Ontario

Baseline Hydrology: For the Southwestern Hudson Bay and Nelson River Watershed Systems

Technical Release

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Additional Information

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List of Acronyms

B: Ice Condition

BFI: Base Flow Index

DA: Drainage Area

dam^3 : Cubic Decameter

DEM: Digital Elevation Model

EVT: Extreme Value Theorem

FDC: Flow Duration Curve

GIS: Geographic Information System

H: Hurst Phenomenon

HYDAT: The archive for Canadian Hydrometric Data

i.i.d: Independent and Identically Distributed

km: Kilometres

L: Length

LFI: Low Flow Index

M: Rank

MAF: Mean Annual Flow

MAR: Mean Annual Runoff

max: Maximum

min: Minimum

m^3/s (cms): Cubic Meters Per Second

n: Years of Record

N: North

OFAT: Ontario Flow Assessment Tool

OHN: Ontario Hydro-Network

P: Probability

R: Scaled Range

SAAS: Streamflow Analysis and Assessment Software

sq. km: Square Kilometres

T: Time

W: West

WSC: Water Survey of Canada

°: Degrees

Δ: Delta

ξ: Shape Parameter

μ: Mean

σ: Standard Deviation

%: Percentage

1 Introduction

In 2010, the Far North Science Advisory Panel clearly illustrated the importance placed on both water quality and water quantity needs for the long-term ecological, economic and social sustainability of the Far North region in Ontario (Far North Science Advisory Panel, 2010). Despite the importance placed on water, the report identified that significant data gaps exist on water resources across the Far North region.

To support the development of Far North community based land use plans and the Far North Land Use Strategy, single station flood and low flow frequency statistics were estimated in the 2012-2013 fiscal year. This included the Water Survey of Canada's HYDAT stream gauges of the Southwestern Hudson Bay and Nelson River Watersheds that occur within the Province of Ontario.

This report represents a continuation of this previous work. Active stream gauges were used to estimate baseline hydrology statistics. The key components of the streamflow regime are studied with respect to the frequency, timing, duration and discharge. Different stochastic models are used for the analysis, and the numerical values of the output parameters to provide inferences about streamflow regime.

These baseline statistics provide information on the water quantity at each gauge location and also a summary at a primary watershed scale. This data will help to address the previous data gaps in the Far North region.

2 Objectives

The objective of this project was to:

A: Provide baseline hydrology information on each of the Water Survey of Canada's HYDAT stream gauges of southwestern Hudson Bay and Nelson River Watershed systems that occur within the Province of Ontario.

B: Generate a review and summary of the streamflow statistics at the primary watershed (Southwestern Hudson Bay and Nelson River) scale for the province of Ontario, based on the summary of the results from objective A.

3 Province of Ontario and the Study Area

The Province of Ontario extends approximately from 42° N to 57° N latitude and from 75° W to 95° W longitude with three primary watersheds: Great Lakes, Nelson and southwestern Hudson Bay. Ontario has three main climatic regions: southwestern Ontario is typical of a moderate humid continental climate, central and eastern Ontario are characteristic of a more severe humid continental climate and the northernmost parts of Ontario (north of 50°N) are within a sub-arctic climate region (Köppen Dfa Dfb Dfc).

Northern Ontario falls into two physiographic regions, namely the Canadian Shield and the southwestern Hudson Bay Lowlands. River systems in the region drain to the Nelson and southwestern Hudson Bay watersheds. Peatlands (non-forested bogs and fens) are the dominating land class in the Far North (McLaughlin and Webster 2013).

The Albany, Severn, and Attawapiskat rivers are the longest river systems within the southwestern Hudson Bay watershed system. The Albany River, with a drainage area of 135200 sq. km, flows northeast from Lake St. Joseph to southwestern Hudson Bay. It is 982 km long to the head of the Cat River. Severn River is also 982 km long to the head of Black Birch River; with a smaller drainage area of 102800 sq. km. Attawapiskat River to the head of Bow Lake is 748 km long and has a drainage area of 50500 sq. km. The above rivers drain to southwestern Hudson Bay watershed system. The English River is the longest river system in the Nelson River watershed system at 615 km in length and a drainage area of 52300 sq. km (Wikipedia, accessed January 2014).

4 Methodology and Analysis

4.1 The Streamflow and the Watershed

4.1.1 General Characteristics of Streamflow

Before getting into the details of estimation and analysis, let us look at the general characteristics of streamflow data of the study area:

- Streamflow can be defined as a space-time random process.
- The magnitude of streamflow varies over a calendar year.
- The streamflow exhibit seasonal patterns and periodicities.
- The streamflow records have clustered events due to precipitation or drought.
- Autocorrelation exists with consecutive streamflow values.
- The daily streamflow fitted to a normal distribution is positively skewed.
- The data has both lower and higher outliers due to drought and flood.
- No negative streamflow values are possible. Zero values are reported in few places where the water level is too small for measurements.
- The basic data is daily time series data with complete record for every year.
- The derived data include threshold above/below, annual maximum, annual minimum and monthly streamflow values.
- Within the stream network, the magnitude of streamflow shows spatio-temporal (upstream-downstream) autocorrelation.
- The unit of streamflow is cubic meter per second (L^3T^{-1}).

4.1.2 Brief Description on the Statistical Descriptors and Theorems

Now let us have an overview of the statistical descriptors as pertinent to streamflow. Statistical descriptors of the random variable streamflow are: central tendency (first moment), variability, also called dispersion (second moment), skewness (third moment) and kurtosis (fourth moment).

The measures of central tendency are the mean, median and mode. Amongst these three, mean and median are used widely in streamflow analysis. In time and space or both, mean is related to the availability of water. Median is used in constructing dimensionless regional ratios and is preferred over mean. The reason is that median provides more accurate results and also nullifies the effect of abnormally large streamflow values with a short period of record.

Measures of dispersion are variance, range, standard deviation, percentile, interquartile range and coefficient of variation. Variance provides information on the sample. Range, standard deviation, percentile and interquartile range are measures of water quantity.

They are used for water quantity assessment in terms of source, extent and dependability. Coefficient of variation is dimensionless and is the ratio of standard deviation to mean. It is used as a regionalization parameter.

Skewness is a measure of the shape of the distribution and characterises the asymmetry of the distribution. This property has to be addressed as streamflow is not a normal distribution (Gaussian) with a skewness of 0 but a value greater than 1 (positively skewed). There are two approaches to account for an asymmetrical distribution: transform the data to get normal variates $[(x-\mu)/\sigma]$ or model data accounting for skewness. Typically skewness used is as a regionalization parameter.

Kurtosis is the measure of peakedness of the distribution. This means the peaks of the bell shaped frequency curve may be sharper or flatter.

Coefficient of skewness and Coefficient of kurtosis with values of 0 (zero) and 3 respectively are used to determine the probability function that best fit the empirical distributions.

Having been given an overview of the descriptors, let us look at the statistical theorems and the distribution that are used and applied as related to the analysis of the present work. The fundamental theorems used in this study are the Central Limit Theorem and the Extreme Value Theorem. Even though data are skewed, Normal (Gaussian) distribution is used to analyse the daily streamflow series, and 3 Parameter Lognormal distribution is used for flood frequency analysis. These two distributions use the Central Limit Theorem. For low flow analysis and the Peak Over Threshold process, the Gumbel and the Generalized Pareto Distribution are used. These distributions use the Extreme Value Theorem. The main assumption for the distributions described above is that the data are independent and identically distributed (i.i.d). Prior to fitting data to any distribution, the data is tested for the following statistical criteria: randomness, independence, stationarity (trend) and homogeneity. The tests performed for the present analysis for flood flow and low flows are:

- The Spearman Rank Order Serial Correlation Test for Independence.
- The Spearman Rank Order Correlation Coefficient Test for Trend.
- The Mann-Whitney Split Sample Test for Homogeneity.
- Runs above and below median for General Randomness.

Combining statistics properties (descriptors) can also be used to analyse streamflow. One of such properties is the Hurst Phenomenon (Klemeš (1976)). It studies the long-term properties of a streamflow series. The phenomenon was named after the scientist who introduced it in 1965 for the Nile River: "to make use of the Nile water to the fullest possible extent". The rationale behind the study is that the reservoir storage capacity required for mean flow depends on the cumulative variability from the mean [Σ (μ - x_i)] with long periods of record. He has found that the rescaled range ($R = \Delta Q_{max} - \Delta Q_{min}$) divided by the standard deviation is proportional to the number of years of record (n) through the Hurst coefficient H with the relationship:

$R/\sigma \sim n^H$ where $0.5 <= H <= 1.0$

The premise behind describing the Hurst phenomenon here is that it has since recent times been used in the study of climate change (Sakalauskienė (2003), Koutsoyiannis, (2009)).

4.1.3 Application Areas of Descriptors in Water Resources

Yevjevich (1972) described application areas of descriptors in water resources. The application areas are:

- Condensation of information in the form of descriptors.
- Transfer of information from one point to another over an area for regionalization. This is done using interpolation techniques like Inverse Distance Weighing or Kriging in GIS or using stochastic models. The common hydrologic parameters of regionalization are mean, coefficient of variation and coefficient of skewness.
- Use of parameters for quantitative analysis of water resources. Mean and standard deviation are the most commonly used.

- Creation of new data series by transforming the old data series with the use of reduced variables. The new data series will have value $(x-\mu)/\sigma$. This will make $\mu = 0$ and $\sigma = 1$ for a normal distribution. The main purpose of the transformation is to make the data series more convenient to analyse.

4.1.4 The Watershed

With the introduction to the streamflow time series in the above section, let us look at the physical unit of analysis, the watershed. A Watershed, referenced with the pour point/outlet, is the main physical unit to study the rainfall-runoff process of the hydrologic cycle. It is defined as the area of land that drains the runoff water to the pour point. The horizontal projection of this area is called the drainage area.

Black (1996) defines watershed functions in two groups: Hydrologic and ecological functions. Hydrological functions include: collection function, storage function and dispersal function. The summary of the hydrologic functions is attenuation of the streamflow downstream. The ecological functions include: the chemical pathway function and the habitat function. An investigation on both of the functional groups of the watershed is necessary in the context of any land use planning and sustainable watershed development.

With the assumption that past events are representation of the future events, historic streamflow time series (daily) data is converted to information. The rationale behind is that there is a relationship between the streamflow regime and watershed function defined in terms of frequency, timing, duration and magnitude.

4.2 Data Source and HYDAT Gauging Stations

The streamflow data series derived for different analysis is shown in Figure 1. Historic daily streamflow records from WSC's HYDAT data base. The period of record is from January 1970 to December 2012. The premise behind using common period of record is to minimize, as much possible, the climate variability. A total of 56 active HYDAT gauges are considered. These include 9 new gauges with less than 10 years of record. The lists of gauges are given in Table 1(a) and Table 1 (b). For the new gauges, only summary statistics are included. The stream gauge locations for the study area are shown in Figure 2.

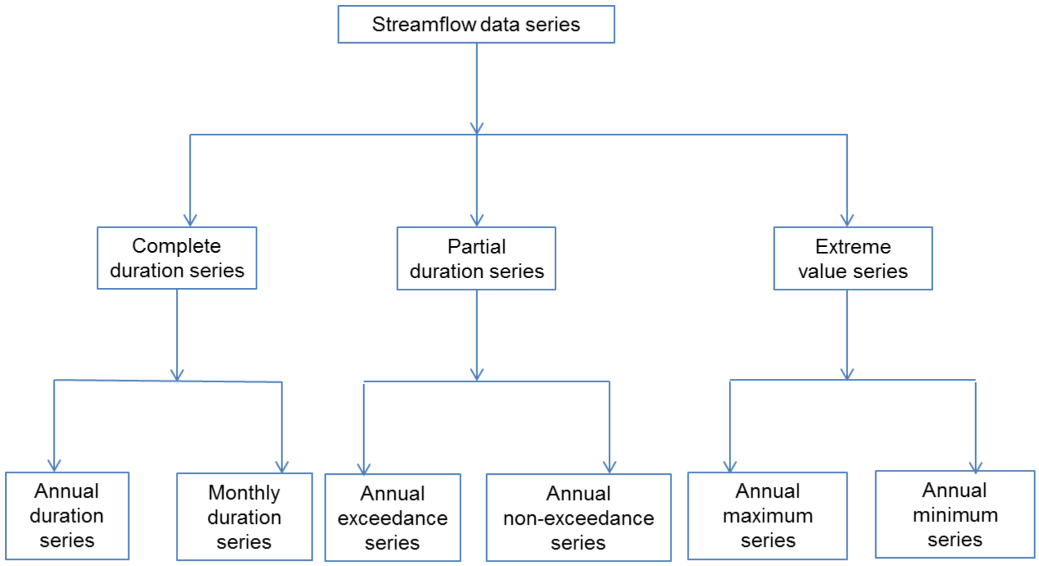

Figure 1. Data Series Derived for Different Analysis

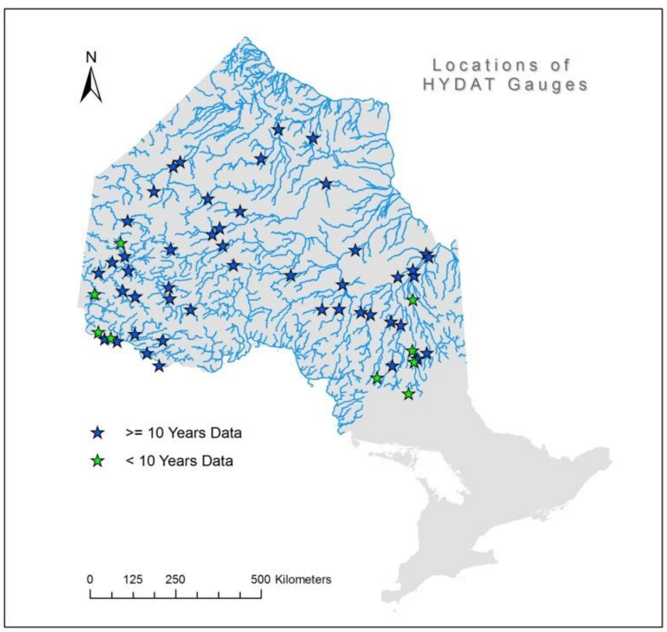

Figure 2. Location of WSC's HYDAT Stream Gauges

Station Name	HYDAT ID	Active/Discontinued	Regulation	Latitude	Longitude	StartYear	EndYear	No of Years
ABITIBI RIVER AT ONAKAWANA	04ME003	Active	Regulate	50.60292	-81.41464	1970	2010	31
ALBANY RIVER BELOW ACHAPI	04GC002	Active	Regulate	51.36658	-89.42228	1971	2011	20
ALBANY RIVER NEAR HAT ISLAND	04HA001	Active	Regulate	51.33056	-83.83333	1973	2011	32
ASHEWEIG RIVER AT STRAIGHT	04DB001	Active	Natural	53.71175	-87.95339	1970	2011	37
ATIKOKAN RIVER AT ATIKOKAN	05PB018	Active	Natural	48.75197	-91.58408	1984	2010	26
ATTAWAPISKAT RIVER BELOW	04FC001	Active	Natural	53.09131	-85.07225	1970	2011	38
BASSWOOD RIVER NEAR WINTON	05PA012	Active	Natural	48.08256	-91.65117	1970	2010	41
BERENS RIVER ABOVE BERENS	05RC001	Active	Natural	51.80983	-93.52122	1980	2011	23
BRIGHTSAND RIVER AT	04GB005	Active	Natural	49.62361	-90.57194	1978	2011	22
CAT RIVER BELOW WESLEYAN	04GA002	Active	Natural	51.17378	-91.59458	1971	2011	36
CEDAR RIVER BELOW	05QE008	Active	Natural	50.50756	-93.25858	1970	2011	42
CHUKUNI RIVER NEAR EAR FALLS	05QC001	Active	Regulate	50.87311	-93.48389	1970	2011	39
ENGLISH RIVER AT UMFREVILLE	05QA002	Active	Natural	49.87339	-91.45992	1970	2011	42
GROUNDHOG RIVER AT	04LD001	Active	Regulate	49.31378	-82.04314	1971	2011	28
IVANHOE RIVER AT FOLEYET	04LC003	Active	Natural	48.25021	-82.44381	2001	2011	11
KAPUSKASING RIVER AT	04LF001	Active	Regulate	49.41442	-82.43994	1970	2011	28
KAWINOGANS RIVER NEAR	04FA002	Active	Natural	51.64831	-89.88692	1970	1992	23
KENOGAMI RIVER NEAR	04JG001	Active	Regulate	50.42286	-84.38153	1970	2010	27
KWATABOAHEGAN RIVER NEAR	04KA001	Active	Natural	51.16083	-80.86394	1973	2010	37
LITTLE CURRENT RIVER AT	04JF001	Active	Natural	50.65833	-86.53194	1970	2011	28
LONG-LEGGED RIVER BELOW	05QE012	Active	Natural	50.677	-93.97019	1980	2011	32
MATTAGAMI RIVER NEAR TIMMINS	04LA002	Active	Regulate	48.40431	-81.44836	1974	2010	32
MATTAWISHKWIA RIVER AT	04LK001	Active	Natural	49.68278	-83.65556	1986	2011	13
MISSINAIBI RIVER AT MATTICE	04LJ001	Active	Natural	49.61392	-83.26667	1970	2011	42
MISSINAIBI RIVER BELOW	04LM001	Active	Natural	50.58544	-82.091	1973	2010	37
MOOSE RIVER ABOVE MOOSE	04LG004	Active	Regulate	50.75158	-81.45139	1983	2010	23
NAGAGAMI RIVER AT HIGHWAY	04JC002	Active	Natural	49.77289	-84.53694	1970	2011	42
NAMAKAN RIVER AT OUTLET OF	05PA006	Active	Natural	48.38256	-92.17631	1970	2011	42
NORTH FRENCH RIVER NEAR THE	04MF001	Active	Natural	51.07672	-80.76408	1970	2010	41
OGOKI RIVER ABOVE WHITECLAY	04GB004	Active	Natural	50.86842	-88.93161	1972	2011	38
OTOSKWIN RIVER BELOW	04FA001	Active	Natural	51.82325	-89.60214	1970	2010	29
PAGWACHUAN RIVER AT	04JD005	Active	Natural	49.76419	-85.22619	1970	2011	42
PINEIMUTA RIVER AT EYES LAKE	04FA003	Active	Natural	52.30828	-88.76033	1970	2011	37
PIPESTONE RIVER AT KARL LAKE	04DA001	Active	Natural	52.58058	-90.18669	1970	2011	42
PORCUPINE RIVER AT HOYLE	04MD004	Active	Natural	48.55014	-81.05431	1977	2010	20
RAINY RIVER AT FORT FRANCES	05PC019	Active	Regulate	48.60853	-93.40344	1970	2010	41
RAINY RIVER AT MANITOU RAPIDS	05PC018	Active	Natural	48.63447	-93.91336	1970	2010	41
ROSEBERRY RIVER ABOVE	04CA003	Active	Natural	52.65508	-92.53242	1970	2009	29
SEVERN RIVER AT OUTLET OF	04CA002	Active	Natural	53.48947	-91.51022	1971	2011	29
SHAMATTAWA RIVER AT OUTLET	04DC002	Active	Natural	54.28975	-85.65153	1970	2011	36
STURGEON RIVER AT	05QA004	Active	Natural	50.16728	-91.54075	1970	2011	42
STURGEON RIVER AT OUTLET OF	05QE009	Active	Natural	50.35225	-94.46641	1970	2011	41
TURTLE RIVER NEAR MINE	05PB014	Active	Natural	48.85022	-92.72383	1970	2011	38
WABIGOON RIVER AT DRYDEN	05QD016	Active	Regulate	49.82917	-92.87083	1971	2012	42
WABIGOON RIVER NEAR QUIBELL	05QD006	Active	Regulate	49.95783	-93.40053	1970	2011	42
WINDIGO RIVER ABOVE MUSKRAT	04CB001	Active	Natural	53.35019	-91.79161	1970	2011	30
WINISK RIVER BELOW ASHEWEIG	04DC001	Active	Natural	54.49961	-87.22769	1970	2011	33

Station Name	HYDAT ID	Active/Discontinued	Regulation	Latitude	Longitude	StartYear	EndYear	No of Years
KAMISKOTIA RIVER ABOVE ENID C	04LB002	Active	Natural	48.62683	-81.62892	2009	2010	2
MOLLIE RIVER AT HIGHWAY NO. 14	04LA006	Active	Natural	47.49611	-81.84878	2008	2011	4
NEWPOST CREEK NEAR THE MOU	04ME005	Active	Natural	49.97203	-81.51203	2010	2010	1
TATACHIKAPIKA RIVER NEAR TIMM	04LA003	Active	Natural	48.32972	-81.58017	2006	2011	7
NEMEGOSENDA RIVER NEAR CHA	04LE002	Active	Natural	47.93817	-83.06069	2007	2011	5
PINEWOOD RIVER AT HIGHWAY NC	05PC023	Active	Natural	48.79802	-94.18452	2008	2010	3
WINNIPEG RIVER WESTERN CHANI	05PE028	Active	Natural	49.77708	-94.52411	2010	2011	2
GOLDEN CREEK NEAR RED LAKE	05QC006	Active	Natural	51.20034	-93.70701	2010	2011	2
LA VALLEE RIVER NEAR BURRISS	05PC022	Active	Natural	48.67844	-93.66522	2008	2011	4

Table 1(a) and Table 1 (b). WSC's HYDAT Gauge Information

4.3 Baseline Hydrology

The physical unit for this study is the discretized watershed with the WSC-HYDAT gauge location as pour point/outlet. The baseline hydrology is studied in terms of:

- The Watershed, Flow Direction and Connectivity
- Summary Statistics
- Mean Annual Runoff and Base Flow Index
- Monthly and Annual Flow Duration Curve
- Flood Frequency Analysis
- Low Flow Frequency Analysis
- Flood/Low Flow Analysis above/below a Threshold Streamflow Value
- Timing of Maximum/Minimum Flows
- Ice Conditions

4.3.1 The Watershed, Flow Direction and Connectivity

The watershed map was discretized (30 m resolution DEM) with the pour point for each of the HYDAT gauge locations using OFAT (http://www.giscoeapp.lrc.gov.on.ca/web/mnr/wrip/ofat/Viewer/viewer.html). The map is overlaid with the drainage network with the direction of flow and the connectivity in the current state (OHN network).

The map also provides the orientation of the watershed using the map element, North Arrow. Orientation (north/south/east/west or combinations) of a watershed with respect to the position of the sun affects the temperature, and hence evaporation and transpiration. Watersheds facing the sun are warmer and losses due to evapotranspiration are more whereas those facing away from the sun are cooler, and evapotranspiration is less. Also the orientation of watershed affects the melting time and speed of collected snow. A sample watershed map with its elements is depicted in Figure 3.

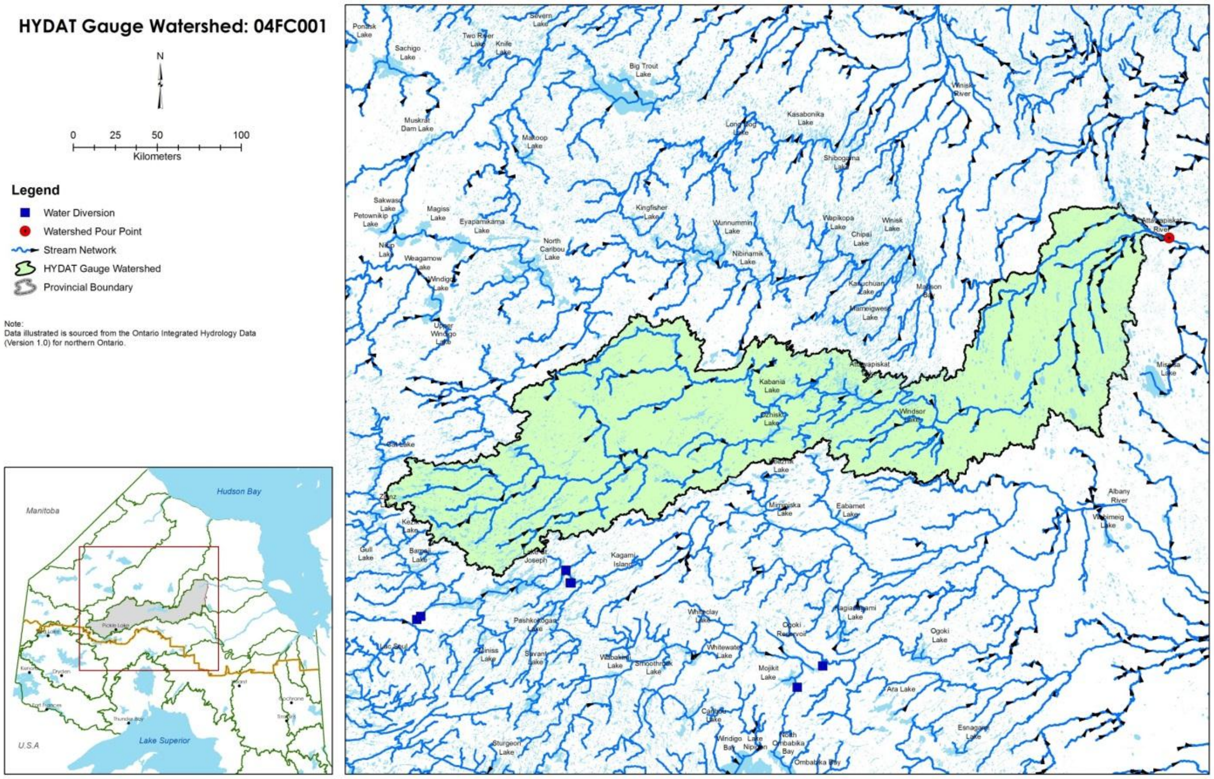

Figure 3. Watershed Map

4.3.2 Summary Statistics

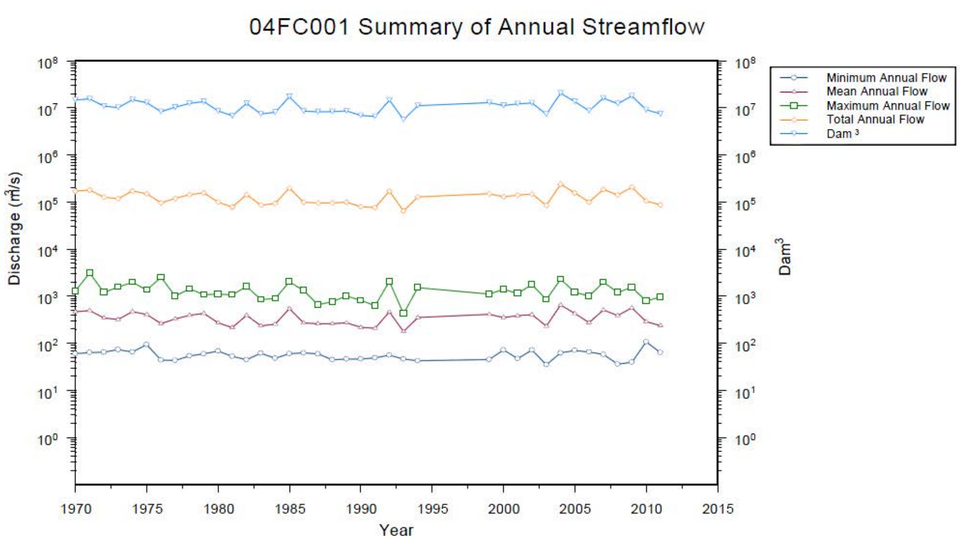

Figure 4. Superimposed Graph of Streamflow Regime

With the watershed along the associated map layers overlaid and displayed, now let us focus on the analysis of the streamflow time series data. Common to any data analysis, the summary statistics of the realizations are provided. This include the sample size (number of daily stream flow values), the mean, the standard deviation, the minimum value, the first quartile (Q_1), median, the third quartile (Q_3) and the maximum value. Further to that, to gain the complete picture and history of the flow regime, the minimum, the mean, the maximum and total annual streamflow along with the total volume of stream flow (expressed in dam^3) for each year are superimposed. A sample of the five superimposed graphs is illustrated in Figure 4. One of the derivatives that can be generated from the summary data is the Flow-Mass curve also called the Ripple curve (Subramanya (1994). Use of the Flow-Mass curve may be referred from scientific literature.

4.3.3 Mean Annual Runoff and Base Flow Index

Mean Annual Runoff is the depth of water averaged (depth-equivalent discharge) over the watershed drainage area and is expressed in millimeters per year. It is computed using the equation:

Mean Annual Runoff (mm) = (Mean Annual Flow (m^3/s) * 31536)/ Drainage Area (sq.km)

where the number 31536 is the conversion factor used to express the runoff as equivalent depth of water. This method (i.e. normalizing with the drainage area and manipulating it with the time factor (here annual)) of expression is useful (1) when considering the water balance of the watershed: precipitation, runoff and the losses/storage in mm, and (2) comparing watersheds with varying drainage area.

Mean Annual Runoff is also referred to as water yield, and Statistics Canada uses the same terminology to provide estimates of stocks of water assets for Water Accounts. The value is used for complementing the economic decision making process (Statistics Canada, 2003).

Base flow is the portion of streamflow that comes from "the sum of deep subsurface flow and delayed shallow subsurface flow" (Wikipedia, accessed January 2014). Base flow separation is often used to determine that portion of a streamflow hydrograph which occurs from base flow, and the portion that occurs from overland flow. To measure the proportion of flows, Base Flow Index is used and is the ratio of the base flow to the total streamflow. The value ranges from 0 to 1.

Streamflow Analysis and Assessment Software (SAAS) version 3 (http://people.trentu.ca/rmetcalfe/SAAS.html) is used to estimate the Base Flow Index for the period of record. The software uses the recursive digital filtering technique of Nathan et al. (1990), which may be referred to for more details.

4.3.4 Flow Duration Curve (Annual and Monthly)

It is well known that streamflow varies over a calendar/water year and the flow duration curve (FDC) is one of the versatile analytical tools used to study this variability. An annual FDC is derived from the complete time series of the streamflow to provide information for the entire range of streamflow. It re-orders the observed hydrograph from one ordered by time to one ordered by magnitude. Other than annual FDC, either a longer or shorter interval (monthly, weekly, mean monthly etc.) may be selected for the construction of the FDC depending on the utility.

The FDC can be defined as a curve that provides the relationship between any given discharge value and the percentage of time that this discharge is exceeded. In other words, it represents the relationship between the magnitude of flow and the frequency of streamflow discharges, and it disregards the sequence of occurrence. It is drawn with streamflow values arranged from highest to lowest (y axis) and percent exceedance (x axis) at each interval.

Exceedance Probability (P) is expressed as:

$$P = 100*[M/(n+1)]$$

Where P = the probability that a given streamflow will be equalled or exceeded (% of time)

M= the ranked position on the listing (dimensionless)

n = the number of events for the period of record (dimensionless)

It is recommended to construct a FDC with record lengths greater than or equal to 20 years of data. Uncertainty will decrease with an increase in the record length. A standard annual FDC is shown in Figure 5.

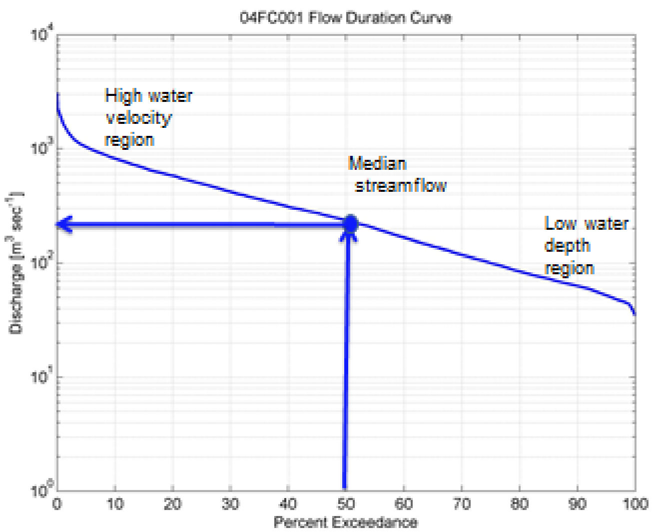

Figure 5. Standard Flow Duration Curve

Area under the curve gives the mean, and 50% exceedance gives the median streamflow. A greater difference between the median and mean streamflow indicates that the data series is highly skewed. Using the FDC, a water resource can be assessed for dependability in terms of % exceedance and the extent in terms of magnitude for a watershed. For example, in Figure 5, for 90 % of time XXX cms of discharge is available for use.

If each of the exceedance values are divided by the area under the curve or in other words the mean streamflow and plotted, the reduced dimensionless curve will have similar shape as the original curve with the area under the curve being unity (same as a normal distribution curve). This property is widely used for the construction of dimensionless regional FDC and to further construct the FDC for ungauged sites. It is also used for selecting similar watersheds.

Some of the important exceedances and characteristics of interest for FDC's are as follows:

- The shape of the FDC reflects the composite effect of physiographic (including geologic) and climatic influences on streamflow and hence watershed response. Walton (1965) studied the shape of the FDC as an index of the effects of geology of a watershed on streamflow. For that he used the ratio $(Q_{25}/Q_{75})^{1/2.}$ This ratio is referenced in the report entitled "An Assessment of the Groundwater Resources of Northern Ontario" published by The Ontario Ministry of the Environment in 2002.
- The slope of the FDC at each extreme end shows the high flow and low flow variability. The slopes at the upper extreme end give information about the flood flows and that of the lower extreme is representative of low flows and surficial geology. The slope also depends on the time interval.
- The 10:90 exceedance ratios are used for comparing extreme flow values. This ratio compares the extremes of flows: the flood flow and low flow, and provides the knowledge of the watershed storage capacity and ground water discharge.
- The high water velocity considerations at lower exceedance (e.g. 5%) magnitudes and low water flow depth considerations at higher exceedance (95%) are key elements to ecosystem modelling.
- Burn et al. (2008) studied the processes, patterns and impact of low flows across Canada. In their study, Low Flow Index (LFI) was derived based on values from the FDC. The LFI is estimated as the ratio of the average of 90 and 75 % exceedance to the 50 % exceedance (average $(Q_{90}, Q_{75})/Q_{50}$).
- For water budget studies, the magnitude of streamflow at exceedance of 90 %, 80%and 50% are recommended in the Water Budget and Water Quantity Risk Assessment Guide (2011), published by Ontario Ministry of Natural Resources and Ontario Ministry of Environment.

The above mentioned matrices are also used for inter-watershed comparison for its response to hydrologic events.

Some of the uses of the FDC are as follows:

- The FDC is the most important data product for assessing hydropower generation capacity of a stream and designing a hydropower system. It is the oldest and most widely used tool for an economic feasibility study prior to the installation. This is because power generated is a function of discharge and head. It also provides information on the storage required for optimal operation (i.e. the peak and off-peak demand of energy). Annual FDC's are used for designing the system and a finer time interval (monthly) data product is used to plan for the critical (low flow) months of operation. Firm flow (compensation flow, 90% exceedance flow) and residual flow (total streamflow minus firm flow) are some of the derivatives that are generated from the main FDC for hydropower studies.
- In evaluating various dependable flows for watershed management for engineering projects and water resources allocation.
- Computing the sediment loading on the stream.
- For water quality studies for both industrial and agricultural pollution.
- The regional FDC is used for constructing daily streamflow hydrographs for ungauged sites (Hughes and Smakhtin, 1996).
- For ecosystem protection and amenities by ensuring adequate water depth and/or velocity even when rates of streamflow are low.
- The FDC is used to study anthropogenic influences and also climate change scenario in the watershed.
- The FDC is used to compare different scenarios like pre and post development for land use changes.
- For development of habitat duration curves to check whether optimal habitat conditions exist for a target species and life stage (e.g. Habitat modelling using PHABSIM software).

Even though the FDC condenses a wealth of complex hydrological information in the graphical form, the main limitation of the FDC is that the serial structure of the streamflow is ignored. In other words, the autocorrelation of the streamflow time series is not represented (Vogel et al. (1995)).

Streamflow Analysis and Assessment Software (SAAS) version 3 is used for the generation of monthly and annual FDC. Within SAAS, the period of record method is used for the construction of FDC.

4.3.5 Flood Frequency Analysis

Please refer to the details of the analysis for the Technical Report

Flood Flow and Low Flow Statistics (https://www.javacoeapp.lrc.gov.on.ca/geonetwork/srv/en/main.home?uuid=1bcabfe3-47ed-461b-ac00-653c365b53f2).

4.3.6 Low Flow Frequency Analysis

Please refer to the details of the analysis for the Technical Report

Flood Flow and Low Flow Statistics (https://www.javacoeapp.lrc.gov.on.ca/geonetwork/srv/en/main.home?uuid=1bcabfe3-47ed-461b-ac00-653c365b53f2).

4.3.7 Flood/Low Flow Analysis above/below a Threshold Streamflow Value for Baseline Information on Climate Change

Climate change studies have become an integral part of any watershed development work. Baseline information about both the extreme streamflow (flood and low flow) above/below threshold streamflow values should be generated. This is done in accordance with the report “Guidelines on Analysis of extreme in a changing climate in support of the informed decisions for adaptation.”(WMO, 2009)

A short technical description of the theory, assumptions and application is given below. The traditional statistical method uses the Central Limit Theorem according to which all the data of the distributions are fitted. Then capturing and understanding the tail behavior (extreme values) is restrictive. In the 1920s, Fisher and Tippet derived the extreme value (minimum/maximum) distribution in a random sample. Since then, in order to study extremes, the Extreme Value Theorem (EVT) is used. A model developed using the Extreme Value Theory for hydrologic studies is the Peak Over Threshold/Point Process method. This approach combines the number of times at which high-threshold exceedances occur by Poisson process (λ) and the number of excess values over the threshold by the Generalized Pareto Distribution (μ, σ ,and ξ). It is also called the Poisson-Generalized Pareto model. The descriptive statistics include location, scale and shape. Similar to the mean and standard deviation of a normal distribution, the location parameter specifies where the distribution is centered and the scale parameter represents the spread. They have the same units as the random variable (streamflow) and the shape parameter is dimensionless.

The extreme value theory assumes that the process is stationary. A stochastic process is stationary if for every collection of time indices 1 ≤ *t1* < *…*< *tm* the joint distribution of (*xt1, …, xtm*) is the same as that of (*xt1+h, … xtm+h*) for *h* ≥1. This would imply that:

- Location (mean) does not change over time
- Scale (standard deviation) does not change over time
- Shape does not change over time

The application of the extreme value theory is done by testing whether the data is stationary or not. This is achieved by taking a data set with the whole distribution as the reference/datum (ensemble) and then having a partial duration series (realizations) by creating sub sets of the whole distribution.

If the watershed has not undergone any changes over time, then the values of the parameters of the reference and the sub sets remain the same. The change may be a shift in mean (location), increase in variance (scale) or change in the shape. In real situations a change is a combined effect, where all the three parameters are changing. Student *t*-test is used to detect these changes. The present information reported in this document provides the values for the period 1970-2012, and can be used in the future for detecting climate change.

The numerical values of location, scale and shape along with the standard error for above/below a threshold for both flood flows and low flows are reported. The principal attributes of exceedance, namely rate of exceedance and extremal index are also included. The rate of exceedance gives the frequency of occurrences. The inverse of extremal index gives the cluster in time. As hydrological events take place in clusters, it signifies the length of the cluster or in other words the short term dependency of events.

The software used for the Extreme Value Analysis is the Extremes Toolkit (“extRemes”), Weather and Climate Applications of Extreme Value statistics, a package from the open source software R (http://www.assessment.ucar.edu/toolkit/). For more details about the software and theory please refer to the User Manual.

4.3.8 Timing of Maximum/Minimum Flows

The timing (month) of the annual minimum and maximum streamflow were plotted as histograms based on the counts for the entire period of record (Caissie et al. (2009)). This helps to understand the month of occurrence and the modularity (usually unimodal or bi-modal) of the events. The month of occurrence gives insight into the type/cause of drought (winter/summer/mixed) (Wayen and Woo (1987), Hulley et al. (2014)) or flood (spring freshet/summer thunderstorm/fall runoff). Besides, a study on the series can infer information about whether there is a forward/backward shift in timing of these extreme annual events. A sample histogram is shown in Figure 6. The months reported are directly taken from WSC’s archived data. The timing of ice conditions are given in the next section.

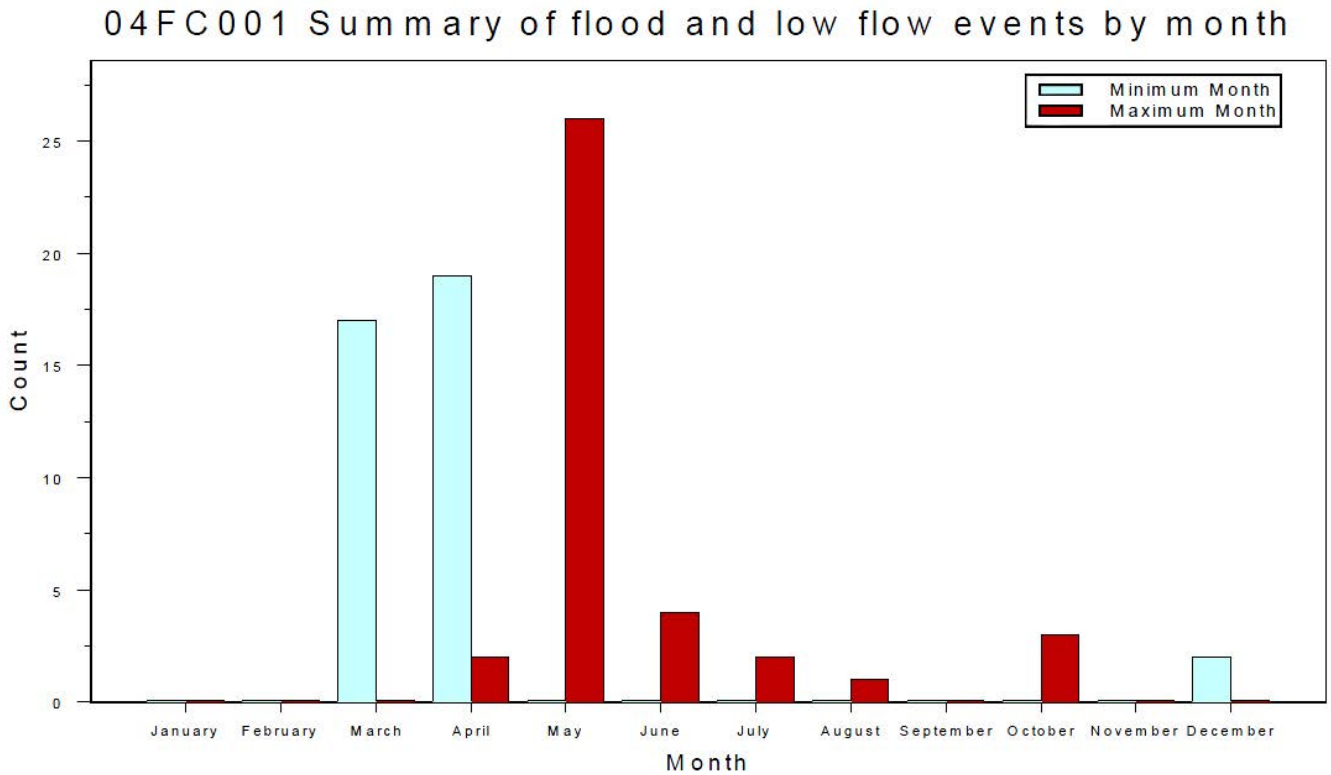

Figure 6. Histogram Showing the Count of Flood and Low Flows for Each Month

4.3.9 Ice Condition

Ice conditions abbreviated as "B" by WSC's archived data was summarized for each winter season (i.e. usually start by October and end by the April of the following year). The start date and the end date together with the number of days for each year is given in the database. The Appendix A has the earliest start and end of ice days for the period of record and the minimum, the median and the maximum number of iced days. This information is useful as ice-cover is influenced by climatic parameters of the watershed (Beltaos and Burrell (2003)).

5 Results

The result of this study is categorized into three parts.

1. WSC's HYDAT stream gauge information in Appendix A
2. Overall review and summary statistics at the primary watershed scale in Section 5.2
3. Streamflow regime data package in Section 5.3

5.1 WSC's HYDAT Gauge Information

This part focused on each of WSC's HYDAT gauges with respect to frequency, timing, duration and magnitude (also referred as streamflow matrix). The analysis is done for gauges that are active and has more than 10 years of record, and the results are given in Appendix A. Appendix A consists of the physical unit of study, the watershed with its elements and the baseline statistics for each of the watersheds. For gauges with less than 10 years of record, only summary statistics is provided and is given in the Section 5.3.

5.2 Overall Review and Summary Statistics and the Primary Watershed Scale

The previous section looked at different streamflow matrices at the WSC's HYDAT gauge locations. Some of these matrices can be standardised to provide a conservative measure at the primary watershed scale: in simple terms a semi-regional perspective of the streamflow regime. Few of these matrixes are regressed with the drainage area so that a value from a particular location can be transformed to a value at an ungauged location.

A consolidated analysis of streamflow at the primary watershed scale for the Southwestern Hudson Bay and Nelson River watershed system is studied in terms of:

- Flood Characteristics and Envelope Curves
- Drought Characteristics and Envelope Curves
- Analysis of Flow Duration Curve
- Mean Annual Flow/Runoff
- Base Flow Index

The flood/drought characteristics and the envelope curves are already available in the Technical Release of “Flood Flow and Low Flow Statistics: For the Southwestern Hudson Bay and Nelson River Watershed Systems” (Flood Flow and Low Flow Statistics, https://www.javacoeapp.lrc.gov.on.ca/geonetwork/srv/en/main.home?uuid=1bcabfe3-47ed-461b-ac00-653c365b53f2), therefore the analysis is not repeated in this document.

5.2.1 Analysis of Flow Duration Curve

The FDC for each HYDAT gauging station was characterized with the 10:90 exceedance ratios to see the high flow low flow variability and the shape of the curve with the square root of (Q_{25}/Q_{75}) exceedance. Figure 7 explains the parameters. It is seen that gauges 04KA001, 04LK001 and 04DC002 have high 10:90 exceedance ratio and the gauge 04LK001 has high square root of (Q_{25}/Q_{75}) exceedance from other gauges.

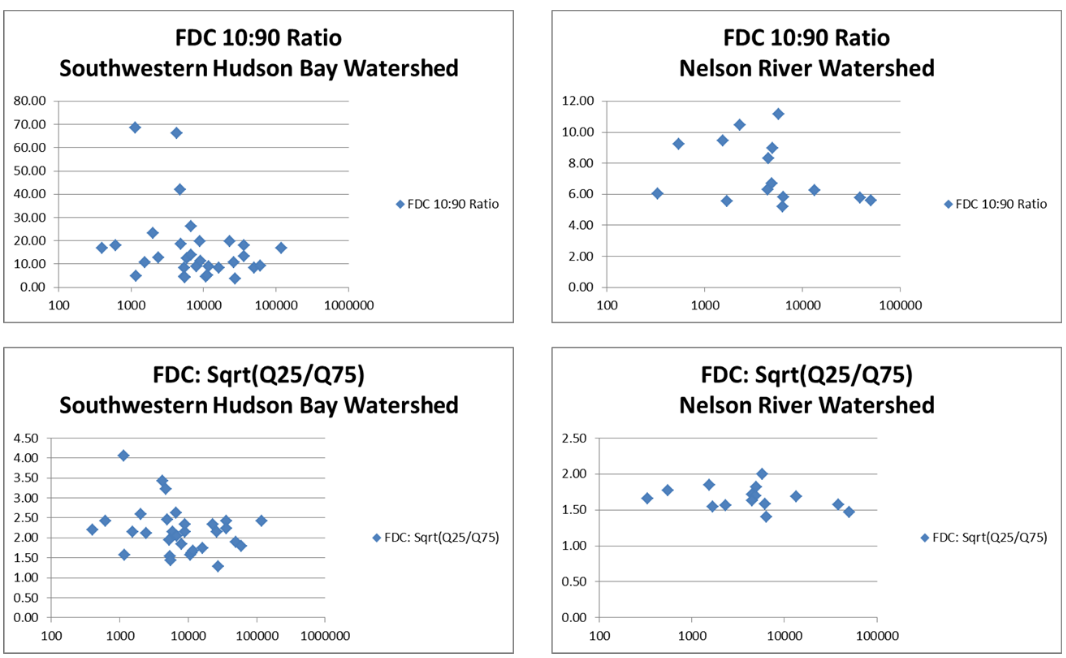

Figure 7. Summary of Flow Duration Curve

5.2.2 Mean Annual Flow/Runoff

Mean annual flow is regressed with the drainage area for all watersheds where the drainage area < 2000 sq.km and > 2000 sq.km. Figure 8 illustrates the relationship of mean annual flow as a function of drainage area. This power function is in Table 2.

Drainage Area < 2000 sq.km (sample size: 9)	Drainage Area > 2000 sq.km (sample size: 37)
$y= 0.0105x^{0.9865}$; $R^2 = 0.9386$	$y= 0.0225x^{0.8606}$; $R^2 = 0.8413$

Table 2. Relationship between Mean Annual Flow and Drainage Area

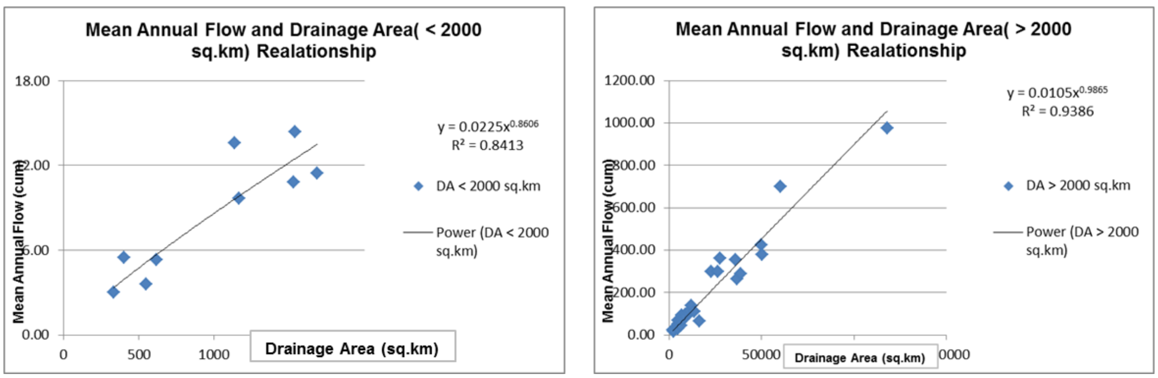

Figure 8. Mean Annual Flow and Drainage Area

Mean Annual Runoff for each gauge is estimated and plotted against drainage area. The graph (Figure 9) showed a clustered pattern with the value ranged between 123 mm to 448 mm.

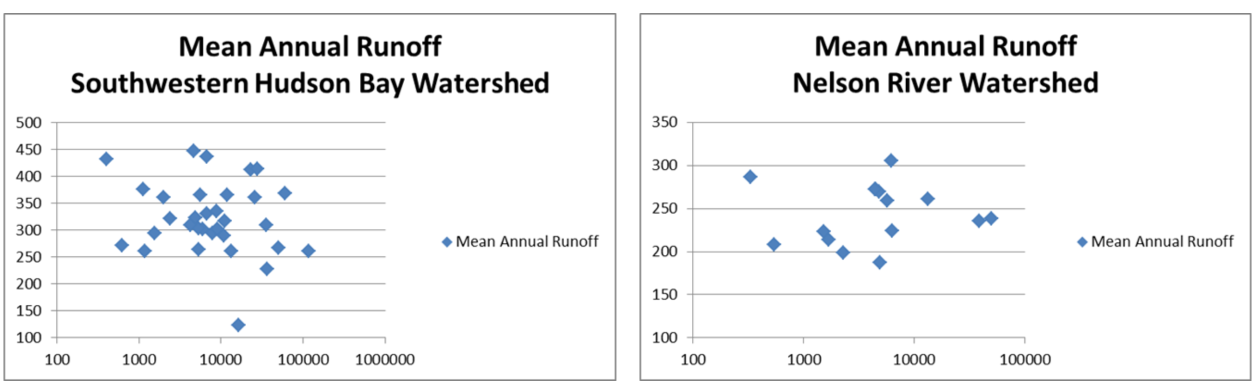

Figure 9. Summary of Mean Annual Flow

5.2.3 Base Flow Index

Base flow index (BFI) for each of the watersheds is plotted against the drainage area and is shown in Figure 10. The graph also showed a clustered pattern with the value ranging between 0.391 and 0.835.

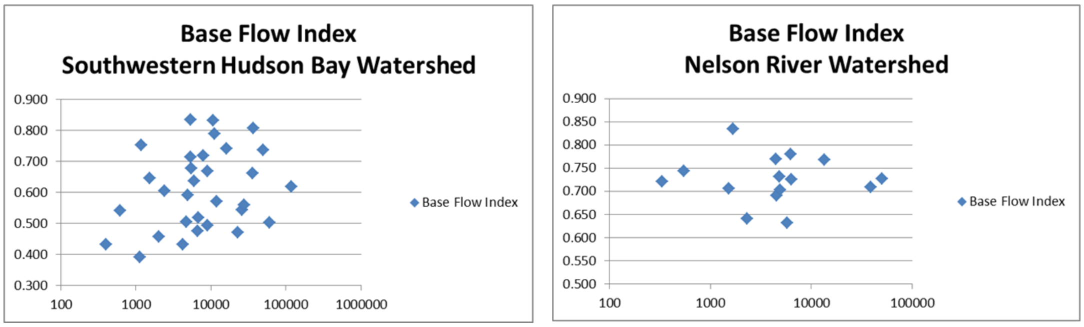

Figure 10. Summary of Base Flow Index

The numerical values of the mean annual flow, the mean annual runoff, the base flow index and the FDC derivatives: 10:90 exceedance ratios and the square root of (Q_{25}/Q_{75}) exceedance for each gauge location with the corresponding drainage area are given in Table 3.

HYDAT	Drainage Area(Sq.km)	MAF (cms)	MAR(mm)	BFI	FDC 10:90	FDC:Sqrt(Q25/Q75)
04CA002	36500	262.97	227	0.806	18.06	2.42
04CA003	619	5.34	272	0.541	18.06	2.42
04CB001	10800	99.43	290	0.832	4.57	1.56
04DA001	5960	57.06	302	0.636	12.48	2.15
04DB001	7950	74.19	294	0.719	8.98	1.85
04DC001	50000	423.00	267	0.736	8.30	1.89
04DC002	4710	66.86	448	0.506	42.11	3.23
04FA001	9010	86.26	302	0.669	11.34	2.15
04FA002	1540	14.38	294	0.645	10.63	2.15
04FA003	4900	50.11	322	0.590	18.71	2.46
04FC001	36000	353.24	309	0.663	13.21	2.23
04GA002	5390	44.99	263	0.835	4.50	1.53
04GB004	11200	112.42	317	0.789	5.13	1.63
04GB005	1170	9.68	261	0.753	4.85	1.57
04GC002	16300	63.35	123	0.742	8.26	1.74
04HA001	118000	975.19	261	0.619	16.99	2.42
04JC002	2410	24.55	321	0.606	12.82	2.12
04JD005	2020	23.14	361	0.456	23.22	2.60
04JF001	5360	51.44	303	0.714	8.37	1.94
04JG001	26200	299.59	361	0.544	10.63	2.15
04KA001	4250	41.71	309	0.431	66.28	3.43
04LA002	5540	64.14	365	0.676	4.31	1.43
04LD001	11900	137.57	365	0.571	8.84	1.68
04LF001	6760	70.99	331	0.519	13.86	2.04
04LG004	60100	701.78	368	0.504	9.40	1.79
04LJ001	8940	95.15	336	0.493	19.67	2.34
04LK001	1140	13.57	375	0.391	68.55	4.05
04LM001	22900	299.84	413	0.470	19.67	2.34
04MD004	401	5.49	432	0.432	16.73	2.20
04ME003	27500	360.52	413	0.559	3.62	1.28
04MF001	6680	92.56	437	0.477	26.33	2.63
05PA006	13400	110.73	261	0.769	6.24	1.69
05PA012	4510	38.89	272	0.691	8.31	1.72
05PB014	4870	41.58	269	0.732	6.70	1.69
05PB018	332	3.02	287	0.722	6.05	1.66
05PC018	50200	378.83	238	0.727	5.58	1.47
05PC019	38600	288.78	236	0.709	5.77	1.57
05QA002	6230	60.41	306	0.780	5.22	1.58
05QA004	4450	38.43	272	0.770	6.28	1.63
05QC001	4920	29.18	187	0.703	8.98	1.82
05QD006	6370	45.34	224	0.725	5.82	1.40
05QD016	2300	14.45	198	0.641	10.47	1.57
05QE008	1690	11.47	214	0.835	5.55	1.54
05QE009	1530	10.84	223	0.707	9.47	1.84
05QE012	548	3.61	208	0.744	9.25	1.77
05RC001	5730	47.10	259	0.631	11.17	2.00

Table 3. Summary Information of Mean Annual Flow/Run off, Derivatives of Flow Duration Curve and Base Flow Index

5.3 Streamflow Regime Data Package

All of the estimated streamflow statistics are included in an accompanying Microsoft Access database named “BaselineHydrology.mdb”. The database consists of two GIS point shape file named “Gauges_Greater10Yrs.shp” and Gauges_Less10Yrs.shp” that stores the HYDAT coordinates (longitude and latitude). The details of the baseline hydrology data files are given below in Table 4.

Name	Type	Information
Gauges_Greater10Yrs	Point shapefile	Gauge locations for > 10 years of record
Gauges_Less10Yrs	Point shapefile	Gauge locations for < 10 years of record
FlowDurationCurve	Table	Flow duration curve (annual and monthly)
GaugeInformation1970_2012	Table	Information on the record
MeanAnnualFlow	Table	Mean Annual Flow
SummaryInformation	Table	Information on minimum, mean and maximum flow, timing, ice days, total flow and dam^3
SummaryStatistics	Table	Summary Statistics of gauges with 10 years of record
ThresholdExceedance	Table	Information on flood low flow threshold exceedance
PrimaryWatershedSummary	Table	Information on MAF, MAR, BFI, FDC derivatives and drainage area

Table 4. Feature Data Sets Included in the Personal Geodatabase “Baseline Hydrology.mdb”

6 Recommended Data Uses and Considerations

6.1 Recommended Data Uses

The baseline hydrology data product can be used for a wide range of business uses in the Far North. Some application areas are: land use planning, integrated watershed management, climate change studies, hydropower studies, etc.

The monthly and annual flow duration curves and the mean annual flow of HYDAT gauges of the Southwestern Hudson Bay and Nelson River watershed systems are displayed within the OFAT (Ontario Flow Assessment Tool) web application (http://www.giscoeapp.lrc.gov.on.ca/web/mnr/wrip/ofat/Viewer/viewer.html).

6.2 Data Use Considerations

- The estimated values are only for active HYDAT gauges from 1970 and onwards.
- The flow values in the regulated gauges are not converted to natural flows.
- The estimated values are only for the HYDAT gauge locations, not for ungauged locations of a river reach.
- The HYDAT gauge locations, coordinates, are snapped to the river network in OFAT. The drainage area as given by the WSC and that from OFAT may differ slightly.

7 Definitions

Base Flow Index

Base Flow Index is the ratio of the base flow to the total streamflow. The value ranges from 0 to 1.

Flood Frequency

Flood frequency is the relationship between flood magnitude and the probability that a flood of that size will be exceeded.

Flow Duration Curve

Flow Duration Curve represents the relationship between magnitude and frequency of streamflow exceedance. It disregards the sequence of occurrence. It is drawn with streamflow values arranged from highest to lowest (y axis) and percent exceedance (x axis) at each interval.

Low/Drought Frequency

Drought frequency is the relationship between drought severity and the probability that a drought of that severity will not be exceeded.

Mean Annual Flow

Mean annual streamflow (cubic meter per second) is the average streamflow if there are daily streamflow values for the complete year.

Mean Annual Runoff

Mean Annual Runoff is the depth of water averaged (depth-equivalent discharge) over the watershed drainage area and is expressed in millimeters per year.

Watershed

Watershed is defined as the area of land that drains the runoff water to the outlet/pour point. The horizontal projection of this area is called the drainage area.

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Appendix A: WSC’s HYDAT Stream Gauge Baseline Information

The information for each WSC’s HYDAT gauge is in a separate document.