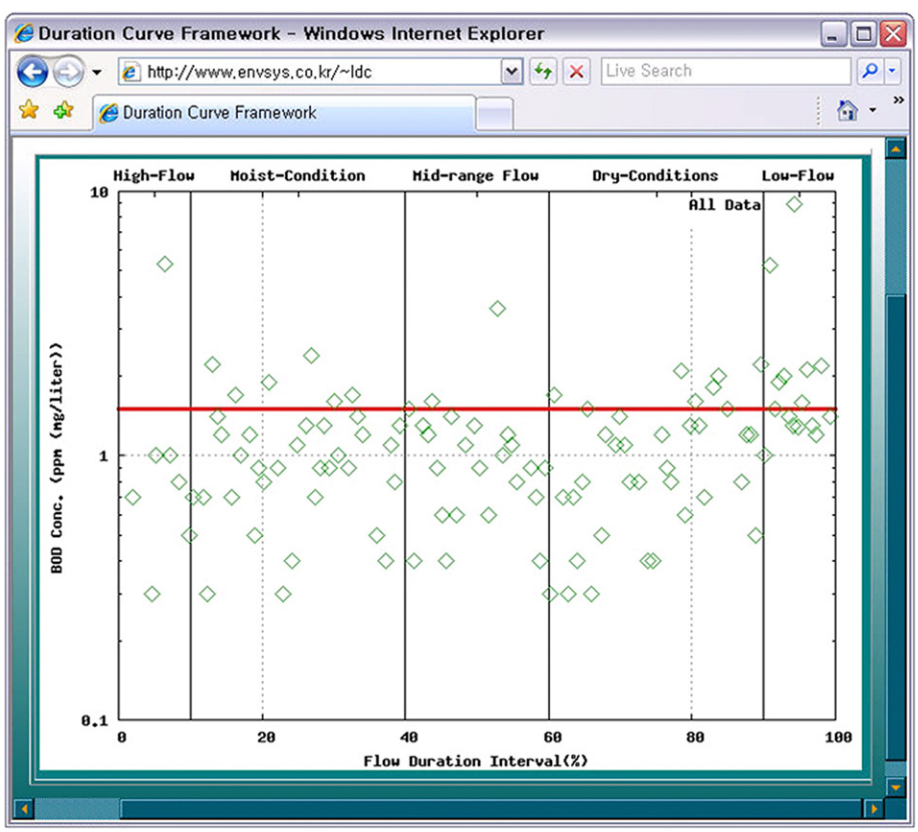

Fig. 11. Analysis of all observed concentration data compared with target water quality for Nakbon-A watershed.

appropriate BMPs (e.g., sewage disposal system, septic system maintenance, educational programs) need to be implemented to restore water quality in this watershed (Cleland, 2006).

4. Conclusions

Thousands of streams around the world are impaired by point and nonpoint source pollutant loads. The TMDL program has been established for water quality restoration and management of point and nonpoint sources of pollution in watersheds. Computer modeling is often applied to simulate the flow and water quality conditions in a watershed using available water quality and flow data. However, the ability of watershed models to accurately predict pollutant loads can be limited by complexities and uncertainties associated with computer modeling in watersheds. On the other hand, LDC analysis is an effective tool for estimating the TMDLs, because it can estimate many TMDLs quickly with limited resources, compared with complex simulation models.

However, TMDL developers generate LDCs simply by using spreadsheet software after downloading flow and/or water quality data from individual projects or publically available data sources. This is greatly time-consuming, and opens the possibility of human error influencing the LDC. Thus, in this study, the Web-based LDC system was developed using Perl/CGI, GNUPLOT, JavaScript, and Google Maps script for the analysis of TMDL and water quality characteristics in watersheds.

The Web-based LDC system developed in this study has a number of benefits, which are described below.

- The Web-based LDC system is easy to use, and as it operates through a web browser and can be used anywhere, without any specific software requirements.
- There are various interfaces provided in the Web-based LDC system to compile stream flow and water quality data. Users can easily collect data with capabilities such as “Enter/Upload flow data for FDC,” “Enter/Upload flow and WQ data for LDC,” “Enter/Upload WQ Data for LDC using USGS Flow Data,” “Enter/Upload WQ Data for LDC using (USGS Flow Data*-Drainage Area Ratio),” and “Enter/Upload Flow and WQ data from Korean gauging Station” in the input interface of the Web-based LDC system.
- The Web-based LDC system provides the Google Maps interface, which can be efficiently used for collecting stream flow and water quality data in the USA and Korea.
- The results are provided in a graphical format to enable an easy understanding of water quality problems and TMDL targets, and output results can be downloaded by users to a spreadsheet program for further analysis.
- This system integrates the LOADEST model to provide estimated daily load on the LDC for comparison of the estimated load data with observed load data. Thus, missing observed data can be predicted with estimated daily load data.
- The Wed-based LDC system can be used by local watershed groups to document water quality concerns and document progress in addressing these concerns.
- The Web-based LDC system can be used to identify BMPs based on generated results for hydrologic conditions in the watershed.

As shown in this study, the Web-based LDC system (https://engineering.purdue.edu/~ldc/) is a useful tool for characterizing water quality problems according to flow conditions, and provides a visual display of results to enable an easy understanding of the problem and TMDL targets. In addition, this system will help decision-makers select appropriate BMPs based on the generated results for watersheds.

References

Aisha, M. S., 2007. Evaluation of SWAT model Applicability for waterbody impairment Identification and TMDL analysis. The degree of Doctor of Philosophy, University of Maryland.

Arnold, J.G., Allen, P.M., Bernhardt, G., 1993. A comprehensive surface-groundwater flow model. Journal of Hydrology 142 (1), 47–69.

Benham, B.L., Kevin, M.B., Gene, Y., Rebecca, W.Z., Theo, A.D., Saied, M., Jeff, W.W., 2005. Development of bacteria and benthic total maximum daily loads: a case study, Linville Creek, Virginia. Journal of Environmental Quality 34, 1860–1872.

Bicknell, B.R., Imhoff, J.C., Kittle Jr., J.L., Donigian Jr., A.S., Johanson, R.C., 1997. Hydrological Simulation Program—Fortran, User's Manual for Version 11. U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga., EPA/600/R-97/080, 755 pp.

Choi, J., Lim, K.J., Won, C.H., Jung, M.S., Shin, M.H., Choi, Y.H., Kim, K.C., Seo, J.Y., 2008. Quantification of NPS Pollution to Meet the TMDL in Korea. ASABE Annual international Meeting.

Cleland, B., 2002. TMDL Development From the “Bottom Up” – Part II: Using Duration Curves to connect the pieces. America's Clean Water Foundation. August 15, 2002 National TMDL Science and Policy 2002 – WEF Specialty Conference, Phoenix, AZ.

Cleland, B., 2003. TMDL Development From the “Bottom Up” – Part III: Duration Curves and Wet-Weather Assessments. National TMDL Science and Policy 2003 – WEF Specialty Conference. Chicago, IL.

Cleland, B., 2006. TMDL Development From the “Bottom Up” – Part IV: Connecting to Storm Water Management Programs. U.S. National TMDL Science and Policy 2007, Seattle, WA.

Eckhardt, K., 2005. How to construct recursive digital filters for baseflow separation. Hydrological Processes 19 (2), 507–515.

Elshorbagy, A., Ramesh, S.V., Lindell, O., 2005. Total maximum daily load (TMDL) approach to surface water quality management: concepts, issues, and applications. Canadian Journal of Civil Engineering 32, 442–448.

EPA (Environmental Protection Agency), 1995. QUAL2E Windows Interface User's Guide. http://coe.uncc.edu/~jdbowen/6141/qual2e_info/manual.pdf.

Johnson, S., Whiteaker, T., Maidment, D., 2009. Automated load duration curve creation for the State of Texas. Journal of the American Water Resources Association 45 (3), 654–663.

Lewis, A.R., 2004. Storm Water Management Model User's Manual, Version 5.0. http://eng.odu.edu/cee/resources/model/mbin/swmm/win/epaswmm5_manual.pdf.

Mostaghimi, S., Benham, B., Brannan, K., Dillaha, T., Wynn, J., Yagow, G., Zeckoski, R., 2003. Total Maximum Daily Load Development for Lincille Creek: Bacteria and General Standard (Benthic) Impairments. Biological Systems Engineering Department, Virginia Tech, Blacksburg, Virginia. www.deq.state.va.us/tmdl/tmdlrpts.html.

NDEP (Nevada Division of Environmental Protection), April 2003. Load Duration Curve Methodology for Assessment and TMDL Development.

Runkel, R.L., Charles, G.C., Timothy, A.C., 2004. Load Estimator (LOADEST): A Fortran Program for Estimating Constituent Loads in Streams and Rivers Techniques and Methods Book 4, (Chapter A5).

Vogel, R.M., Neil, M.F., 1994. Flow-duration curve. I: new interpretation and confidence intervals. Journal of Water Resources Planning and Management 120 (4), 485–504.

Yagow, G., Wilson, B., Srivastava, P., Obropta, C.C., 2006. Use of biological indicators in TMDL assessment and implementation. American Society of Agricultural and Biological Engineers(ASABE) 49 (4), 1023–1032.