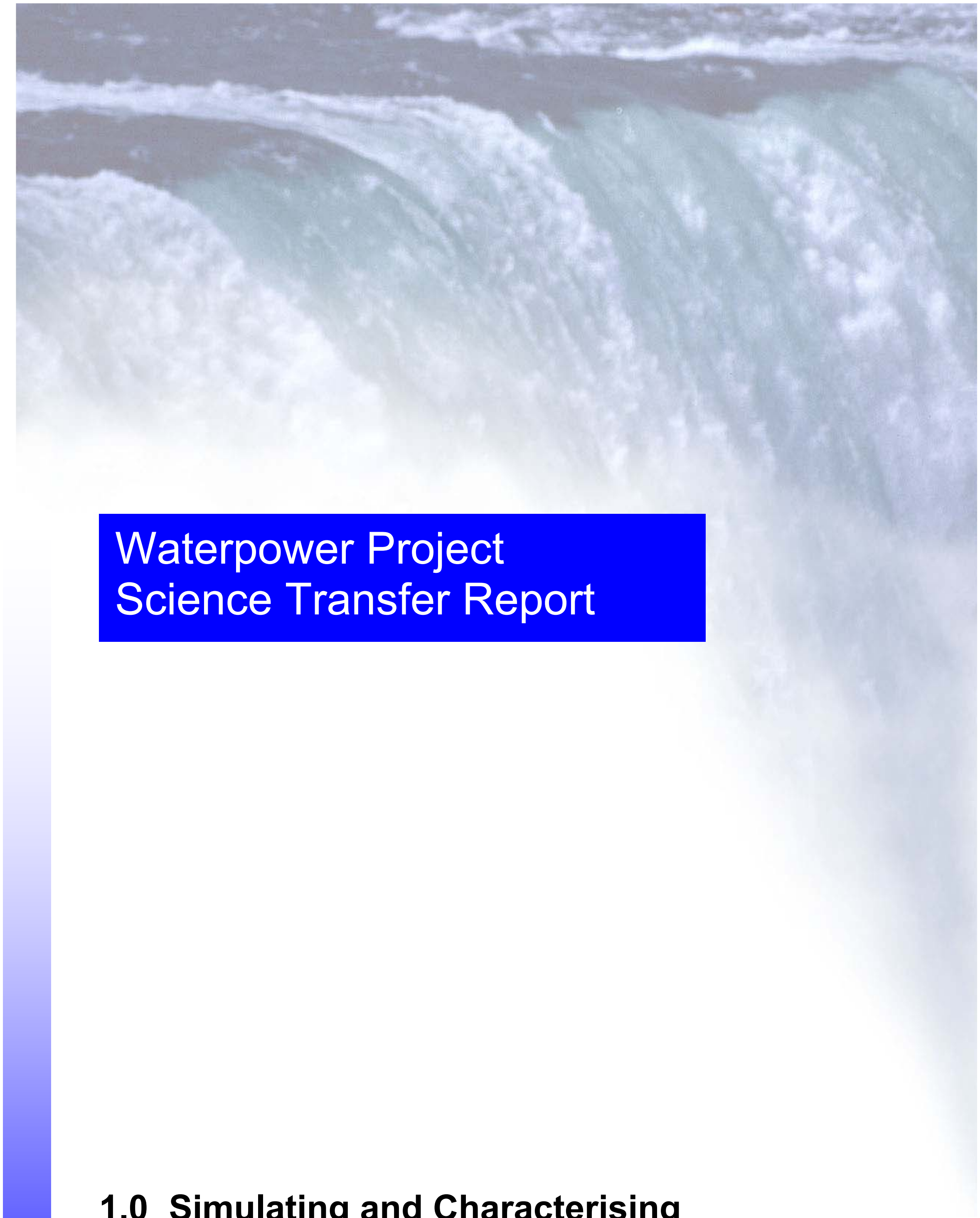

Waterpower Project Science Transfer Report

1.0 Simulating and Characterising Natural Flow Regimes

Simulating and Characterising Natural Flow Regimes

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INTRODUCTION

Flow regulation associated with hydroelectric generation results in the imposition of a flow regime downstream of dams that can be significantly different from the natural flow pattern. Regulation changes the distribution of seasonal flows, flow magnitude, duration, frequency, timing of events, rates of flow increase and recession. The degree and type of flow modification depends upon the type and size of a Waterpower Facility (WPF). Modifications range from only subtle changes downstream of *run-of-river* facilities to the profound large diurnal fluctuations downstream of *peaking* facilities, with impacts on the riverine ecosystem varying accordingly. Such modifications are now recognized as one of the primary causes of aquatic ecosystem degradation related to waterpower development (Moog, 1993).

Each aquatic ecosystem requires a certain amount of water to maintain its ecological integrity. In very broad terms, the environmental water requirements of an aquatic ecosystem can be defined as the quantity and quality of water required to protect the structure and functioning of that ecosystem and to ensure the ecologically sustainable development and utilization of the water resource. These requirements are also referred to as ecological flow needs, environmental flow requirements, or instream flow requirements (e.g. Dunbar *et al*, 1998; King *et al.*, 1999). Earlier approaches to estimate environmental water requirements focussed on simple hydrological characteristics (e.g. low-flow of a certain probability of exceedence) to maintain suitable conditions for specific valued aquatic species. More recently, the emphasis has shifted to more holistic approaches that consider the overall flow variability of a natural flow regime and include an assessment of multiple ecosystem components in order to maintain the complete ecosystem function (King *et al.,* 1999). These more holistic approaches, which are becoming recognized as the future direction for prescribing managed flow regimes (Stanford *et al.*, 1996), include the Building Block Methodology (BBM) from South Africa (King and Louw, 1998), the Holistic Approach from Australia (Arthington, 1998), and the Natural Flow Regime from the United States (Petts, 1996; Poff *et al.*, 1997; Richter *et al.*, 1997).

The natural flow regime is the long term unregulated pattern of flow magnitude, duration, seasonality, and frequency. This pattern eventually determines the functions, integrity and biodiversity of the aquatic ecosystem (Poff *et al.*, 1997). Therefore the concept of the holistic management approach is to identify and reinstate important components of the natural flow regime into the managed system to maintain and enhance the ecological integrity of the riverine ecosystem. In order to develop environmentally sustainable flow recommendations for WPFs in Ontario an important first step is to establish the natural flow patterns at WPFs in the form of continuous daily flow time series. From this time series, ecologically important hydrological characteristics can be estimated and an ecologically justified modified flow regime recommended.

To describe the natural flow regime of a river observed historical flow records or simulated continuous flow time series can be used. Given the scarcity of observed historical records for unregulated streamflow at WPFs and control dams in Ontario, methods and models are required to estimate flow characteristics at these ungauged sites. Hydrological estimation in ungauged basins has been a challenge of hydrological science. Simulations of continuous natural daily flow time-series can be produced using semi-distributed deterministic rainfall-runoff models, or by spatial interpolation and regionalisation methods using available observed flow and precipitation data and their associated daily Flow Duration Curves (FDCs). FDCs show the proportion of time a flow value is equaled or exceeded and, by incorporating the complete range of river flows, provides the most informative summary of a flow regime (Searcy, 1959; Vogel and

Fennessey, 1995). Daily flow simulation methods using these latter techniques have been the focus of considerable research in South Africa for the specific purpose of conducting instream flow assessments (Hughes and Smakhtin, 1996; Smakhtin *et al.*, 1997; Smakhtin, 1999; Smakhtin and Masse, 2000). Results from these studies suggest that spatial interpolation and regionalisation methods using FDCs offer an initial, pragmatic approach for simulating natural flow regimes.

The methods of Smakhtin have been used to simulate natural flow regimes for numerous waterpower facilities and control dams across the province using a minimum of 20 years of historical flow data from the Water Survey of Canada's HYDAT database. These simulations are used for subsequent calculation of hydrologic metrics, including target metrics identified in the Aquatic Ecosystem Guidelines (AEGs) (OMNR, 2002) and Waterpower Science Strategy (OMNR, 2001).

METHODOLOGY

1. Simulating natural flow regimes using spatial interpolation methods

A summary of the spatial interpolation method is provided below. Details of the methodology are provided by Hughes and Smakhtin (1996), Smakhtin *et al.* (1997), Smakhtin (1999), and Smakthin and Masse (2000).

In essence the spatial interpolation method assumes that flows occurring simultaneously at sites, which are reasonably close to each other and hydrologically similar, correspond to similar percentage points on their respective FDC's. Locations requiring a simulated streamflow time series our referred to as destination sites. The gauged locations with available streamflow time series that are used for generating data at ungauged sites are referred to as source sites. Simply, the procedure is to transfer the streamflow time series from the location where the data are available to the location where the time series is needed (i.e. a WPF). The methodology includes three sequential steps: 1) Estimation of a representative regional non-dimensional FDC; 2) Calculation of the actual FDC at the destination site by multiplying the non-dimensional curve by the long-term mean discharge at that site; and 3) Conversion of an actual FDC at a site into a continuous streamflow hydrograph using the spatial interpolation technique.

Step 1: Generation of a regional flow duration curve (FDC)

A representative "regional" FDC may be established by selecting a gauged site with long-term unregulated discharge observations, which is relatively close to the ungauged site(s) of interest and demonstrates a similar pattern of flow variability. The ordinates of the curve are then standardised by dividing flows from the curve by the gauged long-term mean daily flow.

Alternatively, a few gauged, unregulated, similar sized, catchments in a specified region with reliable and unmodified flow records should be identified. Each "gauged" curve is then standardized by the long-term mean discharge, estimated from the observed record, and the average of all curves is calculated. A regional FDC reflects regional flow variability. Averaging of the non-dimensional ordinates of the curves is done for the 17 fixed percentage points (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 %).

Step 2: Generation of a FDC for the destination site

The next step is to calculate the actual reference FDC for an ungauged WPF site. This is accomplished by multiplying the non-dimensional FDC ordinates (standardised flows) by the long-term mean discharge at an ungauged site. Estimates of long-term natural mean annual flow may be obtained using regional estimation methods available in Ontario (OMNR, 2000; Acres, 1994). These models have been incorporated in the Ontario Flow Assessment Techniques software (Chang *et al.* 2002). Alternatively, if a representative gauged site is close to the WPF site of interest, a FDC at the WPF site may be established using a correction factor as a ratio of the catchment areas (at the gauged site and at the WPF site). In any case, a FDC is represented by a table of 17 fixed percentage points listed above and their corresponding flows. Each standardized flow is multiplied by the selected correction factor and a table of actual flow values for the fixed percentage points is produced.

Step 3: Generation of a continuous streamflow hydrograph for the destination site

Conversion of a FDC into continuous daily time series is accomplished using the spatial interpolation technique of Hughes and Smakhtin (1996). This is not strictly a modelling technique, as it deals exclusively with already available records. The main assumption of the method is that flows occurring simultaneously at sites in a reasonably close proximity to each other correspond to similar percentage points on their respective FDCs. This implies that the source and destination flow regimes will display a certain degree of similarity in the sequence of flows (i.e. if there is a peak flow at the source site, there is also a high flow at the destination site). This may be ensured if the source sites are selected from within the surrounding area in close proximity to the destination. The degree of similarity between each source site and a destination flow regime is arbitrary, ranked by assigning a weighting factor to each source site.

If only one source site is used, the core computational procedure for each day includes: i) Identification of the percentage point position of the source site's streamflow on the source site's FDC; and ii) Reading off the flow value for the equivalent percentage point from the destination site's flow duration curve (Figure 1). If more then one source site is used, the two steps above are repeated for each site, resulting in more then one estimate of the destination site flow on the same day (i.e., if two source sites are used, there will be two estimates). The final destination site flow value on each day is estimated as the weighted average of all estimated destination site flow values, repeated for each day.

For streamflow time series generation at a destination site (WPF site), more than one source site is recommended where possible. The use of several source sites is an attempt to account for the fact that a destination site time series may be the result of several influences, which may not be reflected in a single source site time series. Also, part of an individual source site time series may be missing therefore the use of several should decrease the number of missing values in the resultant time series at the destination site.

Additional details about this computational procedure are available from Hughes and Smakhtin (1996) or Smakhtin (2000). Both sources describe a number of case applications of the spatial interpolation approach, illustrate the examples of source site selection, assignment of weighting factors, and examine the implications of both on the resultant destination flow time series.

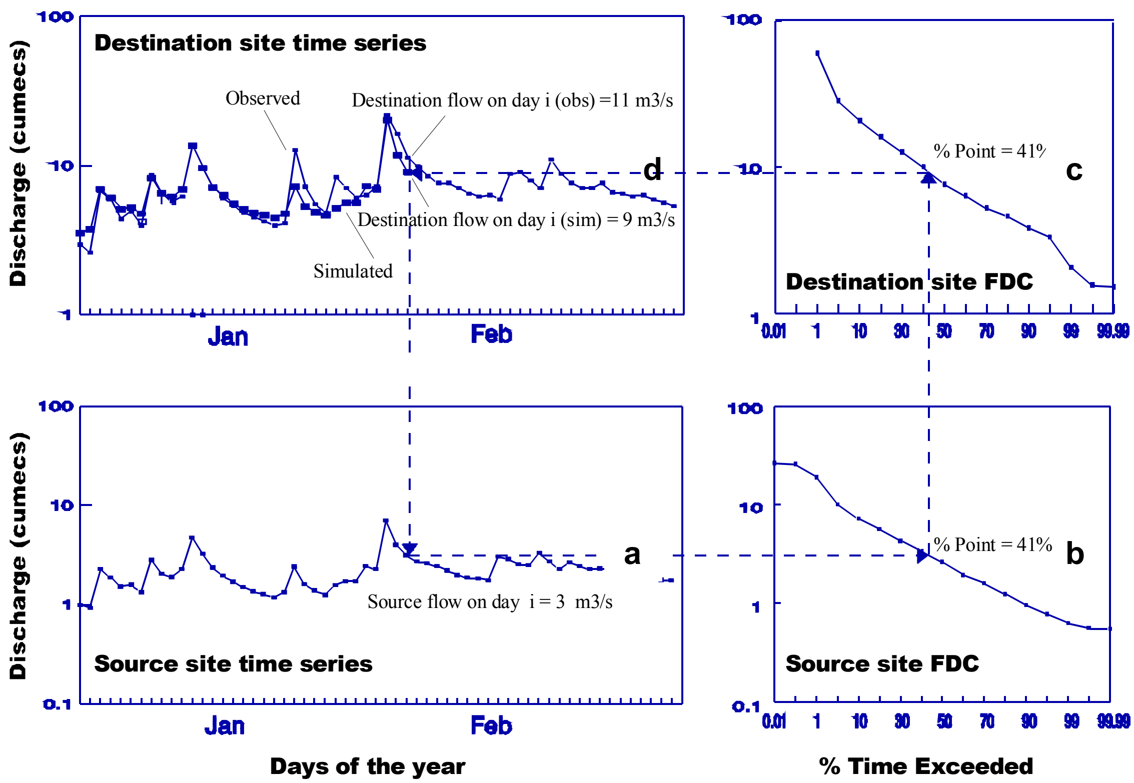

Figure 1. Streamflow generation procedure using an observed hydrograph (a) and position of a daily mean flow on its FDC (b) to find the discharge value associated with the same percentage point on the destination site FDC (c) to create the simulated hydrograph for the destination site (d).

2. Statistical methods for describing flow regimes

Flow metrics from a WPF's simulated time series are calculated using a combination of software packages, including the Hydrological Modelling Application System (HYMAS (v1.10)), Indicators of Hydrologic Alteration (IHA (v.5)) and Consolidated Frequency Analysis Package (CFA (v.3.0)). Table 1 shows the metrics obtained with each software package. An alternative to HYMAS for calculating monthly median flows and measures of dispersion is the Streamflow Toolkit (v.2.0) software; also developed by Environment Canada and available on-line with CFA at the site listed in Table 1. These software packages are not limited to the metrics described here but include many other flow statistics that are valuable for understanding flow regimes.

Table 1. Software used to simulate natural flow time series and to extract flow metrics identified in the Aquatic Ecosystem Guidelines.

Software	Source	Purpose/Metrics
HYMAS v1.10	*Dr. Vladimir Smakhtin* *Principal Scientist:* *Hydrology and Eco-Hydrology* *International Water Management Institute* *Colombo, Sri Lanka*	• *Simulation of natural flow time series* • *Monthly FDCs for deriving monthly median flow and measure of dispersion*
IHA v.5	*Nature Conservancy* http://www.freshwaters.org/eswm/iha/	• *Ramping rates*
CFA v.3.0	*Environment Canada* *(Available through the Watershed Science Centre, Trent University)* http://www.trentu.ca/wsc	• *Flood frequency curve to derive riparian and bankfull flow magnitudes or recurrence interval.*

Key ecological flow components identified in the AEGs and WPSS include minimum flows, riparian flows, bankfull flows and the rate of change of flow. Flow duration (FDC) and flood frequency curves (FFC) (see discussion box) and other methods for quantifying these components are discussed below.

i) Minimum flows

Seasonally variable baseflow conditions in rivers are important for maintaining ecosystem function, where baseflow is defined as the streamflow portion contributed by persistent, slowly varying sources (*i.e.* groundwater, lakes, wetlands) between precipitation events (Dingman, 1994). This flow variability is best represented by median, rather than mean, monthly flows since median values are influenced less by extreme events and thus provide a conservative minimum flow target. Median flows for each month have been extracted from monthly FDCs using the simulated time series. The median flow for each month can be used as a minimum target or the lowest median flow of each season (i.e. Winter, Jan-Mar; Spring, Apr-Jun; Summer, Jul-Sep; Fall, Oct-Dec) can be used to at least incorporate seasonal variation (Petts, 1996). The monthly variability around the median flows is represented by the coefficients of dispersion which are calculated as the 20th and 80th percentile flows from the monthly FDCs. Similar methods have been used by other agencies in the United States (Larsen, 1981, Annear *et al.,* 2002), Altlantic Canada and Denmark (*Dunbar et al.,* 1998).

ii) Bankfull flows

Bankfull flows, also referred to as channel maintenance or flushing flows, are those flows where water just begins to overflow onto the floodplain (Annable, 1996). Optimally, bankfull discharge should be estimated based on field measurements downstream of each waterpower facility undergoing water management planning. Field methods for estimating bankfull discharge are discussed in the Waterpower Science Technical Report: 2.0. Once estimated, the FFC can be used to identify the recurrence interval of the bankfull discharge. Alternatively, where field data is not available, published values of bankfull flow recurrence intervals can be to estimate the associated discharge specific to that site. In a study of 47 rivers in Southern Ontario, Annable (1994) found that bankfull discharges had a recurrence interval between 1.5 and 1.7 years. The discharges related to these recurrence intervals can be identified using the FFC to provide a flow magnitude range for the bankfull flow component. The duration and timing of bankfull flows can be obtained directly from the simulated time series.

iii) Riparian flows

Riparian flows are overbank events that inundate riparian areas, resulting in significant interaction between the channel and floodplain (OMNR, 1994). These events occur between 1:2 year and 1:20 year return periods (OMNR, 1994), or can be determined as flows covering the equivalent of the "confinement area" (Rosgen, 1994). Recommended riparian flows are those that lie within this range (i.e. between the bankfull and the 1:20 year flow), as extracted from the FFC. The duration and timing of bankfull flows can be obtained directly from the simulated time series.

DISCUSSION BOX

Flow duration curves (FDCs) display the proportion of time a flow is equaled or exceeded, providing a complete summary of the frequency of flows from base flows to peak flows (Figure 1b, 1c).

Flood frequency curves (FFCs) provide information on the highest flows in a basin (Figure 2). FFCs are used to predict the average recurrence intervals (years) of high flows of specific magnitudes or the magnitudes of high flows of chosen frequencies. To derive flood frequency curves it is ideal to use the maximum annual instantaneous peak flow for each year of the available record instead of the maximum annual daily mean flow. Although the two values will be very close for larger rivers, the latter will underestimate flow magnitudes in basins with steeper, shorter peak discharges (i.e. "flashier" drainage systems). This should be kept in mind when using the simulated flow series based on daily mean flows. FFCs can be used to determine riparian and bankfull flows based on published return periods as described below.

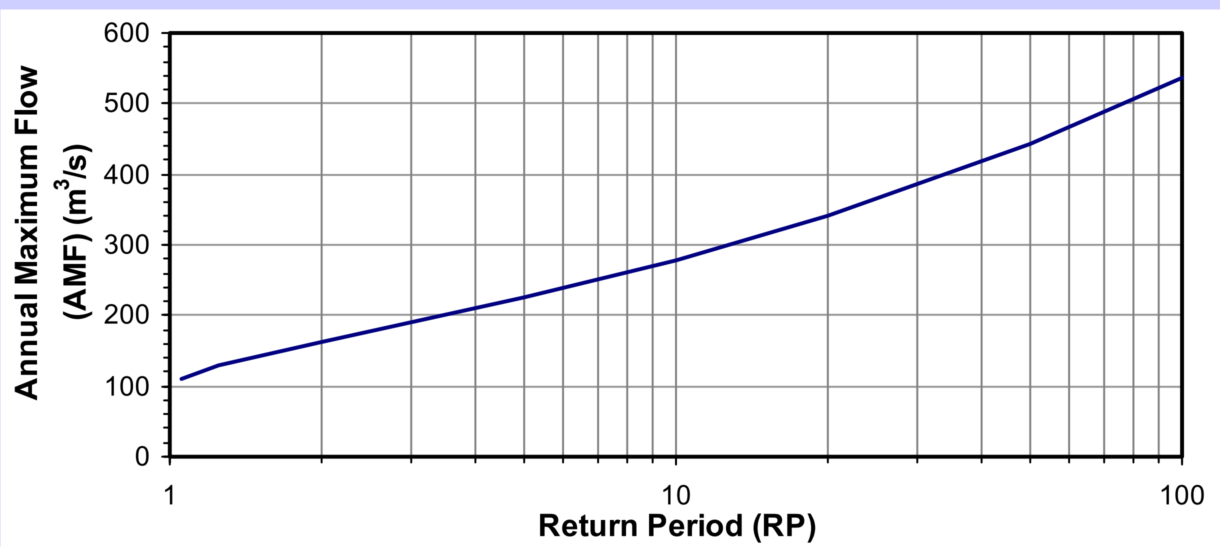

Figure 2. Flood Frequency Curve (FFC) generated using the Log Pearson Type III flood frequency analysis. The FFC can be used to determine target metrics including bankfull and riparian flows.

iv) Ramping rates
Ramping rates are the rate of change of flow either increasing (up-ramping) or decreasing (down-ramping) and are analogous to the rising and falling limbs associated with a rain event on a natural hydrograph. With both HYDAT and subsequent simulated flow time series based on daily mean flows, recommended ramping rates are calculated as the rate of change per day (i.e. m^3/sec/day). The IHA software is used to calculate ramping rates. The software estimates up-ramping and down-ramping rates based on the median values over the entire period of record. Alternatively, rates of change can be calculated manually from the simulated time series for high flows. The influence of data resolution (e.g. hourly vs daily) on the magnitude of rates of change of flow are currently being explored. Generally, rates of change will be less for daily compared to hourly data.

Other flow metrics can be used to provide a more detailed description of a flow regime, thus increasing the understanding of differences between natural flow characteristics and managed flow regimes. Increased knowledge of all flow characteristics provides a sound basis to support flow recommendations, formulating hypothesis of the potential effects of not following or meeting flow recommendations, and interpreting results of an effectiveness monitoring program. These metrics include, but are not limited to, mean annual flows to describe inter-annual variability, the frequency and timing of high flows to provide insight to seasonal variability, and the number of reversals (change in flow from rising to falling or-up-ramping to down-ramping) in the flow time series to describe variability over days.

3. Possible sources of error in simulated flow regimes

It is important to recognize possible limitations and sources of error in every model and the potential influence on the results. Therefore metrics provided based on these data should be examined by users familiar with the systems in question.

A considerable limitation in interpolating recorded flow data to ungauged sites is the availability of source sites in close proximity to destination sites with sufficient years of unregulated flow data. The result is the use of gauges located greater distances from the destination site, challenging the assumption of hydrologic similarity and increasing the potential error in the simulated flow series. There are also problems observed in the early years of many historical flow records (i.e. prior to 1950), resulting in the removal of these flows for the analysis and thus, shortening of the available record.

It is assumed that source sites that are in close proximity to the destination sites are hydrologically similar. To normalize the differences between the source and destination sites correction factors are applied based on Mean Annual Runoff (MAR) and/or basin area. MAR for destination sites are obtained from a regional model using HYDAT flow data to 1995 (OMNR, 2000). Thus error in the simulated time series is sensitive to error in these regionalised values. Opportunities to reduce this source of potential error will occur through increased sophistication of regionalisation techniques using geographical information systems (GIS) and the accumulation of longer flow records.

Although sources of potential error are recognized, an estimate of the magnitude of error is difficult given the lack of gauges for proper calibration. Future calibration may include a comparison of MAR calculated from the simulated time series with estimates of MAR for WPFs from other available sources or approaches. Through the OMNR stream gauge rehabilitation project, several new gauges will be installed and old gauge sites recommissioned on unregulated systems that, through time, will provide additional source site time series data for flow simulations, reducing the potential error in the simulation.

Although there will be error in simulating the magnitude of discrete discharge values in a time series, this is partially addressed through the subsequent use of summary statistics and measures of dispersion to describe the flow record. Significant errors in the simulated flows caused by using source sites not hydrologically similar to the destination site are usually readily apparent after a visual inspection of the simulated flows using local knowledge of the river system.

SUMMARY

As indicated in the Science Strategy (OMNR, 2001) and AEG (OMNR, 2002) the chosen holistic methodology is based on the premise that the natural flow regime is able to maintain the complete ecosystem function of a riverine system. Therefore, if important components of the natural flow regime are integrated or maintained in a managed flow regime the ecological integrity of that system will be enhanced or maintained.

Site specific metrics, based on the simulated flows, will be provided for WPFs undergoing water management planning. These data will be summarized in a Flow Metrics Data Sheet for each WPF. Additional site specific information explaining the results of the flow simulations will be supplied in a supporting document. The values provided are considered recommendations that may be integrated into operational regimes to achieve the maximum overall health of the system while still maintaining the needs of its users. It is understood that these values may not meet the needs of all users; therefore it is the role of the planning committees to determine which uses take precedence for each system in question. These data satisfy the key flow parameters of the AEG (OMNR, 2002).

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