Chapter 21

Modified Low Flow Frequency Analysis Applied to a Wastewater Allocation Study

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The South Nation River was studied for its ability to assimilate wastewater effluents from municipal and industrial point sources for both existing and anticipated future conditions. The watershed, located in Eastern Ontario, is rural with community populations ranging up to 3500 residents. Currently there are ten communities, all with lagoon wastewater treatment, and two industries with custom designed wastewater treatment processes that discharge into streams within the watershed. In the future, an additional five communities and one industry are expected to install sewerage and wastewater treatment facilities.

Streamflows drop to very low values during the late summer and early fall, and as a result all facilities are restricted to spring and/or late fall discharges. Provincial Water Quality Objectives (PWQOs) are often exceeded for phosphorus and ammonia. In this case, Ontario Ministry of Environment (MOE) policy stipulates that the receiver cannot be further degraded (MOE, 1984). In assessing assimilative capacity of the watershed, the traditional approach is to compute n-day low flows with a 20-year return period (usually 7 or 30 days) over the entire discharge season. This computation, in the case of the South Nation River, yielded predictions of 0.0 m³/s for 7Q20s and 30Q20s at several locations in the watershed, particularly during the fall period. This would have resulted in severe restrictions in municipal growth. A wasteload allocation scheme which allowed

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greater utilization of the available assimilative capacity was therefore required. An alternative approach was developed for the low flow frequency analysis component of the study. Complete study details are presented by Gore & Storrie (1992).

21.1 Hydrology

The hydrology component of the study was designed to provide reasonable estimates of low flow conditions and associated travel times in support of the wasteload allocation analysis. A unique low flow frequency analysis approach, addressing temporal variability, was designed and applied. The following discussion outlines the development of this approach in the context of the South Nation River investigation.

Of particular interest was the estimation of receiving stream flows during the spring and fall lagoon discharge periods. Available flow generally governs assimilative capacity and therefore the low flow condition is critical in terms of water quality. The '7Q20' and '30Q20' spring and fall flows are typically estimated using frequency analysis techniques. For a 20-year return period, there is a 95% probability that flows will be at least as high as the 7- or 30Q20. The 7-day and 30-day low flows, with corresponding return periods of 20 years, are commonly used in Ontario for design and analysis purposes (Logan, 1977).

Due to the lack of flow data at several of the discharge locations, a prororation of flow as a linear function of drainage area was required. The assumption is that the flow produced per unit area from a particular watershed is equivalent to that produced from another with similar geophysical characteristics (Logan, 1977). The low flows estimated in the analysis were used as a basis for modelling the river and tributaries.

Daily flow records for all the gauged stations within the South Nation River watershed were obtained from the Water Survey of Canada (WSC). Drainage areas for each location were confirmed with topographic maps. To estimate 20-year low flows, at least 20 years of record is recommended, although smaller sample sizes (8-10 years) may be used if the record of low flows is a well defined frequency distribution (Logan, 1977). A total of eight gauging stations within the watershed were found to have adequate periods of record for analysis.

21.1.1 Traditional Approach

The traditional frequency analysis approach was utilized in the first attempt to estimate low flows.

Methodology

A FORTRAN program was written to scan the WSC data files and

compute 7- and 30-day minimum flows for the spring and fall of each year. For example, for the spring period, the program extracted all daily flow data between March and April of each year and computed the average flow over all the 7-day and 30-day spans in the two month period. The minimum of these averages was then extracted. For each year, minimum spring and fall 7- and 30-day flows were thus obtained.

Each data series was screened for suitability for frequency analysis. Since frequency analysis is probabilistic, the data series must be random, homogeneous, stationary, and serially independent. A few of the data sets were rejected for use in the frequency analysis on the basis of lack of independence between data values.

A frequency analysis was conducted on the remaining data sets using an in-house program for the estimation of quantiles of low flow corresponding to a return period of 20 years. Alternatively, a low flow frequency analysis (LFA) package is available from Environment Canada (Pilon and Jackson, 1988) which would have provided similar results.

Linear regression analysis was performed between the low flow quantile estimates and drainage areas for the spring and fall 7- and 30Q20s. Low flow estimates for the ungauged discharge locations in the watershed were computed from the resultant regression equations.

Results

Results of this analysis are not presented in detail herein. The major problem that resulted from the traditional analysis was that for some stations with small contributing areas, the predicted 7Q20s and 30Q20s were found to be 0.0 m³/s, particularly during the fall period. This occurred when there were 7 or 30 day spans when flows dropped to negligible levels (i.e. streams became intermittent). If these results had been utilized in wastewater allocation, there would have been no assimilative capacity at these locations for any discharge quantity, even at present levels. These results are overly conservative, however, since treatment plant operators do not discharge lagoons when the receiving stream is dry. They generally wait until they believe that sufficient flow exists in the stream for assimilation. In order not to severely restrict future growth in some of the municipalities within the study area, an alternative approach to the low flow analysis was developed.

An additional limitation of the conventional approach is that no information is provided regarding the time variability of the river flow, and thus no information on the optimum discharge periods. The modified approach developed accounts for time variability of flows and provides a method for determining optimum discharge periods.

21.1.2 Alternative Approach

Introduction

An important factor in the determination of low flows is the time period or window used in the computation. The window can have a significant impact on the receiving stream assimilative capacity, or volume available for dilution of a discharge. For example, low flows computed between March and April are likely to be orders of magnitude greater than those computed during May and June. Flows in November and December are likely to be significantly greater than flows in September and October. If a period of time during the discharge season can be found during which river volume is at a maximum, based on a statistical analysis of historical flows, then the optimum window for discharge can be determined. If discharges are controlled to take place during the optimum window, the effective river volume available for wastewater dilution will be significantly increased.

Methodology

A modified approach to conventional 7Q20 and 30Q20 determinations was required to gauge low flows over the spring and fall periods and to allow extended and staggered discharge periods which more fully utilize the assimilative capacity of the streams. Specifically, an analysis was required to assess the minimum streamflows existing at all times in discharge periods of varying length, centred about the peak flood flows in the spring and fall. This allows determination of the maximum dilution based on streamflow and discharge rate.

The methodology encompassed four phases:

- 1) Generate a historical time series using a 7 and 30 day moving window.
- 2) Describe the temporal variability of the 7 and 30 day flows with a return period of 20 years.
- 3) Define the available dilution volume as a function of discharge period.
- 4) Complete a regional frequency analysis enabling watershed-wide application of approach.

An outline of each phase of analysis is provided below.

Phase 1: Historical Time Series

Rather than computing the minimum 7- and 30-day low flows for the spring period of each year, the analysis was conducted on a daily basis.

Beginning on March 1 of each year, and extending to the end of June (to cover the entire spring period), the 7- and 30-day average flows were computed. This exercise may be described as a moving window approach, in which the average flow value is assigned to the date corresponding to the mid-point of the window.

The computations included the average flows from March 1-7, March 2-8, and so on up to June 24-30 (a total of 116 7-day average flows); and from March 1-30, March 2-31, and so on up to June 1-30 (a total of 93 30-day average flows). A similar set of computations was completed for the fall period, from September 1 to December 31 of each year. A total of 418 average flows were obtained for each year resulting in 418 historical flow series. For each historical series a frequency analysis was performed over the years of record to obtain 7Q20s and 30Q20s for each time span.

Generation of the historical series was automated by application of a FORTRAN program which was designed to scan the existing WSC data files and compute 7- and 30-day average flows on a daily basis between March 1 and June 30, and September 1 and December 31, for each year.

Phase 2: Temporal Variability

Due to the large numbers of flow series, a FORTRAN program was developed to automate the frequency analysis computations. The low flow series were assumed to be adequately described by a Gumbel Extreme Value (EV) III frequency distribution. The three parameters (lower boundary, characteristic drought, and shape parameter) were estimated by the method of smallest observed drought. The Gumbel EV III distribution was found by Condie and Cheng (1983) to be the most suitable distribution for low flows, and the method of smallest observed drought was found to provide acceptable fits on low flow data most of the Canadian rivers tested. Computations were based on the methods used in the low flow program, LFA (Pilon and Jackson, 1988). The 20-year quantile estimates were obtained for 7- and 30-day average flows for each time span.

For each station the resultant daily 7Q20s and 30Q20s were plotted as a function of date. The plots provided information on time variability of river flows through the spring and fall seasons. For illustrative purposes daily 30Q20s as a function of time for the spring period are shown in Figure 21.1 for a station on the South Nation River near Plantagenet. The figure shows a typical shape for the spring 30Q20s, with a dramatic increase in late March, and a decrease through the month of April.

Phase 3: Available Dilution Volume

Using the flow versus time plots generated in Phase 2, available dilution volumes corresponding to an arbitrary duration could be determined. The methodology was as follows:

Figure 21.1
Spring 30Q20 flows at Plantagenet

- 1) For a range of flow values, defined by the temporal variability of flow, the corresponding duration over which each flow value is equalled or exceeded was graphically determined. In Figure 21.1, for example, a 30Q20 of at least 20 m³/s is maintained between March 18 and April 27, for a total duration of 40 days. A higher 30Q20 of 60 m³/s is maintained for a shorter duration, between March 27 and April 15 (19 days). For several other 30Q20 values durations may be similarly obtained.
- 2) These flow values and durations were then used to compute a minimum implied dilution volume which is defined as the product of the minimum flow equalled or exceeded and the corresponding duration. This provides a conservative estimate of the total river capacity available for waste assimilation. Both volume and flow were then plotted versus duration. For the example time series plot illustrated as Figure 21.1, a flow and volume versus duration plot is provided as shown in Figure 21.2.
- 3) The maximum implied dilution volume and corresponding flow and

duration were obtained from Figure 21.2. For the example flow station described by Figure 21.2, the maximum volume occurs at a duration of 19 days, corresponding to a 30Q20 of 60 m³/s. Referring to Figure 21.1, the window during which a flow of 60 m³/s is equalled or exceeded is from March 27 to April 15. This represents the optimum window for discharge, based on the 30Q20, during the spring period at this station.

- 4) This procedure was repeated for each station, for each 7Q20 and 30Q20 spring and fall flow. Plots of quantile estimates of flow versus time, similar to Figure 21.1, and flow and volume versus duration, similar to Figure 21.2, were produced for each flow station.

Results of the determination of optimum discharge windows are presented in Table 21.1 for spring 30Q20 flows as an example. Table 21.1 includes the optimum window, duration and optimum 30Q20 for the spring (March 1 to June 30) for each of the eight gauged stations. In this context, the *optimum window* is defined as the duration corresponding to the maximum available dilution volume. As expected, optimum discharge windows were similar from station to station.

Figure 21.2
Dilution volume and duration of flow

Table 21.1
Results of Optimization of Discharge Window for 30Q20 - Spring.

Station	Discharge Window Dates	Duration (days)	30Q20 (m ³ /s)
S. Nation R. at Plantagenet 02LB005	Mar 27 - Apr 15	19	60
Castor R. at Russell 02LB006	Mar 28 - Apr 16	19	6
S. Nation R. at Spencerville 02LB007	Mar 21 - Apr 21	31	3
Bear Brook at Bourget 02LB008	Mar 19 - Apr 17	29	6
S. Nation R. at Casselman 02LB013	Mar 16 - Apr 21	35	20
N. Branch S. Nation R. at Heckston 02LB017	Mar 16 - Apr 24	39	0.6
S. Castor R. at Kenmore 02LB020	Mar 16 - Apr 22	37	1.5
Payne R. at Berwick 02LB022	Mar 20 - Apr 21	33	1

Minimum Window: Mar 28 - Apr 15

Average Window: Mar 20 - Apr 20

Maximum Window: Mar 16 - Apr 24

Phase 4: Regional Frequency Analysis

A regional frequency analysis was necessary in order to extend the site specific flow frequency results generated in Phase 3 to other locations within the South Nation watershed. The approach adopted was a linear proration as a function of contributing area. However, prior to the regional analysis, consistent discharge windows were selected. For the present study, minimum, average and maximum discharge windows were defined. As an example, the minimum 30Q20 spring window was obtained from the results shown in Table 21.1 by taking the latest start date (March 28) and the earliest end date (April 15) of the optimum windows for each of the eight stations. The average window was found from the average start date (March 20) and average end date (April 20). The

maximum window was obtained from the earliest start date (March 16) and latest end date (April 24).

The minimum window provided the largest flow quantile value, while the maximum window provided the lowest (or worst case, and most conservative) flow quantile value. To illustrate, refer to Figure 21.3 which again uses the example of the spring 30Q20 flows at Plantagenet. During the average window (March 20 to April 20), the 30Q20 is always greater than or equal to 26 m³/s. This represents the 'minimum daily 30Q20' for the average spring discharge window. Flow estimates of 57 and 12 m³/s corresponding to the minimum and maximum spring discharge windows respectively, were obtained for this station in the same manner. These represent values that were subsequently used in the regional frequency analysis.

The procedure outlined above was repeated for each gauging station, for the determination of the 7Q20 and 30Q20 average, minimum and maximum discharge windows for the spring and fall periods. Results similar to those in Table 21.1 were obtained. For each of the minimum, average and maximum windows, minimum daily spring and fall 7Q20s and 30Q20s were determined for each gauged station from examination of the flow versus time plots. As an example, the results for the spring 30Q20 flows are given in Table 21.2. The drainage areas at each station (shown on Figure 21.1) are included in Table 21.2.

The 30Q20 flows for gauged stations that were common between this

Figure 21.3
Average spring 30Q20 window at Plantagenet

Table 21.2
Spring 30Q20 Minimum Flows at Gauged Stations.

Station	Drainage Area (km ²)	Minimum Daily 30Q20 (m ³ /s)		
		Min. Window	Ave. Window	Max. Window
02LB005	3820	57	26	12
02LB006	459	6.2	1.6	1.2
02LB007	243	3.7	2.3	1.5
02LB008	436	7	5	3
02LB013	2400	24	20	19
02LB017	106	0.68	0.67	0.6
02LB020	201	2	1.65	1.4
02LB022	150	1.09	1.0	0.86

study and the study of Cumming Cockburn Ltd. (1989) showed reasonable agreement considering differences in the approaches. The latter study examined 30Q20 flows for each month. In the current study no window corresponds to a given month, however some windows do approximately span a month and it is possible to make a comparison.

Linear regression analyses were performed between low flow quantile estimates and drainage areas to obtain a series of regional low flow equations for the spring and fall minimum, average and maximum windows. The data correlated very well, with correlation coefficients ranging from 0.839 to 0.996. A typical plot of the data is given in Figure 21.4 including the resulting regression equation and correlation coefficient.

The regression equations thus obtained were used to calculate flows at all wastewater discharge locations except for fall 7Q20 flows. Fall 7Q20 flows were based on the fall 7Q20 flow for Plantagenet. Flows at Plantagenet are highest since it is the most downstream point in the watershed and the fall 7Q20 could be reliably gauged for this location. The fall 7Q20 flow at each of the other locations was estimated by taking the ratio of drainage area for a location to the drainage area at Plantagenet and multiplying the fall 7Q20 flow at Plantagenet by this ratio.

Figure 21.4
Spring 30Q20 minimum window flow - drainage area correlation.

21.2 Application of Flow Estimates to Wastewater Allocation

The low flow estimates determined as described herein were subsequently used as the basis for river modelling. In addition, optimum discharge windows determined in the analysis could be used to develop specific recommendations regarding discharge times at each point source. As shown from the analysis above, the discharge time has a significant impact on the river volume available for dilution, and thus the quantity of effluent that can be discharged without violating PWQOs.

A wasteload allocation optimization-modelling exercise was conducted for the watershed under projected future development conditions. Details of the optimization exercise are provided by Gore & Storrie (1992). The utilization of the optimized windows for future discharges resulted in a significant increase in implied dilution volume for wastewater assimilation. A wasteload allocation scheme was therefore achievable, which was conservative (based on 20-year return period flow volumes and constant rate discharges) yet still accommodated all future discharges while complying with PWQOs. Using the traditional 7Q20

all future discharges while complying with PWQOs. Using the traditional 7Q20 approach, it is unlikely that any solution would have been found, resulting in severe restrictions in growth rates of the communities within the watershed.

This modified low flow frequency analysis generally provides greater assimilative capacity than conventional approaches and is ideally suited to intermittent flow regimes. This technique is readily applicable to other watersheds in which wasteload assimilation is a primary constraint to future development. The principal data requirements include at least 10 years of daily flow data for several locations throughout the watershed, and hydraulic data for the development of travel time versus flow relationships.

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