

Forestry Water Quality Index – A Planning Tool for the Assessment and Communication of the Impacts of Forestry Activities on Water Quality

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Abstract

The assessment of the impacts of forestry activities on water quality is a critical component of forestry management and planning especially when watersheds are being used for different water uses by different stakeholders. Traditional methodologies for assessing these impacts, while accurate, often do not take into account the intended use of water. Water quality data is inherently technical, and are not conducive to communication to all stakeholders especially the public. There is a need for a communications based assessment tool that assesses the impact of forestry activities on water quality from the perspective of different water uses. This paper describes the development and application of such a tool, the Forestry Water Quality Index (FWQI). The FWQI has been developed specifically to capture, evaluate and communicate the impact of forestry activities on water quality to multiple stakeholders. Initially based on the Canadian Council of Ministers of the Environment's Water Quality Index, the FWQI was specifically adapted for applications in forestry management. Details of this adaptation and its methodology are outlined. Case studies from Newfoundland and Labrador illustrate the use of the FWQI for communication, performance evaluation, planning and technical data analysis. Further potential applications are also discussed briefly.

Key words: FWQI, sustainable forest management, water quality, Newfoundland and Labrador

Introduction

Forestry is one of the important natural resources in Canada which has contributed to the socio-economic development of many communities across the country, as well as to strengthen the national economy. However, there have been concerns regarding the environmental impacts of forest management on water and other environmental aspects. During the last 20 years, a number of studies were undertaken to assess the nature and degree of forestry related environmental impacts. The outcomes of these studies were published in the form of technical reports and other publications, and thus the information

was limited to technical audiences only. The general public either did not have access to this information or the information was too technical to be understood. In spite of substantial efforts by the scientific community to document and understand the impact of forest operations, the public perception about the negative impact of forestry remained somewhat unchanged. Current work has tried to address this issue/gap by focusing on quantification and reporting of forestry impacts on water resources in a simplistic language to be understood by all stakeholders and the general public.

The impacts of forestry activities on water quality are a concern for both water resources and forestry management. These impacts are of particular concern in watersheds that have multiple stakeholders with different water use interests. The assessment and protection of water resources in these ecosystems is critical to the development of integrated resource management plans. The development of integrated resource management plans for multiple stakeholder watersheds is essential for the sustainable development of natural resources.

The assessment of the potential impacts of forestry activities on water resources includes the development of an inventory of potential water uses and users, analysis of historical water quality data from similar adjacent watersheds, the study of the sensitivity of the watershed to changes in water quality and the institution of a water quality sampling program. Sampling programs are typically developed to view pre and post forestry conditions for the watershed area. The analysis of the data obtained from the water quality sampling programs is critical in the assessment process.

Need for an Assessment Tool

Pre and post forestry water quality data is typically analyzed statistically to gauge the environmental impacts of forestry activities. While this type of analysis is very useful, it is extremely data focused and is not always conducive to communication to all stakeholders of a watershed. Multiple stakeholders within a watershed require different levels of information to deal with their watershed interests. For example, water resources specialists require actual water quality data (i.e. parameters and their values), forestry companies may require information (i.e. if Best Management Practices (BMPs) are effective) and the general public and policy makers are usually more interested in general knowledge (i.e. if water is safe to drink). Consequently, in the assessment of the impact of forestry activities it is important to use tools that are conducive to converting data into information and knowledge that can be understood by all stakeholders.

Recognizing the need for such a tool, it was deemed necessary to find and implement an assessment tool that could capture, evaluate and communicate the impact of forestry activities by converting water quality data into useful information and knowledge. Other desirable features of such a tool would be the ability to evaluate the impact of environmental protection measures such as BMPs; and the ability to predict impacts of forestry activities on water quality based on historical data. When dealing with multiple use watersheds, water quality needs to be evaluated from the perspective of different water uses and not just from the statistical change perspective. The assessment tool requires the ability to examine water quality data using multiple use criteria that would be

useful for different land uses within the watershed. The Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) was identified as a potential communications tool for these tasks. Though developed primarily as a communications tool, the CCME WQI methodology was adapted to develop a Forestry Water Quality Index (FWQI) calculator that could be used for communication, performance evaluation, planning and technical data analysis in the forestry sector.

The CCME WQI

The WQI is based on three measures of variance; scope (F_1), frequency (F_2) and amplitude (F_3). The formulation of the WQI as described in the Canadian Water Quality Index 1.0 – Technical Report is as follows (CCME 2001):

The measure for scope is F_1 . This represents the extent of water quality guideline non-compliance over the time period of interest.

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100 \quad (1)$$

The measure for frequency is F_2 . This represents the percentage of individual tests that do not meet objectives (“failed tests”).

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \quad (2)$$

The measure for amplitude is F_3 . This represents the amount by which failed tests do not meet their objectives. This is calculated in three steps:

Step 1- Calculation of Excursion

Excursion is the number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective.

When the test value must not exceed the objective:

$$\text{excursion}_i = \left(\frac{\text{Failed Test Value}_i}{\text{Objective}_j} \right) - 1 \quad (3)$$

When the test value must not fall below the objective:

$$\text{excursion}_i = \left(\frac{\text{Objective}_j}{\text{Failed Test Value}_i} \right) - 1 \quad (4)$$

Step 2- Calculation of Normalized Sum of Excursions

The normalized sum of excursions (*nse*) is the collective amount by which individual tests are out of compliance. This is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives).

$$nse = \frac{\sum_{i=1}^n \text{excursion } i}{\text{Number of tests}} \quad (5)$$

Step 3-Calculation of F_3

F_3 is calculated by an asymptotic function that scales the normalized sum of the excursions from objectives to yield a range from 0 to 100.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right) \quad (6)$$

The WQI is then calculated as:

$$WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \quad (7)$$

The WQI values are then converted into rankings by using the categorization scheme presented in Table 1.

Table 1 CCME WQI categorization schema

Rank	WQI Value	Description
Excellent	95-100	Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels; these index values can only be obtained if all measurements are within objectives virtually all of the time
Good	80-94	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels
Fair	65-79	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
Marginal	45-64	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels
Poor	0-44	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels

Adapting the CCME WQI for the forestry sector

The CCME WQI is primarily a communications tool. In adapting the CCME WQI methodology to develop the FWQI calculator, the role of the CCME WQI was expanded

to include planning, performance measurement and data analysis components. These components were developed solely to address the needs of the forestry sector.

There are many specialized tools, models and protocols available in the forestry sector for planning, performance measurement and data analysis. However, many of these tools and models, due to their inherently technical nature, produce results that are not amenable for communication to the general public and many stakeholders. In light of this, the FWQI was developed as a communications focused assessment tool that is easy to use and will be an additional tool for forestry management personnel (Tobin, 2004). It is not to be used as replacement for detailed forestry planning and analysis.

The communication, planning, performance measurement and data analysis capabilities and applications of the FWQI are explained in the following sections through the use of case studies from Newfoundland and Labrador (NL).

Communications Application

The CCME WQI methodology is designed to convert raw data into information and then into knowledge by comparing water quality data with water quality guidelines. The CCME WQI methodology has been implemented in its entirety in the FWQI. The FWQI can be used directly with pre and post forestry data to derive information on the ranking of a water body for various water uses and on the scope, frequency and magnitude of water quality exceedances. The information determined through these two methods is easily compared and provides a snap shot of the impact of forestry on water quality that is easy to communicate to stakeholders.

Water bodies in watersheds undergoing forest harvesting are often used for a variety of purposes. Thus, in adapting the CCME WQI methodology for the forestry sector, the FWQI was designed to allow the evaluation of water quality datasets against six different water quality guidelines simultaneously.

One of the strengths of using the FWQI as a communications tool is that it can be used to understand the nature of water quality exceedances, i.e. if the exceedances affect many parameters (scope; F_1), if the exceedances occur frequently (frequency; F_2) or if the exceedances are due to very high concentrations (amplitude; F_3). This is because the FWQI also provides information on the scope, frequency and amplitude of water quality exceedances. Table 2 shows pre and post forestry data for Lower Shoal Harbour River as analysed using the FWQI. The FWQI ranks the pre and post forestry water quality for simple comparison of scores and also shows the three measures of variance for pre and post forestry water quality results.

Table 2 FWQI scores, F_1 , F_2 and F_3 values for pre and post forestry water quality of Lower Shoal Harbour River

	Overall		Drinking		Aquatic		Irrigation		Livestock	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post

FWQI	71 Fair	60 Marg.	79 Fair	72 Fair	59 Marg.	48 Poor	100 Excl.	95 Excl.	81 Good	73 Fair
F₁	35	42	19	25	60	58	0	8	8	7
F₂	22	29	16	22	34	44	0	2	8	14
F₃	29	48	27	36	20	53	0	0	31	43

Forestry activity in the Lower Shoal Harbour River watershed began in 1997. Water quality data was available from 1990-1994 and 1998-2001. There is a slight decrease in water quality index scores since the start of forestry activities in 1997.

The examination of the measures of variance in Table 2 provides insight into the reasons behind the decrease of water quality results between pre and post forestry activities. For example, looking at the protection of aquatic life use, the primary reason for post forestry scores being lower than pre forestry scores is that there is an increase in both the frequency and magnitude of exceedances despite the reduction in scope (the number of affected parameters)

Planning Application

To adapt the CCME WQI methodology so that the FWQI could be used for planning purposes, a methodology for predicting the impacts of forestry on water quality was developed. This methodology is based on the use of historical pre and post forestry water quality data from similar watersheds. The data is used to predict changes in water quality in the watershed being evaluated for forestry. It works on the assumption that predicted changes in water quality due to future forestry in a watershed of interest would be similar to changes experienced in a similar watershed that have already experienced forestry activities.

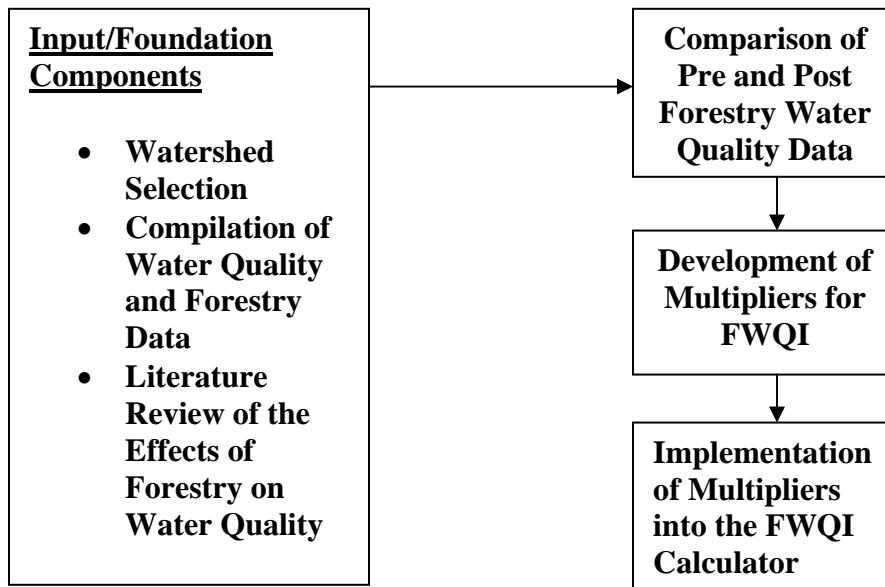
The methodology has two distinct components or steps:

- In the first step, pre and post forestry water quality data from watersheds similar to the one being evaluated are analysed and compared to identify which water quality parameters were affected by forestry activities and by what factor these parameters increased or decreased between the pre and post forestry data.
- In the second step, the same changes identified in step 1 are applied to pre forestry water quality data from the watershed being evaluated to predict the condition of the post forestry water quality.

To help users of the FWQI in NL, a study was undertaken to identify which water quality parameters were affected by forestry activities and by what multiplicative factor these parameters increased or decreased between the pre and post forestry data. The results of this study were then incorporated into the FWQI calculator so that users of the FWQI calculator could evaluate the potential impact of forestry on any watershed in NL without having to repeat step one of the methodology.

This study consisted of three distinct initial components as illustrated in Figure 1.

Figure 1 Steps in adapting the CCME WQI for the forestry sector



Input/Foundation Components

The first component of the study was the selection of watersheds. This was initiated by selecting a wide variety of watersheds that had been subjected to forestry activities since 1993. The selection of watersheds was focused on the island portion of NL because of large gaps in the water quality data record in Labrador. A selection criterion was developed to ensure that the majority of watershed characteristics in NL were represented. The selection criterion consisted of a complete spectrum of land use (developed areas, transitional areas, and pristine areas); regional representation (western, central, and eastern); and size representation (watersheds varying in size from 7 km² to 4250 km²). Based on these criteria, watersheds were selected for use in the development and testing of the FWQI model and are listed in Table 3.

Table 3 Selected watersheds and their characteristics

Community	Watershed	Size (km²)	% Protected
Botwood	Peter's River	198.0	100
Corner Brook	Trout Pond	107.0	100
Gander	Gander Lake	4250.0	12
Lewisporte	Stanhope Pond	27.3	19
Point Leamington	Little Pond	40.5	12
Roddickton	East Brook Pond	39.6	100

There are nine ecoregions established for NL. This study utilized watershed within four of these ecoregions. Table 4 lists the study watersheds and their respective ecoregions.

The ecoregions that are not represented by these watersheds are typically barrens that do not include forest ecosystems, or are in areas that are protected from forestry activities.

Table 4 Ecoregion classifications and corresponding watersheds

ECOREGION	WATERSHED
Central Newfoundland Forest	Peter’s River Gander Lake
Central Newfoundland Forest / North Shore Forest*	Stanhope Pond Little Pond
Western Newfoundland Forest	Trout Pond
Northern Peninsula Forest	East Brook Pond

* Watersheds border both ecoregions.

Forestry and water quality data was compiled to be used as input for the development of the model. The quantity of forestry activities that occurred within a watershed was collected on a yearly basis for the Department of Natural Resources and Corner Brook Pulp and Paper. Water quality datasets (typically taken two to four times annually) were obtained from the Department of Environment and Conservation.

A literature review was conducted on the effects of forestry activities on water quality. The water quality parameters that are typically affected by forestry activities are turbidity, dissolved organic carbon (DOC), nutrients (potassium, phosphorus and nitrogen), temperature and dissolved oxygen (DO).

Development of Multipliers for FWQI

Multiplier values were developed for those parameters that are typically affected by forestry activities as illustrated through the literature review. The multiplier values are used to predict the water quality conditions that will be present after forestry harvesting occurs. The current datasets for the water body of interest are used and multiplied by the multiplier factor to determine future water quality. This process is used as the planning component of the FWQI.

Water quality datasets were averaged on a yearly basis for each parameter of interest. All parameters identified in the literature review were examined with the exception of temperature (not applicable to lakes) and DO (no water quality data available). To assess the impacts of forestry activities, water quality data was compared to data from control sites. Control sites are sites that are adjacent to the study sites but which have not been subject to forestry activities. The yearly averages for the control points were compared with the corresponding water body in the study. All six public water supplies were analyzed in this method for all five parameters of interest (turbidity, potassium, phosphorus, nitrogen and DOC). Each parameter was then statistically examined for mean, standard deviation, maximum, minimum and median annual values for each supply.

The recommended value for use as a multiplier value is the mean + one standard deviation. The maximum value however, should be used if the forestry area is sensitive or if there are other factors that should be considered.

Multipliers were developed for the general overall Newfoundland area (provincial multipliers). These multipliers were developed using the averages of all six water bodies and are presented in Table 5. The multiplier values for each of the study areas in this project (study area multipliers) were also calculated and are presented in Table 6.

Table 5 Provincial multiplier values

Parameter	General Multiplier
Turbidity	2.26
Potassium	1.36
Phosphorus	1.90
Nitrogen	1.38
DOC	1.42

Table 6 Study area multiplier values

Parameter	Peter's River	Trout Pond	Gander Lake	Stanhope Pond	Little Pond	East Brook Pond
Turbidity	1.84	2.45	1.92	2.19	1.91	0.67
Potassium	1.13	1.29	1.44	1.25	1.85	0.59
Phosphorus	1.63	3.90	2.58	1.36	1.04	2.27
Nitrogen	1.66	1.39	1.34	1.80	1.33	1.11
DOC	1.67	NA	1.39	1.49	1.78	0.89

A protocol was developed to assist in the determination of which multiplier set should be utilized to obtain accurate WQI scores for a particular watershed of interest. The appropriate multiplier set is dependent on the location and size of the watershed under consideration. For example, a watershed within the same ecoregion as one of the study areas should be examined first (Table 7). In ecoregions where there are more than one study area within that region, as depicted in the Central Newfoundland Forest ecoregion, a corresponding watershed size should be considered. Results should be determined using this method as well as using the general provincial multipliers (Table 6). The most conservative WQI scores for these two methods should be accepted as the predicted scores for planning purposes.

Incorporating Multiplier Values for Planning Purposes

For the prediction of water quality for post forestry conditions, the developed multipliers were integrated into the calculator. Table 7 illustrates the results of the application of the general province and specific watershed multipliers to a pre forestry water quality dataset from Little Pond.

Table 7 Pre and post forestry water quality data for Little Pond using FWQI

	Overall	Drinking	Aquatic	Irrigation	Livestock
Pre-forestry	82 Good	88 Good	75 Fair	94 Good	89 Good
Post-forestry (General Multipliers)	76 Fair	80 Good	68 Fair	87 Good	83 Good
Post-forestry (Watershed Multipliers)	78 Fair	83 Good	71 Fair	90 Good	86 Good

The water quality data from Little Pond is from 1987 to 2002. The post forestry values presented in Table 7 are the FWQI scores that would be expected if forestry activities were to take place in the Little Pond watershed. The FWQI scores obtained using the general and watershed specific multipliers are slightly different, though the rankings do not change. The FWQI scores obtained using the general multipliers are more conservative and consequently these would be accepted as the post forestry FWQI scores.

Performance Measure Component

For the protection of water resources, BMPs are often implemented in forestry activity areas. The assessment of the effects of BMPs is critical in the management of forest harvesting. To implement such a feature in the FWQI calculator, a pilot study was conducted to evaluate how the CCME WQI methodology could be used to evaluate the impacts of BMPs. A complication in the analysis of the impact of BMPs is that the positive effect of any given BMP on water quality is not immediately visible in a watershed and consequently if a number of BMPs are implemented their effects will be spread out over time.

The application of the FWQI as a performance measurement tool was assessed through analysis of the Gander Lake protected public water supply area. The implementation of BMPs in the Gander Lake watershed began in 1996 as per recommendations from an Environmental Protection Plan. Data from 1993 to 2002 was used for the analysis. The data was split into a pre BMP and post BMP period, but since the effects of BMPs are not immediate a rolling window was used to assess when the effect of BMPs was being reflected in water quality. The use of a rolling window resulted in four sets of pre BMP and post BMP data as shown in Table 8. The WQI score was calculated for the pre BMP and post BMP data for each set and compared.

Table 8 Pre and post BMP FWQI scores using a rolling window

Datasets	Time Frame	# of parameters	# of samples	FWQI Value	FWQI Ranking
1	1993-1996	16	8	84	Good
	1997-2002	16	26	82	Good

2	1993-1997	16	11	84	Good
	1998-2002	16	23	83	Good
3	1993-1998	16	19	82	Good
	1999-2002	16	15	86	Good
4	1993-1999	16	25	82	Good
	2000-2002	16	9	88	Good

In dataset number 3, the post BMP FWQI scores started showing an improvement over the pre BMP FWQI scores. From examining the FWQI scores for all sets, it appears that the effects of the BMPs were reflected in the water quality from 1998 onwards. If the BMPs were not effective, the FWQI scores would show little or no change within the time frames. This analysis allows the forestry sector to determine if the existing practices are meeting the goals and objectives set for the BMPs.

Data Analysis Component

In addition to being a communications and summarizing tool the FWQI calculator has built in functionality for data analysis. This data analysis capability is a by-product of the CCME WQI methodology as it works to convert raw water quality data into insightful and meaningful information.

Seasonal variation of water quality is critical to forestry management planning due to sedimentation and water level issues. Stanhope Pond, used by Lewisporte as a public water supply, has water quality data that was collected through all four seasons between 1986 and 2002. Table 9 depicts the seasonal variation of the water body through examination of FWQI values.

Table 9 Seasonal variation of Stanhope Pond watershed

	FWQI	Category	F₁	F₂	F₃
Fall	79	Fair	21	14	26
Spring	71	Fair	33	16	33
Summer	78	Fair	25	18	21
Winter	87	Good	12	10	17

A comparison of the F₁, F₂, and F₃ values in Table 9 indicates that the number of parameters failing, the frequency, and the amplitude vary significantly between the seasons. This type of analysis is particularly useful for planning and management of the harvesting start date and the time period of activity that can occur within a particular watershed.

The FWQI has additional data analysis features such as summary statistics, sensitivity analysis, and comparison of upstream and downstream datasets. The data analysis or technical analysis component of the FWQI can be used for in-depth analysis when required for report writing and management purposes. This tool would be applicable for forest management in developing the Five Year Operating plans that are required in NL.

Conclusions

Within NL, the multipliers will be updated as new pre and post forestry water quality data is made available through focused monitoring programs. The water quality data used in this study was pre-existing data collected from water supplies in watersheds affected by forestry. The water quality data did not have seasonal coverage and this did not allow for analysis of seasonal variation. To accurately capture the effect of forestry activities, water quality data needs to be collected using a monitoring program specifically designed to capture these effects. This would preferably also involve the use of continuous water quality monitoring equipment.

As demonstrated in the various case studies presented in this paper, the FWQI is an excellent communication based assessment tool that can capture, evaluate and communicate the impact of forestry activities on water bodies by converting water quality data into useful information and knowledge. It is a tool that is easy to use, and is based on a nationally approved methodology for communicating water quality data. It is a versatile tool that has distinct communication, planning, performance measurement and data analysis capabilities.

The FWQI's communication, performance measurement and data analysis capabilities can be used directly wherever there is water quality data and corresponding guidelines for comparison of data. The planning component described, however, is specific to the province of NL since the multipliers are based on historical datasets from the province. Using the methodology to derive multipliers presented in this paper the planning component functionality could be developed for any province or jurisdiction.

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