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Assessment of Canada's Hydrokinetic Power Potential

Phase I Report
Methodology and Data Review

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EXECUTIVE SUMMARY

Natural Resources Canada (NRCan) has identified a need to assess Canada's hydrokinetic potential as a national renewable resource. To reach this objective a three-phase project was commissioned:

Phase I Methodology Review and Data Review – a review of the methodologies, techniques and available data for conducting a regional hydrokinetic power assessment as well as a selection of proposed methodologies and validation datasets and locations.

Phase II Methodology Validation – the implementation of a recommended set of methodologies against the validation datasets including sensitivity/uncertainty analysis.

Phase III Assessment Determination – the application of the recommended methodologies to conduct a nation-wide assessment on the hydrokinetic potential for theoretical energy extraction.

The National Research Council – Canadian Hydraulics Centre (NRC-CHC) was commissioned to contribute to the first two phases of this project. This report constitutes the findings of Phase I.

Section 1 provides an introduction and outlines the goals and structure of this study of hydrokinetic potential. The project goals are to ultimately characterize and quantify the hydrokinetic power potential in Canada. Section 2 of this report identifies the need to estimate a number of hydrologic and physical characteristics at ungauged channel reaches to provide an estimate of hydrokinetic energy potential:

- Flow characteristics as flow duration curves (FDCs)
- Channel geometry
- Channel slope; and
- Channel roughness.

Section 3 presents the findings from a literature review investigating methodologies for regional estimation of flow, geometry slope and roughness characteristics in ungauged basins. The investigation identified many techniques for flow regionalization but primarily for extreme value estimations. The use of regionalization techniques for FDC estimation, as required for this study, was much less common but some studies existed and a few studies have been recently published with applications in Canada.

The investigation discovered few studies employing channel geometry estimation techniques at a regional scale. Most of the studies related geometry predictions to a channel-forming discharge. Other more promising approaches were identified which relate channel geometries to physiographic watershed characteristics or digital maps that include channel widths for larger rivers. The regional estimation of slope showed a predominance of digital elevation model

(DEM) use in the studies investigated, although limitations and cautions in their use for channel slope estimation were identified by many. Some of the limitations of DEMs, including precision issues in low-relief basins, were shown to be surmountable through the use of fitted equations relating channel slope to watershed drainage area. No appropriate regionalization techniques for the estimation of river channel roughness were identified.

In addition to regional estimation techniques for flow and channel characteristics in ungauged basins, uncertainty and error propagation techniques were investigated.

Section 4 presents the results of a data source review and resource investigation. The section identifies a number of national databases that can be employed to act as inputs and validation datasets for the regionalization routines employed in this study. The data sets include measured or calculated properties at a national scale including regional climate data, hydrometric data, digital soil and land use maps, hydro network maps and digital elevation data. Of particular utility is the Water Survey of Canada measurement database, which includes at-site measurements of velocities and cross sections for thousands of water survey hydrometric stations across Canada. This particular database is seen as invaluable in the validation of the various flow and channel geometry regionalization techniques. No databases were discovered that included information that could be used for roughness or slope validation.

Section 5 presents the findings of an investigation of previous hydrokinetic and small hydropower resource assessment studies conducted at a regional or national scale. Many studies were discovered that assessed hydropower resources, usually requiring an average annual flow and an estimated penstock height, and not requiring geometry, slope or roughness estimates. Fewer studies have investigated regional hydrokinetic energy potential, and none at the scale or as inclusive as suggested in this study. Methodology validation of regionalization techniques was rarely performed in the studies examined.

Sections 6 and 7 outline the recommended approach for Phase II and the associated tasks, respectively. It is recommended that a number of flow regionalization techniques be employed and validated in this study including some conceptually simple methods (e.g. Area-Ratio), commonly employed and endorsed methods (e.g. RETScreen) and methods recently developed and employed by the academic community (e.g. CCA with graphical FDC). The recommended approaches for geometry estimation include the use of digital maps of river edges where available, and the use of physiographic and climactic data to drive regression analysis. Channel slope estimation is recommended to be estimated using available DEM data with the investigation of functional smoothing in low-gradient channels. Finally, lacking any regional data or regionalization techniques, roughness is to be estimated as a potential range of values based on published roughness estimates. Validation and uncertainty estimates are to be employed using jack-knife and bootstrap techniques where applicable.

LIST OF ACRONYMS

AAFC	Agriculture and Agri-food Canada
AFDC	Annualized Flow Duration Curve
CanSIS	Canadian Soil Information System – Agriculture and Agri-Food Canada
CCA	Canonical Correlation Analysis
DEM	Digital Elevation Model
DFO	Fisheries and Oceans Canada
DHR	Determination of Homogeneous Regions
EC	Environment Canada
FDC	Flow Duration Curve
GIS	Geographic Information System
GML	Geography Mark-up Language
HYDAT	Hydrometric Database – Environment Canada, Water Survey of Canada
MAD	Mean Annual Discharge
MAF	Mean Annual Flow
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MAT	Mean Annual Temperature
NASA	North American Space Agency
NHN	National Hydro Network
NIMBY	"Not in my back yard"; an expression of opposition by citizens to local public works or civic projects
NRCan	Natural Resources Canada
NRC-CHC	National Research Council – Canadian Hydraulics Centre
PET	Potential Evapotranspiration
PMF	Probable Maximum Flood
RBLI	Regression Based Logarithmic Interpolation
REEEP	Renewable Energy and Energy Efficiency Partnership
REM	Regional Estimation Methods
RETScreen	Renewable-energy and Energy-efficient Technologies Screening tool – Natural Resources Canada
RHAM	Rapid Hydropower Assessment Model
RMSE	Root Mean Square Error
ROI	Region of Influence regionalization approach.
RPM	Rotations Per Minute
SLC	Soil Landscapes of Canada
TSM	Taylor Series Method
UNEP	United Nations Environment Programme
UPGMA	Unweighted Pair Group Method with Arithmetic mean
US-DOE	United States Department of Energy
USGS	United States Geological Survey
VDC	Velocity Duration Curve
WSC	Water Survey of Canada

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

There is significant interest in hydrokinetic or in-stream river potential in Canada and internationally for power production using 'zero head' turbines, which require no dams or barrages. Canada has a vast network of rivers that have been harnessed for over 100 years to generate electricity from hydropower. These rivers also likely contain significant potential for power production from hydrokinetic resources.

Currently, the market potential for this technology in Canada is unknown. A number of Canadian companies invested in hydrokinetic technologies have attempted to quantify the Canadian potential, but estimates vary widely. Internationally, few studies have been conducted to assess the potential within individual countries with little effort invested in developing adequate methodologies specific to this type of assessment.

Natural Resources Canada (NRCan) has identified a need to assess Canada's hydrokinetic potential as a national renewable resource. The challenge is to determine an accurate method of assessment of the hydrokinetic potential of river reaches at a regional scale (10^4 km^2 to 10^7 km^2) using hydrometric and physiographic datasets currently available.

This fundamental research provides support to developing the hydrokinetic market in Canada. Assessment of resource potential has long-term benefits of building non-commercial knowledge to support both government and industry and assists in the development of hydrokinetic current resources. For industry, knowledge of the potential, and where it is located, are key pieces of information for early market entry by technology and site developers. Government requires this information for policy and decision-making. It will also benefit remote regions where decentralized power production from renewable energy sources is an economically viable option in offsetting the high cost of diesel power production.

The study has been divided into three phases:

Phase I Methodology Review and Data Review – a review of the methodologies, techniques and available data for conducting a regional hydrokinetic power assessment as well as a selection of proposed methodologies and validation datasets and locations.

Phase II Methodology Validation – the implementation of a recommended set of methodologies against the validation datasets including sensitivity/uncertainty analysis.

Phase III Assessment Determination – the application of the recommended methodologies to conduct a nation-wide assessment on the hydrokinetic potential for theoretical energy extraction.

The final reports of all three phases will be made available to stakeholders in the industry and the general public via website access. The primary deliverable following Phase III will include a comprehensive national assessment of hydrokinetic potential.

This report addresses **Phase I** of the study. The main objectives of this phase are to:

1. Review the literature to determine the state of the art in methodologies applicable for hydrokinetic resource assessment at the regional scale;
2. Review the available data for use in estimating hydrokinetic resource potential at a regional scale and the data available for methodology validation; and
3. Recommend a short list of applicable methodologies, validation datasets and locations for Phase II.

The report provides a review of available technologies research and data available to conduct the nation-wide assessment:

a) Flow Estimation Techniques – examine other possible techniques relating to flow in ungauged basins, and transposition of flow duration curves (FDCs).

b) Channel Geometry and Slope Estimation Techniques – review of available techniques applicable to a regional study.

c) Data Uncertainty and Uncertainty Analysis Techniques – examine data uncertainty and uncertainty analysis methodologies in using DEM data, flow records, roughness estimations, channel geometries etc., applicable to a regional analysis, and considering the quantity and character of data to be employed in Phase III

d) Regional Channel Current Estimation Studies – investigation of other studies that have attempted to estimate channel currents at a regional scale or techniques that have been developed that could be used to this effect.

2 BACKGROUND

This section provides background and contextual information on hydrokinetic power nomenclature, hydrokinetic power, sometimes termed "river current," in relation to other types of hydroelectric energy extraction, such as small-scale hydro, and general hydraulic and hydrologic considerations relating to hydrokinetic power assessment.

2.1 Nomenclature

Although not a young science, hydrokinetic power and small-scale hydropower both have an imprecise and varied nomenclature, with similar project types often characterized by different names or descriptors. This section will attempt to briefly summarise the types of classification that will serve as a touchstone throughout this document.

2.1.1 Small Hydro Systems

Hydropower projects are often classified by their power generation potential although there is no universally accepted approach for classifying these systems. The following classifications of hydropower by size have been employed by NRCan [73]:

Table 1 - Hydropower Classification by Power Generation

Classification	Size in kW
Large	>50,000
Small	1,000-50,000
Mini	100-1,000
Micro	<100

Although other published classifications vary slightly from this definition [66, 96, 101] this list remains a useful delineation of the various hydropower project types. It is important to know that the classification type relates to the power generation capacity of the project. For instance, some "small hydro" projects require large turbines if they have a low-head and large volumes of water to operate [66].

Projects can also be defined by the degree of hydraulic head required for operation. Low head hydro has been defined as less than about 15 m with normal or "high head" hydro operations generally having hydraulic head greater than this value [39].

Further to the power generation and the hydraulic head requirements, the way in which the deployments control the flow of water in a river can be used to define the project type. Run-of-river systems refer to hydro projects that do not significantly alter the natural elevation of the water in the river system and the hydraulic head in these systems will fluctuate with changes in the stream flow [66]. Often run-of-river hydro projects will employ a penstock to gain hydraulic head by keeping diverted water at a high elevation and then capturing the potential energy further downstream. Figure 1 illustrates a run-of-river hydropower configuration with a penstock [107].

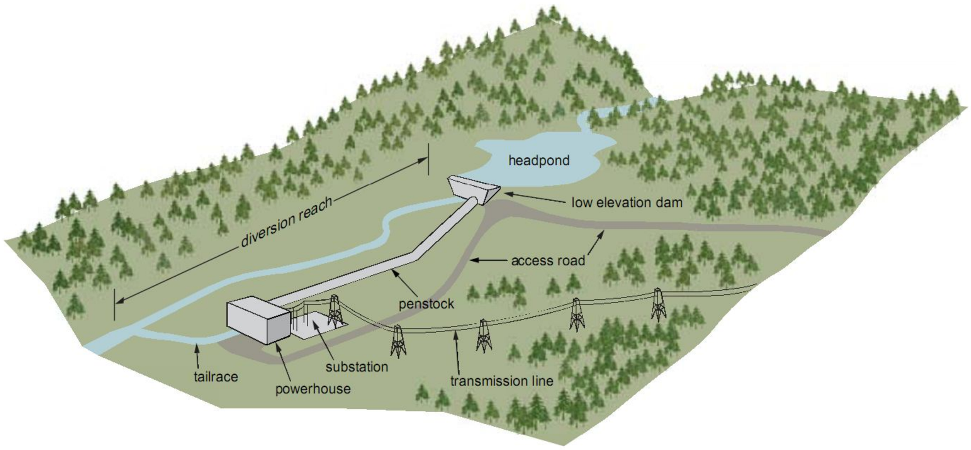


Figure 1 - Run-of-river Hydro project employing a penstock [107]

2.1.2 Hydrokinetic Systems

Hydrokinetic systems convert kinetic energy from flowing water into electricity, or other forms of energy [103]. The resource assessment being conducted in this study is designed to characterize and quantify the energy resource specifically for hydrokinetic systems. There are a number of characteristics that make hydrokinetic energy systems distinct from other hydropower systems [50, 103] in that they:

- Rely on existing kinetic energy in the water stream;
- Do not rely on artificial water-head from impoundments, or barrages;
- Do not require large civil works for implementation; and
- May operate in the water stream's natural pathway and do not require a stream flow diversion.

Figure 2 presents an illustration of a submerged hydrokinetic turbine.

Figure 2 - Kinetic Energy Turbine (verdantpower.com)

Hydrokinetic systems offer a number of advantages over run-of-river and water storage options, particularly with regards to environmental impact and capital cost. For example, civil works required for the development of run-of-river and water storage hydropower often represent the most significant portion of the project development and can often render a project financially unviable [66]. Works not requiring a barrage or similar have a much lower capital cost. However, the efficiencies and power production capacity of hydrokinetic turbines is also lower than run-of-river or water storage hydropower. Hydrokinetic turbines have other ancillary advantages. They may be deployed on an incremental basis, as a single unit or in a clustered configuration. Additionally they remain below the water surface and not as predisposed to NIMBY issues, and have a lower RPM and fewer noise and vibration issues than conventional turbines.

2.2 Resource Assessment Levels

When considering this study it is important to reflect on the degree of investigation that is involved. When considering a location for hydropower or water resource assessment one can divide the developmental into five basic stages [66, 96]:

1. pre-reconnaissance,
2. reconnaissance,
3. pre- feasibility,
4. feasibility, and
5. final design.

The primary difference among them is the degree of confidence one has in the results obtained. The first level, pre-reconnaissance, can be considered a low confidence analysis, but also a low cost and low effort analysis for the results obtained. It involves desk studies, map analysis, drainage area delineation, and is used for narrowing down sites for investigation. Reconnaissance involves site visits, assessments and rankings. The pre-feasibility and feasibility stages involve study investigation of selected sites and then detailed physical studies of the selected site. The final design stage is a very high confidence analysis suitable for ultimate deployment and requires a much greater effort and time commitment to obtain the required confidence sought in a design.

This study is designed to quantify the national potential and assist in the pre-reconnaissance stage or screening stage of assessing water resources for hydrokinetic power potential. This study will assist in the identification or screening of promising locations for hydrokinetic power extraction and help focus further efforts of reconnaissance and feasibility level analysis on areas with a high resource potential.

2.3 Hydrokinetic Power

2.3.1 Instantaneous Hydrokinetic Power

The kinetic energy of a flowing fluid can be determined from the density of the fluid, the velocity at which the fluid travels and the cross sectional area at which the energy will be extracted.

$$P_K = \frac{\rho}{2} A V^3 \qquad (1)$$

Where P_K is the available kinetic power; ρ is the fluid density; A is the cross sectional area of extraction and; V is the flow velocity. Hydrokinetic power is often reported as a power density which is the power normalized to a unit area.

$$\frac{P_K}{A} = \frac{\rho}{2} V^3 \qquad (2)$$

When considering flows in rivers, one can make the reasonable assumption that the density remains essentially constant, even with changes in temperature. The velocity and area remain the only variables required to determine the kinetic power. Consequently the determination of the velocity in a river, specifically the time averaged velocity frequency distribution, is the essential and the primary factor in assessing the available kinetic energy available in a river. The calculation of the kinetic power depends of the cross section area which is either the river cross-sectional area for an assessment of the total energy in the river, or the area of the device that will be used to extract the kinetic energy. For the purposes of this study and to generalize the power potential over such a large land mass, the river cross sectional area will be used.

2.3.2 Time-averaged Hydrokinetic Energy

In fact, the velocity in a river is rarely constant and will be expected to vary significantly on a daily or monthly basis. Determining the average energy at a location requires the integration of the kinetic energy over a period of time. Assuming the velocity will change with time but the area for extraction is unchanged then the following equation applies.

$$\overline{P}_K = \frac{\int P_K(t)dt}{\int dt} = \frac{\int \frac{\rho}{2} A(V(t))^3 dt}{\int dt} \tag{3}$$

If one is interested in the entire average kinetic energy available in a river then the area will also change with time, as the flow changes.

$$\overline{P}_K = \frac{\int P_K(t)dt}{\int dt} = \frac{\int \frac{\rho}{2} A(t)(V(t))^3 dt}{\int dt} \tag{4}$$

Consequently, the total energy available at a river cross section is also strongly influenced by the velocity and the temporal flow variability plays a significant role when assessing the total available energy.

2.3.3 Representative Flow Velocity

The above equations represent the energy with an average flow velocity across the cross-sectional area of interest, that being the entire river cross-sectional area or the cross-sectional area of the turbine device. In fact the velocity may vary within the cross-sectional area itself. This is particularly the case in natural channels if the turbine cross-sectional area is not small compared to the cross-sectional area of the channel, or if the area considered is the entire cross-sectional area of the channel.

Velocity within a channel at a given cross section will vary substantial both in the vertical and the horizontal directions. Figure 3 illustrates the type of variability that may exist, with zero velocities at the bank edges and maximum velocities near the top of the water column and near the thalweg of the channel (although flow conditions and approach geometry will impact the velocity distributions substantially).

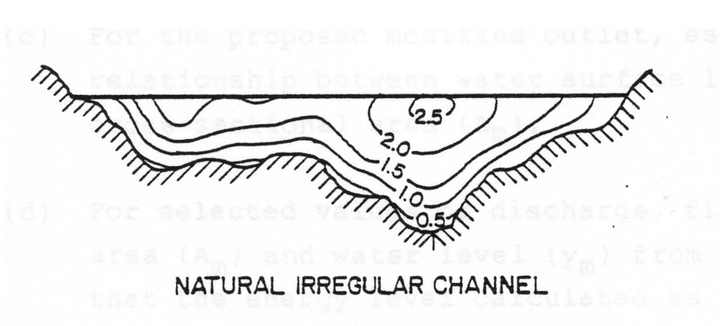


Figure 3 - Velocity Contours in an Irregular Channel [2]

Velocity profiles along the vertical axis are generally required for any type of hydrokinetic device. As power is a function of the velocity cubed, it is necessary to have a complete vertical velocity profile and knowledge of where the device is anchored.

In this study, the total hydrokinetic energy in the stream will be assessed using the predicted average flow velocity across the river cross section. Average velocity of a cross section does not represent the average kinetic energy flux across a cross section, as the relationship between velocity and power is non-linear. The power available will likely be some value greater than that calculated with the average velocity, depending on the nature of the velocity distribution. While the spatial velocity variability across a river cross section is expected to have an impact on hydrokinetic energy assessment, the complexities associated with predicting that variability at a regional scale across Canada, preclude its consideration in this phase of the study. As this upcoming phase of the study involves the validation of regionalization techniques, it will be sufficient to evaluate the techniques based on their ability to predict flow and average velocity. For the final phase of this study, involving a quantification of the hydrokinetic energy resources, investigations will be made into the impact of velocity distribution across a river cross section in terms of total hydrokinetic energy assessment and quantification.

2.3.4 Integration of Power Potential Over River Length

The evaluation of the available hydrokinetic energy at a cross section within a flowing channel is evaluated by integrating the power over the cross sectional area. To asses the hydrokinetic power potential along a river requires the longitudinal integration of the available hydrokinetic power over the entire length of the river. Integration of this type will require assumptions as to energy extraction by installed turbines, and estimates for the allowable spacing between installed turbines along a river length. Phase II of this study will not attempt to integrate power potential longitudinally as part of the final deliverable. However, Phase III may require the integration of the power potential along the river length. As part of Phase II, techniques for determining longitudinal integration of power potential will be proposed, if not evaluated.

2.4 Hydrokinetic Turbines

Hydrokinetic turbines are designed to extract the kinetic energy of flowing water, driving a generator to produce electricity. Hydrokinetic turbine systems differ from other “run-of-river” or “small hydro” turbine systems in that they are virtually zero-head turbines and are not constrained in a confined, pressurized flow environment. Small hydro turbines, by contrast, tend to be confined in a penstock or other conduit that conveys pressurized water from an elevated hydraulic head through a turbine. As a consequence of the confined flow and the associated turbine designs, the efficiency of small hydro turbines can be very high, approaching 90%.

Turbines that operate in open channels harvesting the kinetic energy of the water with no pressurized flow are hydrokinetic turbines. The nomenclature for this type of turbine is varied, with this turbine type being sometimes called a “water current turbine”, “free flow turbine”, “stream turbine” or “zero-head turbine” [50]. In all cases these describe turbines which:

a) Extract only kinetic energy from the flowing water
b) Operate in an unconfined, open channel environment and do not require a hydraulic head differential; and
c) Do not require a dam or barrage for operation.

Most hydrokinetic turbine designs can take a number of forms, but most are of the vertical or horizontal axis variety. Each has its own engineering and performance advantages, but all operate on the same principle of kinetic energy extraction. The turbines can be anchored in a number of ways either as bottom mounted, line-anchored or from the surface using a flotation device [103]. Figure 4 illustrates the various types of hydrokinetic turbines, in the three major groups: horizontal axis, vertical axis and cross-flow turbines.

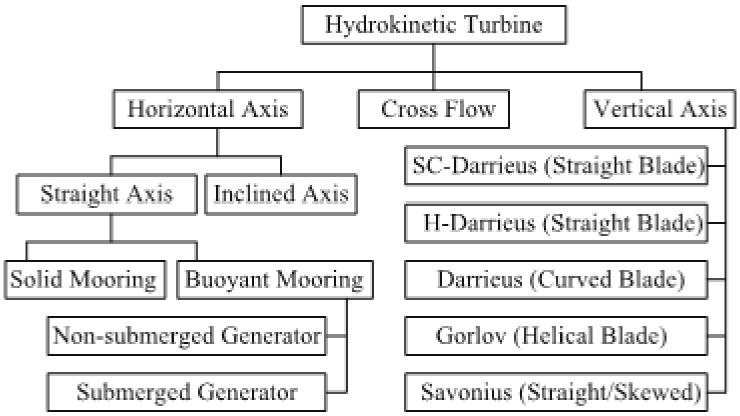


Figure 4 - Turbine Classifications [50]

Hydrokinetic turbines operate at much lower energy extraction efficiency than their pressurized counterparts. Betz derived a theoretical efficiency limit of 59.3% for propeller type turbines in free flow. In practice water current turbines operate with efficiencies between 16% and 42%, depending on the turbine type, make and hydraulic conditions [30, 36]. For turbine energy extraction the calculation must consider the efficiency of the turbine

$$P_K = \eta \frac{\rho}{2} A_S V^3 \tag{5}$$

where η is the efficiency of the turbine and A_S is the swept rotor area of the turbine. In fact, turbine efficiency is not a constant and will vary with device design and flow conditions [36].

$$P_K = \eta(V) \frac{\rho}{2} A_S V^3 \tag{6}$$

Considering the Betz limit on turbine rotor efficiency the maximum power extractable from a turbine is

$$P_{K-Max} = 0.593 \frac{\rho}{2} A_S V^3 \tag{7}$$

where $P_{K\text{-}Max}$ is the theoretical maximum power extractable from a turbine as per the Betz limit ($\eta = 0.593$).

2.5 Hydrological Considerations

Hydrologic conditions upstream of a given location play a critical role in determining the available kinetic energy at that location. The meteorological inputs, climactic conditions as well as the hydrological characteristics of a watershed determine the flow in a river, and these flow rates, when constrained by channel geometries, slope and roughness, dictate the flow velocities in the channels.

Specific flow time-series are not required for the assessment of a long-term hydrokinetic power potential at a location. However, the frequency with which a specific flow rate is expected to be observed at a location is important. That is to say, an accurate description of the expected flow frequency would provide enough information to quantify the river power potential at a given site. In hydrological terms, the flow duration curve (FDC) is typically employed to describe the flow frequency at a location and provide a graphical representation of stream flow variability [55, 83]. Figure 5 illustrates a typical flow duration curve.

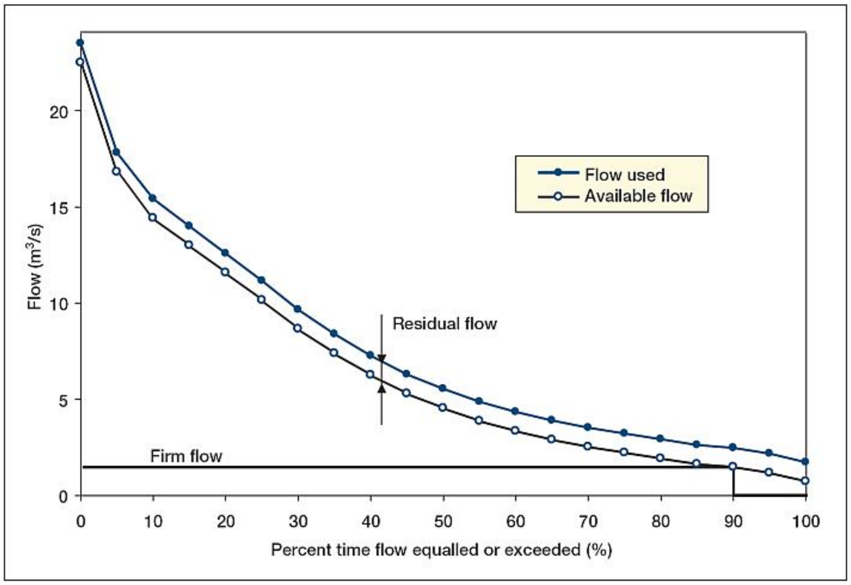


Figure 5 - Typical Flow Duration Curve (FDC) identifying firm flow at Q_{90} [67]

Other hydrological considerations are important when considering kinetic energy extraction, particularly regarding probable maximum floods (PMFs) and the design limits of the turbines themselves. The employment of these techniques will have little impact or utility in calculating the time-averaged kinetic energy available at a site. Although very large, PMF values are inherently infrequent and will not contribute meaningfully to energy calculations, but could have an influence on turbine design and deployment considerations.

The estimation of the flow duration curve at a location can be conducted by a number of means including transposition from other locations, empirical or regression methods, and hydrologic modelling. These techniques are further discussed in Sections 3.2 and 3.3.

2.6 Hydraulic Considerations

Hydraulic characteristics of a site must be considered when transforming the hydrologic flow data to velocity data. The channel velocity can be estimated a number of ways, the most common being the use of a hydraulic open-channel flow equation such at the Manning equation.

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{8}$$

The Manning equation and equations like it relate the average flow velocity *V*, to a hydraulic radius *R*, with a known roughness *n*, and water surface slope *S* for uniform flow conditions. Consider the continuity equation

$$Q = VA \tag{9}$$

which relates flow rate Q to the average velocity V and the cross sectional area A. The area and the hydraulic radius, which is the channel area divided by the wetted perimeter, are dictated by the channel geometry and the depth of flow. If the geometry is known and the water depth is known then both A and R are also known:

$$A = f(D) \tag{10}$$

$$R = g(D) \tag{11}$$

where D is the flow depth and f and g are function describing the relationship between flow depth D, and A and R respectively. This provides a system of four equations and four unknowns, which can be solved to provide the flow velocity and cross sectional area, both important in determining the total kinetic energy in a river system.

With the average velocity known, the hydrokinetic power can be determined. Figure 6 shows the flow duration curve alongside a velocity duration curve (VDC) and power duration curve (PDC) for a sample Water Survey of Canada gauge (02BF009) from a small drainage basin. This figure illustrates the relationship among the flow, the velocity and the kinetic power frequencies. The exponential relationship among the three characteristics adds weight to the higher flows, with most of the total power available in a stream presenting itself during the highest of flows. In this particular case nearly all of the available energy in the river occurs within only 2% of the time. This highlights the need for accurate estimation of flow velocities over the complete range of return frequencies especially considering that design requirements may be tied to a frequency of exceedence of a particular flow velocity.

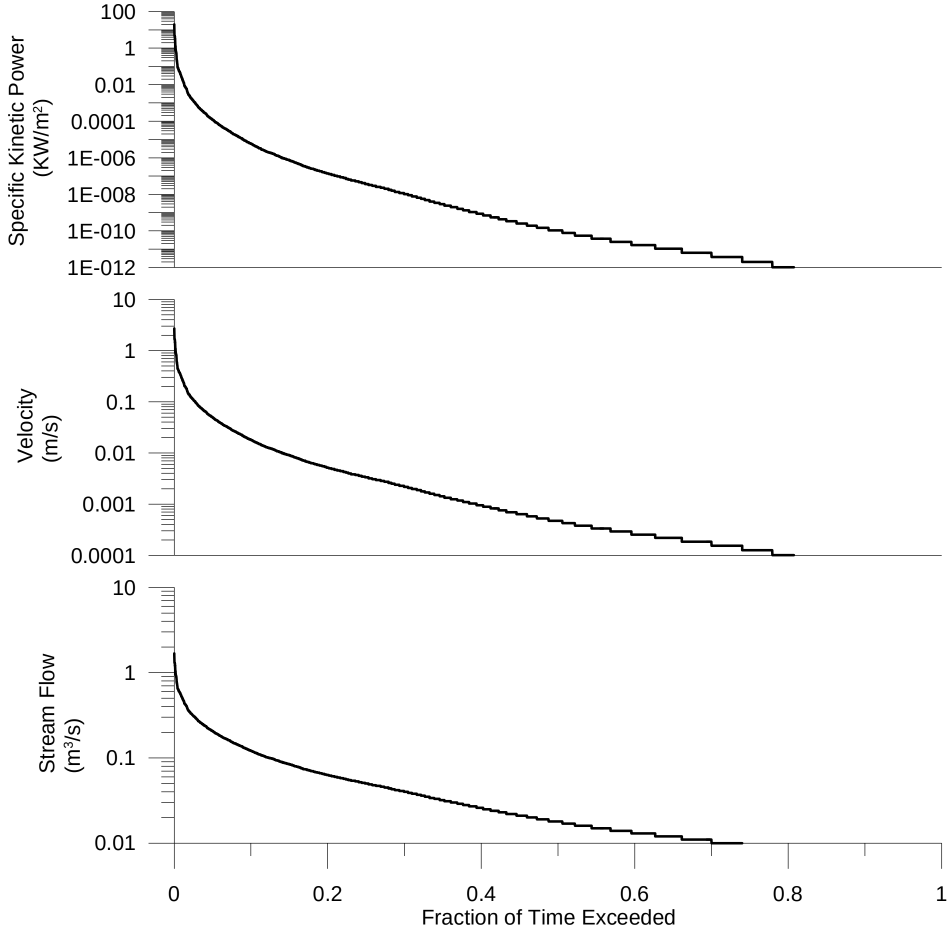


Figure 6 - Flow, Velocity and Hydrokinetic Power Distribution Curves - WSC Station 02BF009

The total time averaged energy available is an integration of the power as represented by the area under the specific kinetic power duration curve.

2.7 Study Scope

The scope of this study has the following limitations:

1. The objective of this study is to provide national/regional level hydrokinetic power potential estimates. It is not intended for site-specific assessment.
2. The study will examine technique to predict flows in unregulated rivers. Predicting the flows in regulated rivers will not be attempted or considered.
3. Impacts of river ice, ice jams or ice cover will not be explicitly considered in this study.
4. This study will consider only average flow velocities within a river cross section and will not consider the impacts of irregular velocity distributions in terms of hydrokinetic power assessment.
5. The study has precluded the use of hydrological models in the estimation of flow at ungauged locations. Although potentially a useful approach for this study the necessity to reduce the scope to a computationally and resource efficient techniques has excluded the use of hydrological models at this time.

3 HYDROLOGIC AND HYDRAULIC REGIONALIZATION TECHNIQUES

This section provides a review of published scientific literature that was found to relate to one of the following fields of research:

1. Estimation of Flow Duration Curves at Ungauged Basins;
2. Regional Channel Geometry Estimation;
3. Regional Slope Estimation;
4. Regional Roughness Estimation; and
5. Uncertainty Estimation and Error Propagation Techniques.

Recommendations for this study based on the literature reviewed in this section are presented subsequently in Section 6.

3.1 Estimation of Flow Duration Curves at Ungauged Basins

One of the challenges in determining the river power potential at a regional or national scale occurs in making a reasonable estimation of the flow conditions at all channel reaches. Considering the quantity of data to be processed for a national hydrokinetic energy assessment, the flow estimates need to be acquired in an efficient way with a minimal manual effort. This sub-section examines some of the techniques employed in flow estimation at ungauged sites with special attention paid to Canadian studies and studies that examine FDC regionalization.

Some published studies were found to be particularly noteworthy in terms of the analysis flow duration curves and their use in water resources. Vogel and Fennessey [105] provide an excellent review of the development of the FDC, techniques for development and interpretation as well as common applications in water resources [104]. Vogel and Fennessey [105] also examined the utility of the flow duration curve and suggested an annualized interpretation of the FDC to characterize the flow duration for a typical year in what they called the annualized flow duration curves (AFDC). AFDC represents the median hypothetical year not affected by observation of abnormally wet or dry periods. This interpretation allows for the development of confidence intervals around a median flow duration curve based on the distribution around the period of record. The AFDCs are less sensitive to the record length than are the period-of-record FDCs. It should also be emphasized that FDCs are generally more resilient and insensitive to outlying extreme events, as their impact on the shape of the FDC is typically minor and limited to extreme percentiles. Still, changes in climate could alter the shape of an FDC. House [43] authored a literature review for the Ontario Ministry of Natural Resources, Waterpower project. In it the author examined a number of topics relating to hydropower and the ecological impacts associated with it. The review included topics such as water level fluctuations in reservoirs, ecological effects of hydropeaking. Also reviewed were advances in regional flow estimation techniques, although the emphasis was not specifically related to FDC regionalization. As part of a review of contaminant transport estimation techniques for Environment Canada, Durand et al. [26] examined a number of flow transposition techniques, but they were largely restricted to area ratio method techniques (see Section 3.2). Bobee et al. [8, 9] conducted a review of regional flood frequency methods and performed a detailed intercomparison of a number of methods of delineation of homogenous regions and regional estimation methods using data from Quebec and Ontario.

When estimating flow at ungauged basins there are two primary considerations:

1. The nature of the flow characteristics that need to be known at the target locations, e.g. maximum annual flood, flow duration curve, low flow values.
2. The technique employed in regionalizing the flow characteristics from locations with data, to locations without data.

This second consideration, the regionalization technique can be considered as two separate sub-techniques [8]:

1. The determination of homogenous regions (DHR), which classifies or groups similar source data sites, and
2. The regional estimation method (REM) which transfers the data from the source data sites to the target ungauged sites.

3.2 Regional Estimation Methods

This section reviews a number of techniques from the literature that have shown some connection or promise with regard to FDC estimation in ungauged basins. Castellarin et al. suggested FDC transposition to ungauged basins can be conducted in one of three ways [15].

1. By determining a statistical function and then determining estimates of the shape parameters through regressive means.
2. By parametric means, by which a number of parametric equations are used to describe the shape of the FDC and the parameters are regionalized by some regression function, or
3. By graphical methods, which do not employ fitting a curve to the FDC.

Although not all techniques fit neatly into these three categories it is a useful way to segment the various approaches. In all cases, regardless of classification made by Castellarin et al., assumptions are made about the FDC shape or how the shape is to be captured mathematically and then parameters that describe the shape are regionalized to allow for FDC prediction at an ungauged location.

The remainder of this section summarizes some of the more commonly employed regional estimation methods.

3.2.1 Index flood method

The index flood method was one of the first regional flood frequency assessment methods, originally proposed by Dalrymple [23]. The principle is that the flood frequency curves in a homogenous hydrologic region are identical, varying only by a scale factor that can be described by watershed characteristics. It requires first the identification of homogenous regions and then determining a standardized (or normalized) flood frequency curve. The original method proposed the delineation of physical geographic regions and the employment of the Gumbel distribution.

$$Q_k(T) = \mu_k Q^*(T) \qquad (12)$$

where Q^* is the normalized flood frequency curve as a function of return frequency T, μ_k is the scale factor and Q_k is the flow duration curve at the target basin. Several studies employed an index-flood method or similar type method for transposition of flow duration curves. Acres

Consulting [2] employed the index flood method and the FDC was normalized to the 2-year return flow, which needed to be predicted in the target basin. The technique employed by the RETScreen [66, 67] application employs a variation of this approach. In this application a representative FDC was determined for a region normalized to the mean annual flow. The mean annual flow is then estimated at the target basin by employing a published specific runoff map and calculating the drainage area of the basin.

A number of techniques for using the index flood method and FDCs have been considered. Smakhtin [91] employed the method using FDC curves from gauges closest to the ungauged site within a homogenous region. Other approaches have used a number of curves are averaged to determine a combined representative curve for a region as described in Smakhtin and Masse [89]. In both cases are normalized to the mean annual flow, or some other flow metric, and expanded based on an estimated mean annual flow (MAF) at the site of interest. That is often done by determining a mean annual flow in a region normalized to drainage area and then multiplying by the calculated drainage area at the ungauged location.

3.2.2 Drainage Area Ratio Methods

One of the simplest methods employed to estimate flow in ungauged basins is a drainage area ratio method. This method scales the discharge from a known location to an unknown location by a ratio of the drainage areas. The drainage are ratio method would likely be classed as a "graphical" method based on the categorization by Castellarin et al. [15] because no underlying representative function is prescribed that describes the FDC. In principle the drainage area ratio method is very similar to the index flood method, with the index being a drainage area ratio value rather than a flood index value.

The general area ratio equation is

$$Q_u = Q_g \left(\frac{A_u}{A_g} \right)^m \tag{13}$$

where Q_u and Q_g are the ungauged and gauged flow rates, respectively and A_u and A_g are the ungauged and gauged upstream drainage areas, respectively and m is a calibration factor to account for the non-linearity of the relationship. The exponential parameter m requires calibration, but is often left as unity for simplicity or from lack of calibration data [72, 84]. A complete FDC curve could be generated at an ungauged site using this method by translating a percentile flow on the source FDC to a target FDC using the above equation. Caution is generally warranted when using the drainage area ratio methods as the relationship between runoff and drainage area is affected by a number of factors, drainage area being merely one, and the strength of the relationship drops off quickly as the drainage area ratio diverges significantly from unity [19, 56]. The Sauer Weighting function method is a variation of the drainage area ratio method that uses a combination of drainage area ratios and the predicted flow rates determined from USGS state regression equations for streamflow. Drainage area differences of more than 25 - 50% have been considered limits of applicability for this method by some authors [26, 56]. A number of FDC transposition studies have employed this method [61, 63, 71].

Mohamoud and Parman [61] also employed modified drainage area ratio methods in a study of the US Mid-Atlantic region

$$Q_u = Q_g \tan\left(\frac{A_u}{A_g}\right) \tag{14}$$

$$Q_u = Q_g \arctan\left(\frac{A_u}{A_g}\right) \tag{15}$$

3.2.3 Parametric FDC Characterization

When parametric methods are used to predict the regional FDCs at ungauged sites the FDC is assumed to be represented by analytical equations. These equations could be polynomial or exponential equations, the parameters of which are estimated through regional analysis. One of the first FDC regionalization and transposition studies was conducted by Quimpo [79]. In this study, conducted in the Philippines, regionalization of FDCs was conducted by presenting each FDC as an exponential function of the following form:

$$Q = Q_a e^{-cD} \tag{16}$$

where D is the percent of time a flow Q will be exceeded, Q_a and c being calibrated positive parameters. A power equation was also considered, but the natural logarithm decay equation was found to match the observed data better. Stations were selected that had 8 to 21 years of data and point values for Q_a and c for each gauge were determined. The values of c, which controlled the slope or shape of the FDC were regionalized and a contour map of the values for c was developed for the region. The Q_a values were scaled based on the drainage area of the ungauged basin using the equation

$$Q_a = pA^{-m} \tag{17}$$

where A is the drainage area and p and m are positive constants. A curve was developed using available data for all drainage areas in excess of 100 km^2, as smaller basins showed a high degree of variability.

Franchini and Suppo [34] proposed a parametric technique for estimating the flow duration curve by fitting a curve to three quantiles of the FDC. The authors proposed two possible equations for describing the lower portion of the flow duration curve

$$Q = c\left(\frac{1-D}{a}\right)^{1/b} \tag{18}$$

$$Q = c + e^{(a+bD)} \tag{19}$$

where D is the frequency of exceedence and Q is the corresponding flow rate. Parameters a, b, and c are calibrated using ordinary least squares methods to points on the FDC. The authors provide a number of regional regression models to estimate the quantile information as a function of watershed characteristics. Interestingly, this method regionalizes flow quantile values rather than parameters based on watershed characteristics. Castellarin et al. [15]

expanded on this method to employ four percentiles in stead of three and found it improved FDC representation.

3.2.4 Statistical FDC Characterization

Statistical FDC Transposition involves characterizing the source FDC curve as a probability distribution. This is not strictly appropriate, as the auto-correlation inherent in the data used to generate an FDC precludes the data themselves from being described as a pure probability distribution. However the shape of the distribution can be representative and transposition of a properly calibrated distribution can produce meaningful results at ungauged stations.

Leboutillier [52] conducted a flow regionalization study in British Columbia by fitting a two-component, two-parameter lognormal mixture distribution to the flow duration curve data. This distribution is a weighted combination of two lognormal distributions each with a position and shape parameter. The result is a 5 parameter fit for each flow duration curve.

The values of each of the parameters were clustered into 7 regional clusters using a two-stage density linkage cluster analysis technique. The generated clusters showed distinct contiguous regions within the province of BC. The average parameter values were then determined and representative flow duration curves were generated for each of the prescribed cluster regions. The predictive capabilities of the generated FDC curves were not investigated.

3.2.5 Graphical FDC Characterization

Castellarin et al. [15] characterized the technique developed by Smakhtin [91] as being a “graphical” FDC transposition method. In this method FDCs at gauge sites were normalized or standardized to a prescribed index flow and a regional FDC was determined by averaging percentiles of the FDC within the a region. The index flow values at the ungauged sites were estimated using a linear regression technique. Shu and Ouarda [84] concluded that the distinctive characteristic of this technique was that the method made no assumptions about the shape of the FDC, it being derived entirely from the observed site FDCs. This has inherent advantages if the entire FDC is required, or a region of the FDC is required that is not easily or consistently represented by a statistical or other analytical function

Mohamoud [60] employed a percentile flow prediction using step-wise regression by grouping 15 percentile flows into low, median, and high ranges, with five percentile flows in each, and determining unique predictors for each range. The source site selection was based on grouping by pre-defined landscape classifications.

Shu and Ouarda [60] expanded on the techniques of Smakhtin [91] and Mohamoud [60] by employing a regression based logarithmic technique to interpolate between measured or predicted percentile values on the FDC to generate a continuous curve. A stepwise regression analysis was performed for each of 17 percentile flows and the FDC data were transferred to ungauged basins using various distance weighting schemes employing area, positional and physiographic data from multiple sites. In a study in Quebec the authors found the FDC technique outperformed area ratio methods and that the inclusion of multiple source sites consistently improved predictive performance.

3.3 Determination of Homogeneous Regions

At their essence, regionalization techniques for flow estimation in ungauged basins involve procedures for deciding which sites with data will contribute to the estimation of a site with no data. The principle is that sites with data that are the most hydrologically similar to those of the ungauged site will be the best predictors of flow behaviour at that site and should be included in the estimate calculations. Conversely, sites that are dissimilar to the ungauged site should be excluded. When considering the prediction of FDCs some difficulty arises because the processes that influence the low flow portion of the flow duration curve may not be the same as those that influence the high-flow portion. For instance Dingman [24] and Searcy [83] suggested that the lower flows of a FDC are controlled less by climactic drivers than by basin geology and physiography, whereas in a runoff-dominated watershed, the local climate would have a very significant impact on the higher flows and would impact the FDC accordingly. Regionally, precipitation, temperature and evaporation will affect river flows but locally flows can be controlled by basin physical properties including geology, land use, the presence and position of surface water bodies [42].

There are many possible approaches to determining how data are regionalized; one of the most popular and easiest to interpret is the geographically contiguous region. If an ungauged site falls within a geographic region (on a map) then the characteristics of the region as a whole (or sites within the region) are used to predict the flow characteristics and data from other regions are not included. One of the only studies to identify hydrologic regions nationwide was conducted by Acres Engineering [2] in which 12 Hydrologic regions were identified. This was done by first identifying a number of predefined physiographic regions within Canada and then sub-dividing by the presence or absence of permafrost and regional climactic differences [3].

Gingras provided regionalization studies in Ontario and Quebec, determining nine independent regions with similar flooding characteristics [35]. The regions were delineated using a parametric frequency analysis and relationships between the magnitude of the flood and the drainage area of the basin at the ungauged location could be estimated.

The Ontario Ministry of the Environment delineated the provincial regions differently, depending on the flow characteristics that had to be predicted as described in the Ontario Flow Assessment Techniques (OFAT) manual [17]. For instance, to predict low flows six regions were delineated within the province, but using the index flood method 12 different regions were delineated.

Leboutillier and Waylen [52] conducted a regionalization study to develop flow duration curves for the province of British Columbia. A distance weighting technique was employed for statistical parameters that described FDC shape and magnitudes to develop a surface over the province. These were combined in a cluster analysis to describe seven hydrological regions on a map of the province.

3.3.1 Delineated Homogeneous Regions

Hydrologically homogenous regions are identified areas that behave in a hydrologically similar manner. This approach has been widely used as it provides a conceptually straightforward mapping of regions to facilitate the prediction of behaviour in sites that are ungauged or lacking data [52, 66, 67, 75, 92]. This approach can prove problematic; however, as regions that are hydrologically similar may not necessarily be geographically contiguous [1] and a more robust method would be to determine the statistical groupings based on influential parameters and then examine the fit of an ungauged basin within the available groupings.

A commonly employed technique for hydrologic region delineation is cluster analysis [52, 65, 92], which is a technique to assign observations to groups or clusters based on parametric similarity. In the case of FDC estimation in ungauged basins this clustering is based on similarity of watershed characteristics of a gauged or ungauged site. The goal of clustering is to establish similarity within a cluster and establish dissimilarity between clusters. The results of the clustering analysis will depend on the selection of the similarity measure (e.g. Euclidean distance, absolute differences) and the method that links data to a cluster (e.g. Ward's method, UPGMA). An ungauged site can then be associated to a cluster using discriminant analysis or similar statistical approach [65].

The problem of ungauged sites being not well placed statistically within any one cluster can be overcome by weighting the contributions from a number of clusters on the target site. Tasker et al. [93] employed multivariate cluster analysis when determining 50-year floods in ungauged basins in Arkansas, USA. The authors also employed a discriminant analysis to determine the probability that a site existed within a delineated cluster. The final prediction of the 50-year flood value was determined by employing weighted averages of predicted values for each cluster, the weights being dictated by the probabilities derived from the discriminant analysis. This technique has also been called fractional membership [1].

The use of hydrological regions, especially as geologically contiguous regions seems to be the most popular approach based on the number of studies conducted that employ the technique [2, 52, 66, 67, 75, 92].

3.3.2 Region of Influence (ROI)

The region of influence (ROI) method identifies homogenous sites based on hydrologic or physiographic characteristics and not necessarily a physical boundary between basins. The technique was originally suggested by Acreman and Wiltshire who suggested dispensing with physical or contiguous geographical regions [1]. Regions are identified based on a watershed's proximity to other watersheds (Euclidian distance) which can be a determined by a combination of differences in station attributes including physiographical, climatological or hydrologic information. A weighting function is defined to assign the importance of each catchment characteristic in calculating the Euclidean distance.

ROI is generally used to generate larger datasets to allow for more accurate generation of extreme value estimate techniques [12, 13]. Tasker et al. [93] reviewed various regionalization methods for 50-year flood estimation for a study in Arkansas and found ROI gave the best results for that region when compared to various region subdivisions and a cluster/discriminant analysis for region delineation. ROI has also been used to estimate flow characteristics at ungauged sites [109], naturally excluding the use of hydrologic predictor variables in the approach.

It appears that up to now only one attempt to estimate FDCs at ungauged locations using the ROI approach has been conducted. In that study conducted by Holmes et al. [42] the ROI approach was used to predict the Q_{95} flow value in the ungauged basin. The FDC curves at the ungauged sites were generated by comparing the predicted Q_{95} value with Q_{95} values of standardized FDCs developed in the region. A linear interpolation between these standardized curves was used to generate the resulting target FDC.

3.3.3 Canonical Correlation Analysis

Canonical Correlation Analysis (CCA) is a multivariate statistical technique that permits the establishment of interrelations between two groups of variables by determining linear combinations of one group that are most correlated to linear combinations of the second group. The technique has been employed as a regionalization method in flood frequency analysis, where one group of variables represents the flood characteristics and the second represents the physical and climatological characteristics of the basin, the principle being that by knowing the second the first can be predicted [9]. Regions can then be defined by examining the proximity of a gauge to other gauges in the parametric or hydrological space. A Chi-Squared distance is defined and based on judiciously defined confidence level a region influencing each an ungauged basin can be defined.

The procedure has been employed for flood frequency analysis in Quebec [80] and Ontario [76]. Although there appears to be no reason why the CCA regionalization approach could not be applied to a FDC transposition to ungauged basins, in any of a parametric, statistical or graphical context, none of those techniques was found in the literature.

3.3.4 Non-Linear Spatial Interpolation Technique

Hughes and Smakhtin [44] developed a non-linear technique for infilling missing data at proximal gauges, and re-building flow time series using flow duration curves as a transfer function. Although this technique was developed primarily to reconstruct time series data, it is relevant in this current work considering the techniques employed to apply and transfer flow duration curves between gauges. The technique employed monthly 1-day FDCs for each calendar month for both the target and source stations and allowed for time series transfer on a monthly basis. Smakhtin et al [89, 90] developed and extended a technique for ungauged stations where the FDC at the target site was unknown. The authors suggested normalizing FDCs using an index flow, and then determining the target FDC and determining the index flow at the target location. The source FDC is represented as a discharge table for fixed percentage points and data between points was interpolated using a logarithmic interpolation function.

Source gauges are used to estimate the target ungauged FDC by a weighted interpolation based on the similarity of the source gauges to the target location. The authors recommended that up to five gauges be used as source sites. The standardized FDCs created for ungauged basins were then standardized with index flows determined by regional regression analysis. The authors also suggested avoiding the direct use of catchment area and preferred the use of mean annual runoff or mean daily flow values at the site of interest in the regression analysis. This information was readily available in the South African case study sited. The authors also suggested 20 to 25 years of data being adequate for the application of the method. This method has been reviewed favourably by Metcalfe et al. [57] for inclusion as a tool for establishing flow regimes in Ontario and is considered a reasonable ungauged basin estimation technique.

3.3.5 Regression Based Logarithmic Interpolation

Shu and Ouarda suggested a method – Regression Based Logarithmic Interpolation (RBLI) – similar to Smakhtin et al. [89, 90] in that it employed the transposition of a number of percentiles on known FDC curves to ungauged locations to construct FDCs at these target locations. Like the Smakhtin technique the FDC curves were interpolated between points using a logarithmic interpolation technique but unlike the Smakhtin technique the regional regression was performed on the FDC percentiles without normalizing to an index flow value.

The authors investigated a number of regionalization approaches and looked at single and multiple source FDC estimation, and also compared the FDC transposition to drainage-area ratio methods. The authors also experimented with the number of source gauges and the distance weighting scheme used to regionalize the FDCs. The FDC transposition methods outperformed the area ratio methods in this study, conducted in Quebec. Multiple source sites were found to show substantial improvement over using single sites in most cases, and of the distance weighting schemes examined (area, geographic distance, physiographic differences) a geographic distance weighting scheme was found to perform best. A method adapted from the above is being employed by Ouarda in the investigation of ungauged basins for the International Joint Commission (Prof. Taha Ouarda, Personal Communication)

3.4 Notable FDC Transposition Studies

This section examines a number of studies that have looked at FDC transposition studies conducted to compare various techniques used in a region and to determine their predictive capabilities.

Yu et. al. [108] studied 15 watersheds in Taiwan and examined parametric (polynomial equation) and area ratio methods for FDC transposition. The authors used bootstrap resampling to determine the variance around the estimated values for both methods. The polynomial method described the FDCs based on regression equations that included drainage area, mean altitude of the basin, and average annual rainfall and predictive variables. The polynomial representation of the FDCs showed less error, as exhibited by tighter confidence intervals, than did the area ratio method.

Castellarin et al [15] examined a number of techniques for regionalization of flow duration curves, particularly for low flow (Q_{30} to Q_{99}) transposition. The study examined statistical techniques proposed by Fennessey and Vogel [31], a parametric technique presented by Franchini and Suppo [34] and a graphical technique described by Smakhtin [91]. The regionalization methods employed drainage area, permeable portion of the basin, maximum, mean and minimum elevations, and elevation range. Climactic variables employed were mean annual temperature, mean annual precipitation, mean annual potential evaporation, and mean annual net precipitation. The models were compared on a 52 station study with a jack-knife cross validation quality assessment. The authors found that all three methods produced results of similar quality, but the techniques produced satisfactory results (based on authors evaluation metric) only 60% of the time. Interestingly, it was discovered that five years of flow data records was enough to produce adequate flow duration curves which was better than any of the regionalization methods. This aspect of the study highlighted the importance of employing observed data whenever possible or practicable.

3.5 Channel Geometry Estimation

An estimate of the channel geometry at the ungauged locations is an essential component in the estimation of the hydrokinetic energy in a river. River geometry prediction generally attempts to relate the channel geometry to some other measurable quantity. The channel geometry is largely dictated by the sediment and water discharge rates to the reach and constrained by the channel geological characteristics.

River geometry pattern prediction advanced significantly with the relationships developed in a landmark paper by Leopold and Maddock [53] who identified a power law relationship between the width, depth and mean velocity and a corresponding discharge. Their work was based on the examination of 20 natural river cross sections. The relationships are:

$$w = aQ^b \tag{20}$$

$$d = cQ^f \tag{21}$$

$$v = kQ^m \tag{22}$$

where Q is the channel-forming discharge and w, d, and v, represent channel width at the water surface, mean depth and average flow velocity respectively, and where a, b, c, f, k, and m are numerical constants. The characteristic discharges employed in the downstream geometric analysis have varied from study to study and the choice remains controversial [48], however most use either a mean or bank full flow. Mean stream flow geometry equations have been used for flow requirement determinations and bank full flow geometry equations have been employed in channel restoration studies [61]. There are restrictions on what values the constants can take as described by the equation of continuity.

$$Q = wdv \tag{23}$$

By combining the continuity equation (23) with equations (20) (21) and (22) the following relationship is developed:

$$Q = ackQ^{(b+f+m)} \tag{24}$$

which provides two functional restrictions applied to the scalar coefficients (25) and the exponential coefficients (26).

$$ack = 1 \tag{25}$$

$$b + f + m = 1 \tag{26}$$

Further to the above, Singh et al. [87] also identified in their analysis the variation of roughness and slope with flow rate, shown in equations (27) and (28) respectively.

$$n = NQ^p \tag{27}$$

$$S = sQ^y \tag{28}$$

Analysis of the relationships between geometry and flow is generally divided into two types, both of which employ the same set of equations: “at-a-station” and “downstream” geometry relations [48]. The at-a-station geometry relations describe the change in hydraulic geometry with discharge at a particular reach. Downstream geometry relations describe the variation of hydraulic geometry between rivers at a particular characteristic discharge. The exponents of the equations (20) (21) and (22) were found to vary widely by Park [77] when examining the results of a number of available studies conducted worldwide and differently for at-a-station and downstream relationships. This is illustrated in Figure 7.

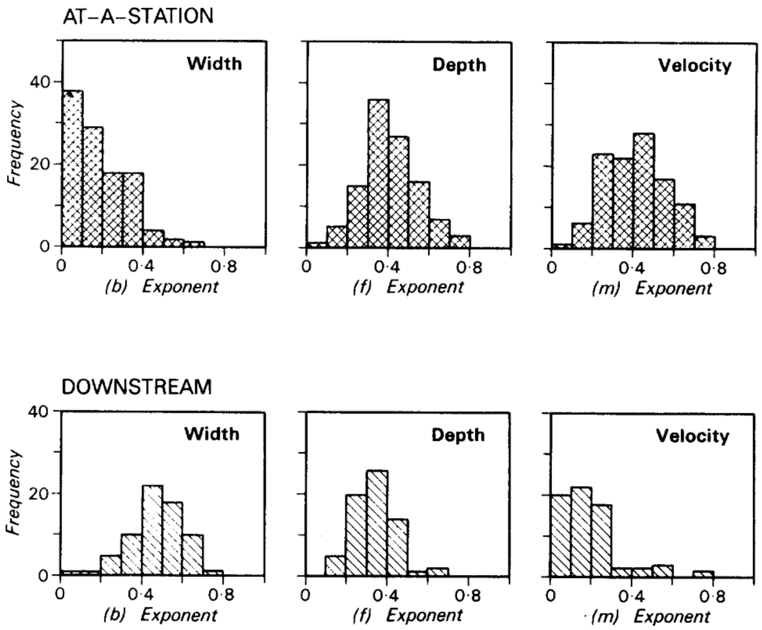


Figure 7 - Variability in Channel Geometry Coefficients [77]

Many studies have been conducted to estimate the parameters of the above power relationships for rivers in various regions. The literature review by NRC-CHC [26] collated and summarized a large number of these published studies. It reported on finding difficulty in employing these relationships primarily because of the limited transferability to regions, river types or characteristics other than those employed in the studies themselves.

Allen et al. [5] conducted an analysis of data from 674 stations across the United States to develop parameters for equations (20) (21) and (22). Through linear regression analysis the authors determined the following as the best fit to the available data

$$w = 1.22Q^{0.557} \tag{29}$$

$$d = 0.34Q^{0.341} \tag{30}$$

$$v = 2.42Q^{0.1035} \tag{31}$$

where flowrate (Q) is in units of ft^3/s at bankfull flow, width (w) and depth (d) are in units of ft and velocity (v) are in ft/s. The coefficients of determination were found to be acceptable for the equations for width (R^2=0.88) and depth (R^2=0.75), however the variation in velocity was not as well explained (R^2=0.14). The authors validated the width and depth models against a smaller, 41-station dataset and found the models performed well with a Nash-Sutcliffe efficiency of 0.87 or higher.

Jowett [48] developed estimates of channel hydraulic geometries in New Zealand using the Maddock and Leopold power equations and mean annual streamflow using reach-averaged geometry. Both the at-a-station and downstream geometric relations were found to fall within the survey conducted by Park [77].

Booker and Dunbar [10] performed a study that developed a channel geometry prediction technique using multi-level models for reaches within the United Kingdom. The authors employed a set of gauges within the UK to provide flow estimation and measured geometry looked at both at-a-station and downstream predictive characteristics. The authors noted that the stations employed were not strictly random, and had been chosen preferentially for their utility as flow gauging sites. This study looked at a three-tier approach to examine the variability associated with the geometric parameters: reach, river, and region. Booker showed that the greatest variability in terms of geometric characteristics in the UK study sample existed at the scale of the river and that the individual reaches showed and the regions showed least variability on average.

Singh et al. [86, 85] performed a number a similar model studies of the downstream channel geometry model development. In it, the authors examined a theoretical model development that considered changes in downstream geometry, slope or roughness based on the principles that adjustments to stream power will result in adjustments in stream geometry to accommodate, and that a principle of maximum entropy will be observed. The theory considered a number of possibilities for channel adjustment with changes in stream power. That is, a change in stream power could be accomplished by changes in roughness and width, or depth and width, or depth and roughness, etc. such that the new stream power condition is balanced. The authors applied the technique to datasets available from a number of countries including Canada and the models showed reasonable estimation of channel geometry. In a related study, Singh and Zhang [88, 87] applied a geometric estimation technique to examine at-a-station geometric model development and validation. The principles applied were the same as those of the downstream geometry study by Singh et. al. [85, 86] but applied to at-a-station geometry changes. The authors examined an international dataset and showed reasonable predictive capabilities.

Mohamoud and Parmar [61] estimated channel geometry at ungauged stations, employing the power equations developed by Leopold and Maddock, and they calibrated the coefficients based on a USGS database of known geometry and flow data for the US Mid-Atlantic region. In this study the mean flow was employed as the representative flow and the calibrated relationships were validated against an independent dataset.

Schulze et al. [82] in a study simulating river flow velocity on a global scale employed the equations developed by Allen et al. [5] to calculate a hydraulic radius. Assuming the channels had a rectangular shape and that the width to depth ratio remained unchanged for all flow regimes the authors calculated velocities based on the Manning equation. This approach did not account for a change in width to depth ratios with a change in flow regime and as a consequence overestimated flow velocity.

Other studies have used relationships other than those described by Leopold and Maddock, and instead used relations to watershed parameters other than a characteristic flow. Numerical hydrologic models including BASINS [6] and WATFLOOD [51] employ default channel geometries as a function of drainage area. Ames et al. [6] conducted a study in Idaho attempting to estimate channel geometries (width and depth) employing readily available GIS data. The study was designed to evaluate regression equations that rely on multiple input parameters as compared to single drainage area parameters commonly employed in modelling software. The argument against employing drainage area exclusively was that the correlation between drainage area and the flow rate of the channel-forming discharge is not necessarily strong. Other parameters including annual precipitation, elevation, and basin slope were selected based on stepwise linear regression analysis. Using bootstrap sampling the authors compared the predictive power of single variable relationships to that of multiple variable relationships. The multiple variable equations outperformed the single variable equation. The strongest explanatory variable remained drainage area, and precipitation was the next strongest followed by elevation and slope variables.

3.6 Channel Slope Estimation

Without extensive slope surveys, channel slope estimates are generally made with topographic data either in the form of elevation maps [97] or from digital elevation data [49, 68, 71]. Although commonly employed, data obtained from these sources can produce misleading results when the geometry at the channel scale is not well represented [54].

Lunetta et al. [54] employed GIS data in the characterization of salmon habitat in the Pacific north-west and performed slope calculations using GIS data. The authors found best results when the finest available DEM resolution product was employed (30m) and used 150m reach lengths for slope calculations (or 5 DEM cells). The authors sited a trade-off with changing reach length because shorter reach lengths were more readily subject to local DEM errors while longer reach lengths would mask local changes in slope.

Neeson et al. [68] compared GIS-calculated channel slopes with measured surface water slopes on a study reach in Ohio, USA. These slopes were calculated with the assistance of river channel shape files, with the GIS elevations employed in the calculations determined from the shape file reach locations. The authors found a significant correlation between measured and GIS-derived slopes. The accuracy increased with the reach length. The authors found the inability of GIS data to capture river sinuosity tended to produce higher estimated slopes in those areas. Also it was observed that GIS data has inherent minimum slope calculation limits based on the numerical resolution of the DEM data over a reach length. Some studies (eg. Schulze et al. [82]) have corrected for the error due to river sinuosity by introducing meander factors which effectively increase the channel length estimate and reduce the slope estimate.

An NRC-CHC [71] study examining an automated hydrokinetic estimation technique, calculated slope using DEM data and employed a 400 m reach length (200 m upstream and 200 m downstream from a channel location) using a 90 m DEM horizontal resolution.

Peckham [78] presented a technique that accounted for DEM elevation resolution issues in regions with gentle slopes. It applied a profile-smoothing algorithm based on Flint’s Law. Flint’s Law suggests that the slope is a function of the drainage area in a watershed based on a power function relationship. Peckham found that the algorithm produced more accurate slope estimates, but that it did not accurately represent elevations.

3.7 Roughness Estimation

No studies have been found that provide insight for estimating of roughness characteristics in Canada in the absence of a site visit or similar characterization. A number of hydraulics texts and reports provide some means for estimating stream roughness coefficients based on matching qualitative descriptions [18, 40], estimates based on grain size distributions and other measurable quantities in a river bed [21] and based on estimates made by comparison to photographed reaches where roughness studies have been previously conducted [7].

Schulze et al. [82], in attempting to develop methods of velocity estimation at a global scale, concluded that there were three ways to estimate channel roughness in the absence of a regional study:

1. Use a roughness tuning factor relating flow to velocity data without validation;

2. Use a constant river roughness; or
3. Use topographic of geologic information to estimate river roughness locally.

In their study Schulze et al. either tuned the roughness to available data or set the value to an assumed constant value. In most hydrokinetic studies reviewed in this document the roughness is estimated and assumed to be constant [58, 71, 97].

Mohamoud and Parmman [61] estimated roughness in their regionalization study at sites where all channel geometry was estimated, including local channel slope, and the Manning equation was then used to calculate the roughness. The estimated roughness values were then compared against published ranges.

Considering the uncertainty in roughness estimation, some authors suggest a range of values. For instance Henderson 1966 suggests 0.025 to 0.030 for clean and straight reaches, 0.033 to 0.040 for winding reaches with pools and shoals and 0.075 to 0.150 for very weedy, winding and overgrown reaches [40].

3.8 Uncertainty Estimation

In this study the estimates of hydrokinetic energy are determined based on a number of other parameters, and the measurement or determination of each of those parameters contains a degree of uncertainty. Many other studies have examined estimations of the power with assumed values of roughness or channel geometry, etc. providing a very precise estimate of the hydrokinetic energy and power potential. Still, there is a great degree of uncertainty in all of the input parameters which may translate into a significant uncertainty in the hydrokinetic energy estimate. To add confidence to the reported hydrokinetic energy values, Phase II of this study is to include an uncertainty analysis in hydrokinetic energy estimation. This section examines techniques for propagating uncertainty as well as published studies that have estimated uncertainty for some of the important estimated parameters.

3.8.1 Error Propagation Techniques

Error propagation occurs when errors in the input of a model or a calculation influence the errors in the output of that calculation [41]. In the review of the literature it was found that two general approaches were commonly used for propagation of error through a model or calculation: Taylor Series Methods and the Monte Carlo Method and its variants. These methods and their use in hydrologic applications are expanded upon below.

Taylor Series Methods

The Taylor Series Method (TSM) involves representing the model variable as a Taylor series and then combining the series with a predictive equation [11, 95]. The expanded Taylor series for the model variable, either as a 1st or 2nd order series, can then be combined with the derivatives of a predictive equation for the model variable. The result is an analytical equation that describes mean and variance of the model input. If the variability of the input parameters is known the error associated with the input parameters can be propagated to the estimate value. For instance, consider the Manning equation.

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{32}$$

A first-order Taylor series expansion of channel velocity, combined with derivatives of the Manning equation predicts the following equation describing the propagation of the error in the estimate:

$$\frac{\Delta V}{V} \approx \frac{2\Delta R}{3R} - \frac{\Delta n}{n} + \frac{\Delta S}{2S} \tag{33}$$

where the delta terms represent the variability or range of values in the input parameters. This analysis shows the relative sensitivities to change in input parameters. With relative errors being equal, the roughness is the most sensitive, followed by hydraulic radius and slope. It should be noted that one may expect much more overall variability in the hydraulic radius in an ungauged basin than in the roughness or slope. The method has the advantage of providing a clear analytical solution that describes the propagation of error in the system, but requires an analytical representation of the predictive model and a clear quantification of the error ranges.

Monte Carlo Methods

Monte Carlo methods of uncertainty estimation are able to account for uncertainty propagation by randomly sampling input variables from a known joint distribution to determine the resulting probabilities of the modelled variable. The Monte Carlo Method is a generic method and involves few assumptions about input distributions or relationships and it is limited largely by the computational time required to execute the required number of simulations [11]. As with the TSM, some information is required about the statistical distribution of the input parameters.

3.8.2 Error Propagation with Distributed Data

When considering GIS or distributed data, the spatial distribution of the associated uncertainty needs to be considered. In general the error propagation approach depends on the type of operation being conducted using the GIS data. The operations can be classed into two types [41]: Neighbourhood operations, which involve calculations in close or immediate proximity; and Global Operations, which involve calculations that employ GIS data over an area.

Neighbourhood operations in GIS processing are the type that employ only data in the near or immediate vicinity of the location at which the calculation is being made [41] and can be call constrained operations [74]. For example, the calculation of a local slope magnitude and direction using a DEM is a neighbourhood operation. Global operations, by contrast, are based on far-reaching spatial interactions in distributed data [41] and can be called unconstrained operations [74]. For example, the delineation of a watershed would be considered a global operation.

Propagation of error with distributed data can account for errors in the spatial data by perturbing the spatial data-point values using a random process. However, many disturbed data sets show a high degree of autocorrelation, and the incorporation of autocorrelation into the error field can be important when determining the error range of the derived values obtained from GIS operations [41, 74].

3.8.3 Error Estimates using Hydrometric and Geographic Data

This section outlines studies that have examined specifically the use of techniques estimate uncertainty in stream flow estimates, the estimates of watershed characteristics derived from DEM data and channel geometry estimates.

Flow Duration Curve and Stream flow Uncertainty

Estimation of uncertainty in FDC determination has been conducted in relatively few studies. The work by Vogel et al. [105] and the development of an annualized FDC provides a means to asses the degree of variability that can be observed around an annual median FDC at a given location. No other errors associated with FDC estimation have been discovered in this literature review. This is likely due to the fact that the traditional means of producing an FDC for a site is rather robust and random errors in measured flow would produce a similar FDC curve provided that a long enough data record would be available. It is believed that propagating the uncertainty associated with the underlying stage-discharge rating curves at a given gauge location to the development of a FDC would produce more meaningful results regarding FDC uncertainty, but no study of this type was discovered.

Murdock and Gulliver [63] examined the uncertainty associated with FDC transposition based on an area ratio method. The authors fit an area ratio curve to the available drainage area and flow data, and the residuals of the resulting curve were used to estimate the errors in the FDC at the ungauged site. Yu et al. [108] in their study of FDC transposition in 15 basins in Taiwan employed a bootstrap cross-validation technique to determine the confidence intervals for the estimated FDCs.

Harmel et al [38] examined error propagation in water quality data for small watersheds and looked at a number of sources of error including streamflow. The authors surveyed estimated errors associated with each stage of data or sample collection and measurement, and combined the errors by using the Topping Method [95] by estimating the total error from the square root of the sum of the squares of the contributing errors. This provided a useful survey of error estimates for streamflow measurements, stage-discharge relationships and continuous stage measurement and their contributions to total error in streamflow measurement and pollutant load estimates.

Watershed Area and Slope Uncertainty

DEMs are used to calculate slope, drainage area and other topography-related parameters. They are often employed as error-free data sources with the errors associated with their accuracy ignored in modelling and analysis. There are typically published RMSE estimates with respect to vertical accuracy on most modern DEM products based on validation tests with known elevation points. This RMSE data provides an estimate of the vertical accuracy at any particular point. However, there exists a high degree of natural spatial autocorrelation in DEM data, and errors associated with the DEM may also be correlated at short distances. This autocorrelation relationship can be important in estimating errors in calculations made with DEMs, although the relationship is rarely known [41].

A number of studies have investigated the impacts that uncertainty in DEM datasets have on the calculation of derived properties such as slope, aspect, viewshed and watershed drainage area. Early work by Fisher [32, 33] examined the effects of introducing errors to a DEM on the calculation of the viewshed area, or the area of land surface visible from a point on the DEM surface. Fisher identified significant increased variability in viewshed area calculations with an increase in the RMSE employed in a Monte Carlo error propagation applied to the DEM. The inclusion of an autocorrelation field had less predictable results when compared to the RMSE applied randomly at DEM grid points, but the results show convergence with the original DEM with increased autocorrelation.

Huevelink [41] published a manuscript on the propagation of errors in GIS data and examined error propagation in slope and aspect calculations (local GIS operations) using DEM data both theoretically and in a case study. The author examined slope and aspect of a DEM employing a number of functions for calculating the variables (2^{nd} and 3^{rd} order finite difference) and employed an exponential autocorrelation function with a range of correlation parameters. A Monte Carlo method was employed to determine the resulting variances with the original DEM. It was found that the zero correlation scenarios produced the highest variance and were considered a reasonable “worst-case” scenario for slope and aspect calculations.

Hunter and Goodchild [45] published a study examining the uncertainty in slope and aspect calculations from DEMs and investigated the effect of an spatial autocorrelation function on the error field. An autocorrelation function was employed when generating the error field with varying degrees of correlation. The authors discovered that the variance of the errors were greatest with no correlation and remained near the maximum error at lower correlations. As the correlations increased and approached unity the variance or error, would decline precipitously. The authors suggested a worst-case scenario being the employment of an autocorrelation function that produced a near-maximum variance and maximum autocorrelation (i.e. an autocorrelation value less than the point at which the variance begins to drop rapidly).

Oksanen and Sarjokoski [74] examined the effect of error propagation on slope and drainage area delineation using DEM data. The authors examined the effect of varying the random error filed by adjusting the RMSE values of a DEM of a Finnish island, and the autocorrelation range for an exponential and Gaussian spatial autocorrelation using a Monte Carlo method. The authors discovered that the maximum variances of the surface slopes were greatest not with zero autocorrelation but at some value 2.34 to 2.72 times the DEM mesh size depending on the autocorrelation function employed. This represents a departure from the previous understanding that the worst-case scenario was created by a random field with zero autocorrelation. The slope and watershed delineations were most sensitive to the RMSE values and constrained operations (slope) proved to be more sensitive to autocorrelation parameters than were unconstrained operations (watershed delineations).

Channel Geometry Uncertainty

Very few studies have examined uncertainty in hydraulic geometry estimation and the quantification of the associated errors. Harman et al. [37] evaluated the uncertainty in channel hydraulic geometry for a number of rivers in Australia. The authors provided regression estimates of channel geometry and velocity using log-transformed geometry and flow parameters. The errors were propagated using either a best estimate of the error ranges or through the employment of bootstrap methods to estimate the error in derived parameters. The errors were combined using Monte Carlo simulations.

Roughness Uncertainty

No studies have been found that consider the range of errors associated with regional roughness approximations in the estimation of stream velocities.

4 DATA AND RESOURCE REVIEW

This section summarizes the datasets available for conducting the validation study in Phase II of this project, as well as available tools to facilitate this phase of the study. Recommendations for how the data identified here will be included in Phase II are presented subsequently in Section 6.

4.1 National Hydro Network (NHN)

The National Hydro Network (NHN) is a GIS product that includes a geometric description and a set of basic attributes describing Canada's inland surface waters. It provides geospatial vector data describing hydrographic features such as lakes, reservoirs, rivers, streams, canals, islands, obstacles (e.g. waterfalls, rapids, rocks in water) and constructions (e.g. dams, wharves, dikes), as well as a linear drainage network and the toponymic information (geographical names) associated to hydrography. NHN datasets are available in GML (Geography Mark-up Language) and ESRI shape file formats [14].

It is anticipated that the NHN database will be used in this study in the estimation of river widths at gauge locations in Phase II.

4.2 HYDAT

Environment Canada (EC) maintains HYDAT, an archival database that contains all water information collected through the National Hydrometric Program. These data include: daily and monthly means of flow, water levels and sediment concentrations for over 2500 active and 5500 discontinued hydrometric monitoring stations across Canada [28]. The data are available online, and also through the Environment Canada Data Explorer (ECDE) desktop application developed by NRC-CHC for EC as illustrated in Figure 8.

In Phase II of this study, HYDAT data will be required to select and acquire station data to generate FDCs for gauge locations at the validation sites. The FDC curves generated from this data set will be used for calibration and validation of the regionalization techniques.

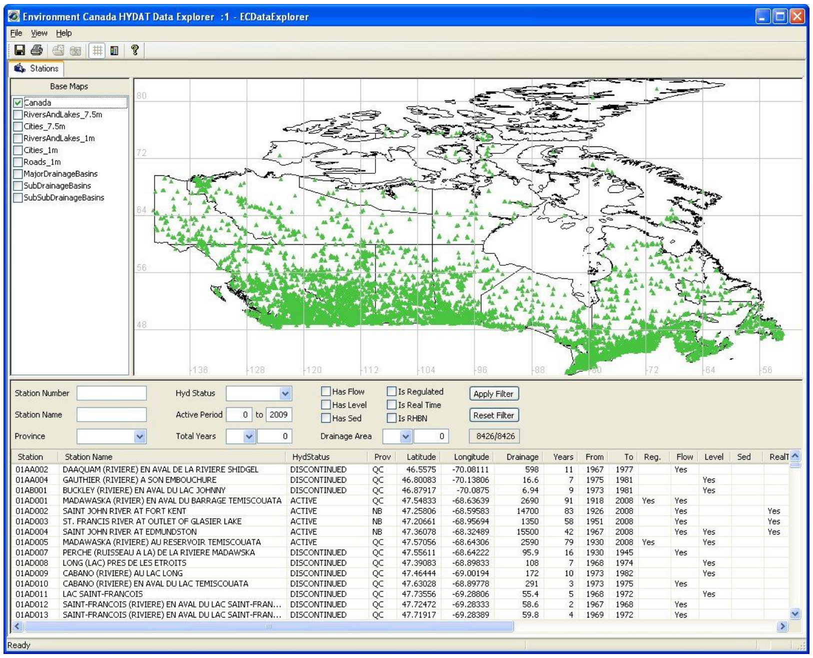


Figure 8 - Environment Canada Data Explorer (ECDE)

4.3 Canada Water Survey Measurement Database

The Canada Water Survey Measurement Database is an MS-Access database developed for internal use by Environment Canada and is a repository for hydrometric field measurement data. Data include cross-sectional information on channel geometry and velocity for conducted surveys. The database originally included no data from Quebec or Manitoba stations but was updated recently to include contributed data from the province of Manitoba. Currently, no data for the province of Quebec are found in the Measurement Database.

This database will be employed as a calibration and validation dataset for regional estimation of channel geometry and may also be employed in extracting actual velocity measurements and velocity duration curves for gauge locations at the validation sites in Phase II.

4.4 Canadian Digital Elevation Data

The Canadian Digital Elevation Data (CDED) consists of an array of ground elevations or digital elevation model (DEM) extracted from the National Topographic Database and other data sources from the provinces and territories [16]. The geographic resolution is 0.0001 decimal seconds (maximum 93m pixel resolution) and provides information for the entire nation.

The CDED database will provide necessary information for watershed delineation upstream of measured gauges including drainage areas, delineated contributing areas, slopes, etc. which be employed in the flow regionalisation and slope estimation in Phase II.

4.5 Physiographic Datasets

Agriculture and Agri-Food Canada (AAFC), through efforts of the Soil Landscapes of Canada Working Group and the Canadian Soil Information System (CanSIS), has created a series of GIS coverage maps that show the major characteristics of soil and land for the whole country. Soil Landscapes of Canada (SLCs) were compiled at a scale of 1:1 million, and information is organized according to a uniform national set of soil and landscape criteria based on permanent natural attributes [94]].

4.6 Canadian Climate Data

The incorporation of regional climate data is important for driving the regionalization effort to estimate flows and channel geometries at ungauged basins which will be conducted in Phase II of this project. A collection of available datasets that include regional climate data across Canada are described below.

The Canadian Daily Climate CD-ROM contains data from Environment Canada's National Climate Data and Information Archive [29]. CDCD contains daily temperature, precipitation, and snow depth data recorded at over 6900 active or inactive meteorological observation stations across Canada between the years of 1830 and 2007. This data is currently fully integrated with the GreenKenue™ software package.

Agriculture and Agri-Food Canada (AAFC) has produced a national ecological framework for Canada and introduced national ecodistricts with associated climate normals based on 1961 to 1990 data [4]. The ecodistricts are delineated in ArcView shape files and include information for mean annual rainfall, mean annual snowfall, mean annual precipitation, average, minimum and maximum average daily temperature, potential evapotranspiration, growing degree days, and growing season start and end dates.

AAFC, in collaboration with NRCan, EC and the Australian National University, has developed a Daily 10 km Raster-Gridded Climate Dataset for Canada south of 60° North (1961- 2003) [94]. The dataset contains grids of daily maximum temperature (°C), minimum temperature (°C) and precipitation (mm) for the Canadian landmass south of 60°N. These grids, which are available in two file formats (text and GeoTIFF), were interpolated from daily EC climate station observations using a thin plate smoothing spline surface fitting method implemented within ANUSPLIN V4.3 [46].

A national Mean Annual Runoff (MAR) was produced by the Department of Fisheries and Oceans (DFO) and the Environment Canada's Inland Water Directorate in 1978 as part of they Hydrology Atlas of Canada. The map is available online through NRCan's National Atlas website. AAFC, in collaboration with EC, StatsCan and NRCan, is currently developing a National Unit Runoff Database and associated maps. The final product will characterize the spatial and temporal characteristics of the surface water resources in Canada and is expected to be completed early in 2010.

EC has produced a map of the annual mean total precipitation over the time period from 1971 to 2000 that represents average conditions across Canada.

4.7 RETScreen

RETScreen is a decision-support system developed by NRCan and designed to support assessments of clean energy project viability. The RETScreen Online Hydrologic Database includes representative FDC data for each of the hydrological regions delineated as part of that study. Additionally, the RETScreen application includes two maps: one of hydrologic regions and one of the MAR for all of Canada. These datasets will be evaluated in Phase II for potential application in the national assessment of hydrokinetic potential. More details regarding the RETScreen application are presented in Section 5.2.

4.8 GreenKenue™

GreenKenue is a Microsoft windows-based software package that provides an integrated numerical modelling environment for hydrological applications [69]. The application is based on the EnSim core libraries which, in addition to supporting the GreenKenue software, supports the BlueKenue software for hydraulic and hydrodynamic modelling [70], the EC Data Explorer (see Section 4.2), the NRC-CHC hydrokinetic methodology investigation [71] and other graphical decision support systems.

The GreenKenue software library includes routines for watershed delineation, parsing shape file and raster data and other GIS operations that can be automated to facilitate and expedite the Phase II investigation.

5 PREVIOUS HYDROKINETIC AND HYDROPOWER RESOURCE ASSESSMENT STUDIES

Hydropower resource assessment studies seek to estimate the availability of a hydropower resource regionally. This can be done for hydropower projects of various sizes and types but most often it has been conducted for large or medium hydropower, low-head and run-of-river type hydropower systems. These systems involve the construction of a barrage or penstock to generate an artificial hydraulic head which drives a pressurized turbine. For these systems the necessary inputs required for assessment are the mean annual flow or the flow frequency at the location and the hydraulic head that can be produced at the study site. With these two variables, as well as assumptions about diversion or turbine efficiency, an estimate of the resource at each location can be made.

Regional hydrokinetic energy resource assessments require information about flow velocities and the frequency with which they occur (velocity duration curve) to assess the resource potential. However, the estimation of the velocity can be difficult in river systems, because it requires flow, channel geometry, roughness, and slope data at each location. By comparison, in coastal systems the flow patterns are more regular and predictable and the geometry is more easily acquired and less variable than in river systems, making the velocity predictions more readily and accurately obtainable [20].

This section reviews previously-published studies and examines both the hydrokinetic and hydropower studies in river systems. This section also summarizes the findings of each of the studies and discusses the approaches taken to estimate the important pre-requisites in resource assessment, including flow, geometry, roughness, slope, etc. A table summarizing the characteristics of the studies reviewed here is presented at the end of this section (Table 2, page 44).

5.1 Hydrokinetic Energy Assessment Studies

There have been only a small number of regional hydrokinetic assessment studies that have been conducted in Canada. This section highlights a number of prominent or comprehensive studies found in the literature and it describes their techniques and findings.

5.1.1 UMA Group (1980)

The only known Canada-wide study of current-power potential was conducted by UMA Group for NRC in 1980 [97]. In addition to hydrokinetic potential in certain rivers, it examined tidal power potential at some Canadian coastal locations. A large domain assessment of stream-power potential across Canada was undertaken with data that were available at the time: HYDAT monthly data records and topographic map data.

The scale of the study and the limited data availability required some assumptions and simplifications in the hydrokinetic power assessment methodology. These included the assumption of uniformity of reach over large areas (100s of kilometres), assumed roughness values and channel geometry, and assumed universal turbine efficiency (40%). Average reach widths were determined manually from national topographic maps, as were channel slopes.

The study was restricted to a small number of rivers (the largest in Canada) and river reach inclusion was limited by threshold flow (> 450m^3/s), velocity (> 1.5 m/s), width (> 50 m) and depth (> 3m) values. Flow was based on HYDAT data records having a minimum 20 years of data. Monthly mean flows (or "firm flow") were employed in power estimation, and reach flow rates were pro-rated to flow recorded at HYDAT stations by contributing drainage area.

The study provided a coarse assessment of hydrokinetic potential across Canada. Figure 9 presents a representative map from the report highlighting the current potential in the Mackenzie, Fraser, Slave, Churchill, Nelson and St. Lawrence rivers. The width of the cross-sectional bars indicates the degree of energy flux potential for each analyzed reach.

The UMA Group study did not examine a large number of small to medium rivers that, although possibly providing less available energy than those examined, could still offer hydrokinetic power potential. And because the study was limited to techniques and data available circa 1980, it limited the spatial resolution of the analysis to very large reaches and manual techniques for channel property estimation. Advances in the types and quality of the data as well as computational power available today would allow for a much more thorough and detailed investigation.

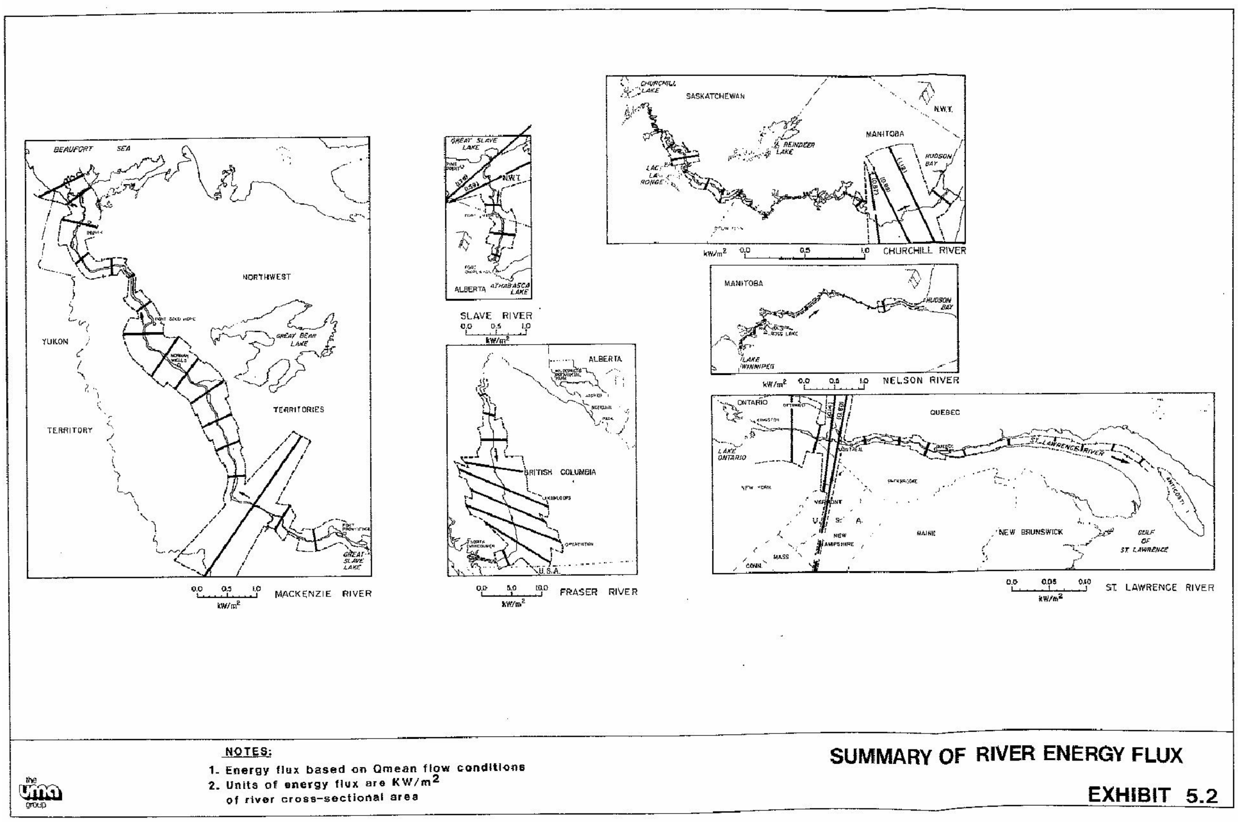


Figure 9 - UMA Group - River Energy Flux [97]

5.1.2 NYU Study (1986)

Miller et al. [58] conducted a study for the US Department of Energy to estimate the hydrokinetic resource potential in the United States. The methodology involved first dividing up the continental US into 16 physiographic/hydrologic regions. Hydrometric data from the USGS were examined and analysis was restricted to river reaches with greater than 113 m^3/s (4000 cfs) mean flow rate and 1.3 m/s (4.3 ft/s) flow velocity. Flow rates were determined for each river developing a relationship between the channel distance to the mouth of the river and the mean flow rate. This was done by developing a linear relationship between channel distance to the river mouth and the drainage area, and then developing a relationship between drainage area and flow rate and combining the two to provide the desired channel distance – flow rate relationship. Channel slope and geometry were estimated from USGS topographic maps and a rectangular cross section was assumed. The flow velocities were estimated using the Manning equation as per the UMA Group study [97]. Miller et al. estimated the total resource potential by making the following assumptions about turbine configuration:

- Only 25% of each cross section width is usable
- Only 25% of the length of any reach is accessible
- Each turbine installed has a diameter equal to 80% of the mean depth
- Turbines are spaced across the river cross section with a gap of ½ the turbine diameter between them
- A 5-diameter downstream distance is allowed between arrays of turbines
- Turbine efficiency is assumed to be 40%

This approach was considered to provide a conservative resource estimate and the total US hydrokinetic energy resource was thus estimated to be 12,500 MW, with the Western, Northwest and Alaskan areas exhibiting the greatest overall resource contributions.

5.1.3 NRC-CHC (2008)

A study commissioned by Natural Resources Canada was conducted by NRC-CHC in 2008, to develop a methodology to assess the hydraulic kinetic energy contained in Canadian rivers [71]. This study provided a technique to identify potential sites where hydraulic kinetic turbines could be installed using digital data available at the watershed scale. The analysis was based solely on GIS information and measured flow information provided by Environment Canada - Water Survey (WSC). GreenKenue™, a software package developed by NRC-CHC, was employed as a platform to prepare the methodology.

This technique employed DEM data to estimate channel slopes and to delineate drainage areas. Channel widths were determined from published shorelines in digital topographic map data provided by Natural Resources Canada. Flows were determined using a pro-rated method by drainage area from HYDAT hydrometric data, and mean monthly flows only were considered. Channel roughness was estimated using a single value for the study area. Flow velocities were calculated using the Manning equation. A sample of the graphical output of this analysis within the GreenKenue™ framework is shown in Figure 10.

The study represented a proof-of-concept, and it illustrated the feasibility and potential utility of the method, particularly when integrated into the GreenKenue™ hydrologic software package. This methodology was not validated or compared with other methods.

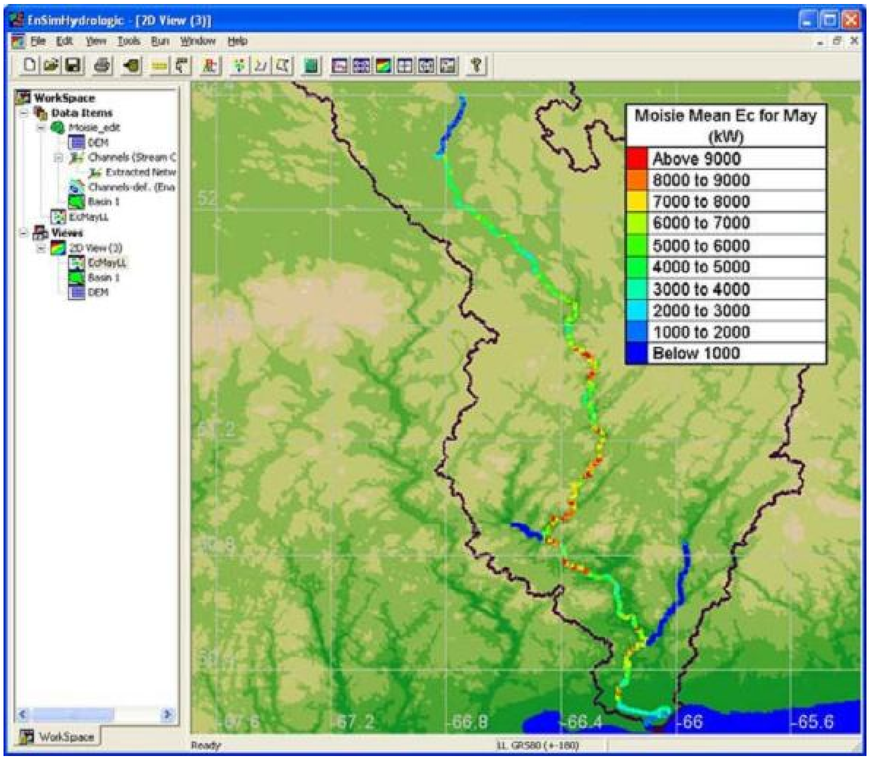


Figure 10 - Stream kinetic energy assessment in the GreenKenue™ platform [71]

5.2 Hydropower Assessment Studies

There have been a number of regional hydropower assessment studies that have been conducted over the last several decades. This section highlights a number of prominent or comprehensive studies found in the literature and it describes their techniques and findings.

5.2.1 ACRES (1984)

Acres conducted a study for Environment Canada, Inland Waters Directorate, in 1984 to develop a pre-feasibility methodology for assessing hydropower resources in Canada [2]. The study was initiated by an “off-oil” initiative of the National Energy Policy to explore renewable energy sources, and the need to assess locations with small hydro (<20 MW) potential at ungauged locations. The report was designed to provide a methodology that required little judgement to execute and could provide an acceptable estimate of power potential at an ungauged location.

The study identified 12 hydrologic regions in Canada of which 11 were included in analysis (the arctic islands region was excluded). For each hydrologic region a representative flow duration curve was created, which was normalized to a median flood flow rate. The Index Flood Method (see Section 3.2) was employed to apply the regional FDC to a local site, although an integration of the FDC was used to produce a “turbinable” flow curve for each ungauged site. That in turn related a design discharge to a “turbinable” discharge, or a discharge that would be passed through a turbine, rather than bypassed. The application of the turbinable flow curve to each location was done with an estimate of the mean annual runoff at the location (from MAR maps) and a series of regression equations that characterized the shape of the turbinable flow curve for each hydrologic region.

Figure 11 shows a relationship between the turbinable flow curve ant the flow duration curve. The shape of the turbinable flow curve is derived by integrating the FDC over the normalized discharge from zero to the design discharge. The use of the turbinable flow curve seems to have been done in large part because the shape of the turbinable flow curve can be approximated reasonably by a simple polynomial relationship, which facilitated the development of regional regression equations to describe them.

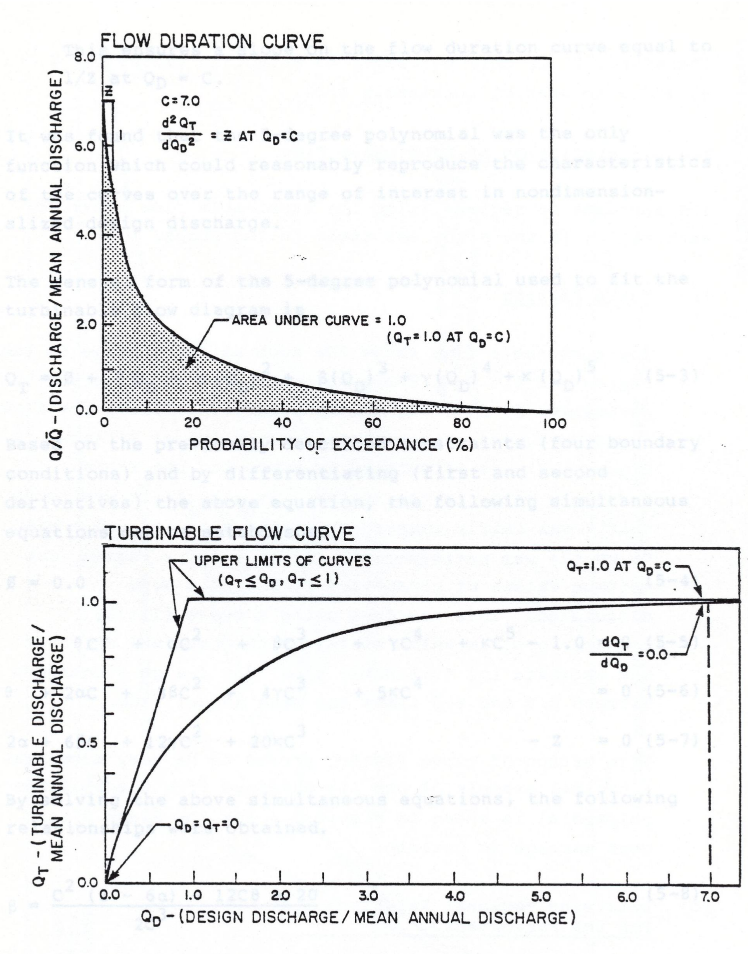


Figure 11 - Flow Duration Curve to Turbinable Flow Curve Conversion [2]

Special considerations in the Acres study were made to account for regulated rivers. This was done by re-visiting the flow duration curve at a location by cutting off the FDC at a prescribed maximum flow and adding an equivalent area to the low-flow area of the FDC. This adjustment would add a substantial turbinable flow quantity to the reach.

A different technique was identified for locations that included another gauge in the basin. The guidelines suggested if the drainage area difference between the ungauged site and the gauge location was less than 30% then a simple linear area/MAR pro-ration could be used to translocate the FDC from the gauge site. If the area difference was between 30 and 70% then a judicious decision (depending on the similarity of the physiography etc.) was recommended. If the area difference was greater than 70% then the ungauged method was recommended.

This study focused primarily on small hydro facilities relating hydropower generation to turbinable flow and hydraulic head estimations. A hydrokinetic power generation was addressed in this report, but it required data to be collected in the field to characterise the location to be investigated. The method recommended by the study was as follows:

1. Establish local FDC (from Index method);
2. Determine a relationship between cross sectional area and hydraulic radius for the channel using field data;
3. estimate the friction slope;
4. estimate the Manning roughness value (using Chow [18] or similar);
5. employ the Manning equation to relate flow to depth;
6. employ the continuity equation to estimate velocity; and
7. generate a velocity duration curve (VDC)

Also discussed was the importance of velocity variability across the stream, but no means of accounting for this in the method was explicitly discussed.

This method was validated against a simulated flow analysis and showed an average of 5% absolute error in turbinable flow estimations across all 11 regions. The standard deviation of the percent error was found to vary from 5 to 20%. Hydrologic regions 7 and 8 presented the largest errors. Region 8 represented the Canadian Prairies and region 7 represented the eastern Northwest Territories (today including Nunavut) and Northern Manitoba.

5.2.2 Tudor Engineering (1984)

A study was conducted by Tudor Engineering in 1984 (republished in 1991) for the World Bank, Industry and Energy Department, to provide a methodology for the rapid and accurate assessment of the number, size, cost and economic feasibility of small hydro projects [96]. The study provided a means for assessing the number of new potential sites in a region through statistical extrapolation in hydrologically similar areas (or hydropotenial zones). This methodology required some knowledge of the number of potential sites in a small sub-area of a hydropotential zone to match a Poisson distribution which was then applied to the entire hydropotential zone.

The hydrology of new sites was assessed through the derivation of a representative flow duration curve, based on regional hydrologic study, requiring precipitation, runoff and evaporation data regionally and at the new site area. The study used a common approach of developing a regional FDC but considered the adjustment of the FDC based on drainage area with the understanding that the shape of the FDC will change. Larger watersheds have much slower response and relatively attenuated flows when compared to headwater catchments which would produce a more gradually-sloped FDC. This tendency is illustrated in Figure 12. the Tudor study recommends the analysis of a number of FDC curves in a region and generating a modified normalized FDC for the target site.

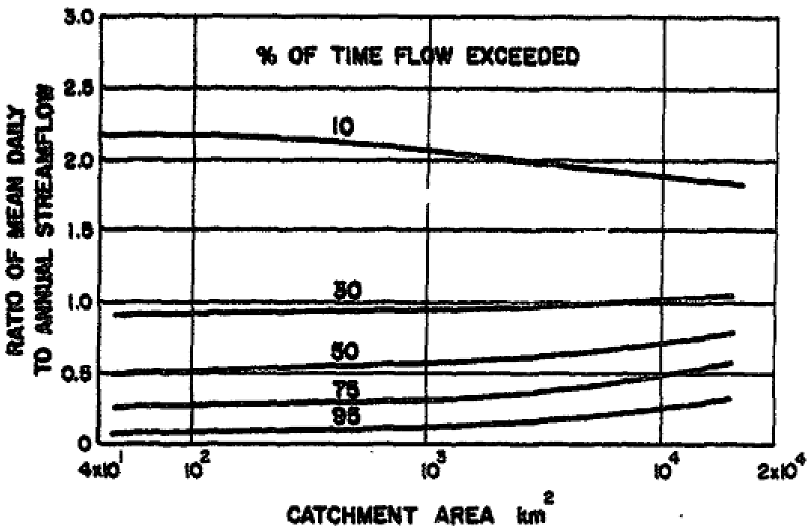


Figure 12 - Drainage Area Adjustment of FDCs [96]

The steps identified for developing the local flow duration curve are as follows:

1. Perform a regional study to derive the regional dimensionless flow duration curve parameters;
2. Determine the drainage area of the new site;
3. Determine a local dimensionless flow duration curve;
4. Determine the local annual runoff;
5. Determine the local flow duration curve;

The local annual runoff was determined using a linear proration method that considered precipitation, evaporation and drainage areas associated with both the new site and existing gauged sites. If multiple sites were present then values derived for each should be considered and deviation from the calculated mean of the annual runoff analyzed.

This study examined data from a Malaysian study to demonstrate the efficacy of the statistical extrapolation routine but the techniques for hydrology assessment of new sites were not validated against existing data in the report.

5.2.3 RETScreen - Natural Resources Canada (2004)

The RETScreen clean energy project was developed by Natural Resources Canada in partnership with National Aeronautics and Space Administration (NASA), the Renewable Energy and Energy Efficiency Partnership (REEEP), the United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF). RETScreen is a decision-support system designed to support assessments of clean energy project viability and is used in many countries as a small hydro prefeasibility site assessment tool. Included within the RETScreen product is a hydrology and energy production component that is used for the estimation of flow-duration curves and other hydrologic prediction components. Although not a study itself, the RETScreen resource provides a framework and set of techniques for the study of small-hydro resources. The hydrology required for analysis is either taken as a user input, or if within Canada, can be estimated by selecting another representative WSC gauge, or a representative FDC from a prescribed hydrologic region, and applying it to the un-gauged location by estimating the specific run-off (from a Canadian specific runoff map) and multiplying it by the calculated drainage area.

The FDC Hydrologic Region Map in Figure 13 was generated by identifying ecozones identified by Environment Canada and then selecting Environment Canada water survey gauges within each ecozone that had extended periods of record (30 years). FDCs for each gauge within an ecozone were normalized to mean measured flow, then plotted together and visually inspected. If a representative gauge could be identified by producing something approximating a mean FDC, it was selected as the representative gauge. If by visual inspection it was clear that the FDC populations required sub-division this was done and sub-divided ecozones were created and representative gauges were again assigned based on visual inspection [75].

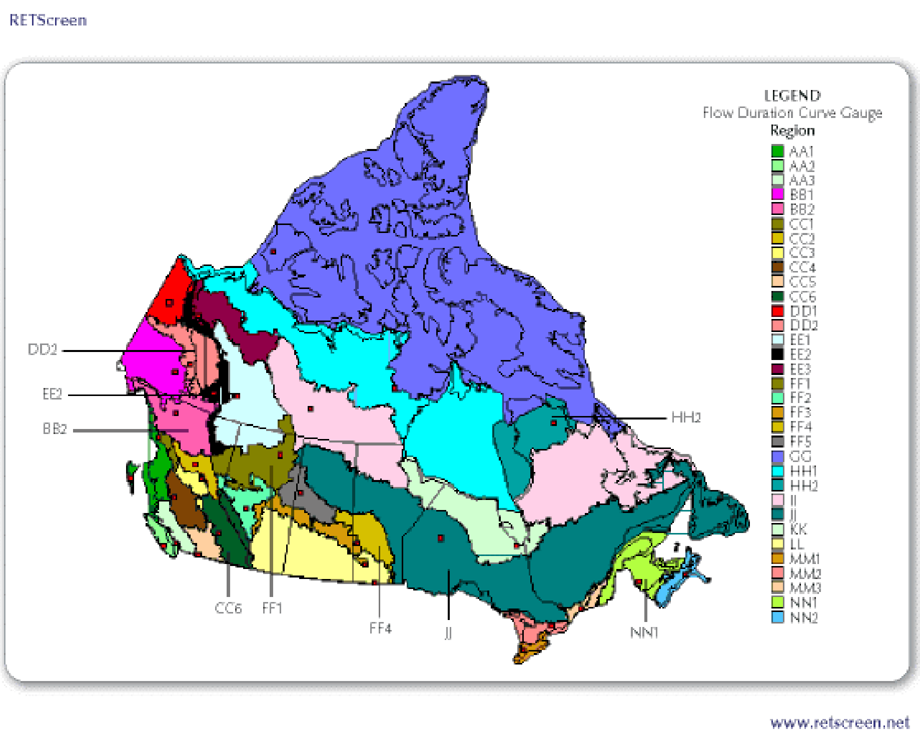
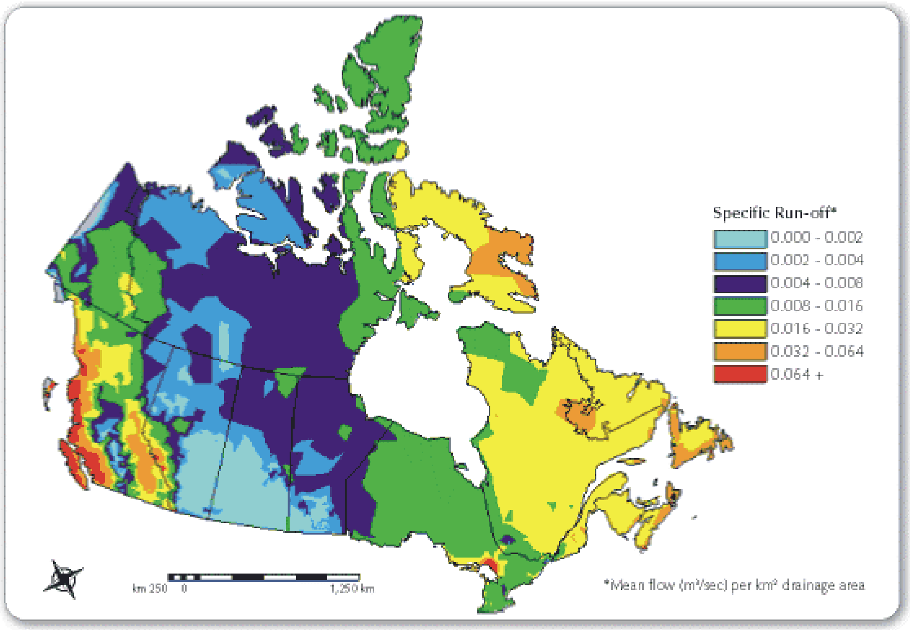


Figure 13 - RETScreen - Flow Duration Curve Map [67]

The representative normalized FDC for a particular ungauged location (after being identified by ecozone or sub-ecozone) was reapplied, corrected, to the ungauged location by taking the specific runoff at that location based on a provided national specific runoff map (shown in Figure 14). The drainage area upstream of the ungauged was also required.

RETScreen



www.retscreen.net

Figure 14 - RETScreen Specific Run-off Map [67]

5.2.4 U.S Department of Energy (2004, 2006)

The U.S. Department of Energy (USDOE) conducted a feasibility study to examine the hydropower energy resources across the United States for small- and low-power hydro [102, 101]. This study focused on employing geographic information tools and digital elevation model data to determine the assessment, and the focus was on low-head and low-power resources. This nation-wide study was preceded by a number of regional studies that examined the feasibility of the technique in Arkansas, the Pacific Northwest and the North Atlantic regions [99, 98, 100].

The principal determination of available hydropower was conducted by determining a mean annual flow at a location and estimating the potential hydraulic head that could be developed at that location. It used GIS data to determine stream locations, delineate stream segments and power potential, or possible penstock height. Calculations of hydraulic head were based on elevation drop using DEM data. Only natural water courses were considered, and estuaries or tidal areas were not examined. The study identified specific power generation types including conventional turbines, unconventional systems and microhydro. Kinetic energy extraction was identified as a constituent of microhydro, however the analysis did not consider the estimation of stream velocities. Mean annual stream flow was determined using a regional regression models for the United States [106], so no variability in flow over the year was considered. Required data included temperature, precipitation, and drainage area.

The study suggested some uncertainty in the estimation of the power potential, but the error sources were not identified or quantified. The results identified 98,700 MW as potential feasible untapped potential hydropower projects with a complete national resource of 297,436MW of hydropower potential. Additionally hydropower resources were reported on a per-area basis, identifying states with high power density, particularly Hawaii and Washington.

5.2.5 KWL (2007)

In 2007, Kerr Wood Leidel Associates (KWL) developed a GIS assisted hydropower assessment system for BC Hydro and the BC Transmission Corporation called the Rapid Hydropower Assessment Model (RHAM) [49, 62]. RHAM was used to conduct an inventory of potential run-of-river hydroelectric sites across British Columbia. In this study run-of-river referred to low-head hydropower with a constructed penstock. The study identified over 8,000 potential hydroelectric opportunities with over 12 GW of power generation potential in total.

The study by KWL used DEM data to determine drainage areas and slopes along delineated channels. Mean annual discharge was determined using MAR maps and multiplying the result for a location by the calculated drainage area. Potential for power generation was not determined considering hydrokinetic energy extraction in this study. Rather, a penstock length was estimated for each potential location, and a hydrostatic potential was determined by examining the elevation drop over the penstock length using the DEM data. With flow and static head estimated, a run-of-river power generation estimate could be calculated. This study also made use of distance-to-road data to develop cost estimates for implementing run-of-river facilities at the various locations automatically using GIS systems.

This study showed an interesting use of distributed GIS data for assessment of power potential, but did not consider hydrokinetic power assessment. The mean annual streamflow estimates were reportedly validated against WSC gauge data but the validation results were not presented.

5.2.6 Rojanamon, et. al. (2009)

A relatively recent study to assess river power potential was conducted in Thailand [81]. This study was perhaps the first automatic power assessment conducted in that country and combined a combination of hydrology, economic, environmental and social factors when considering the location and potential run-of-river resource as specific locations. Like the KWL study, this one employed DEM data to determine the hydraulic head. This study differed from others in that it did not employ a mean annual flow averaging technique but, due to the run-of-river focus of the study, required the development of flow duration curves at all the various locations. The authors employed an FDC normalization and averaging technique by mean annual flow to develop a normalized FDC curve for the study region. The de-normalized FDC curves at each location were developed by calculating the mean annual flow using regression methods. The Q_{30} was employed as a design flow. The study allowed for evaluation of potential sites as a combination of power potential and a number of other socio-environmental factors.

Table 2 – Hydrokinetic and Hydropower Resource Assessment Studies

Author	Year	Flow Estimation Technique	Regionalization (Domain)	Regionalization Technique	Hydrokinetic Energy Assessment	Channel Geometry Estimation Technique	Roughness Estimation Technique	Published Methodology Validation	Sensitivity / Uncertainty Analysis
UMA [97]	1980	MAF, Q_{95} / Regression from WSC Gauges / Flow – Area – Distance	Yes (National – Canada, but restricted to major rivers)	River basin-specific regression equations	Yes	Slope / Geometry from topographic maps	Estimated global, static value	No	No
Tudor Engineering [96]	1984	FDC – MAD Indexed and corrected for drainage area	Regional	Hydropotential zones – local MAD determined by pro-ration to Area, Precip., Evap.	No	N/A	N/A	No	No
NYU [58]	1986	MAF – watershed-based regression to channel distance to river mouth	Watershed-based linear regression (US – National)	Development of hydrologic/ physiographic regions	Yes	Slope / geometry from topographic maps	As per UMA [97]	No	No
Acres [2, 3]	1984	FDC as turbinable flow – MAR indexed	Yes (National – Canada)	Contiguous Hydrologic regions – regional regression for turbinable flow curve parameters / Area-MAR proration for nearby gauges	No**	No**	No**	Yes	No
NRCan (RETScreen) [66, 75]	2004	21-Point Representative FDC - MAR Indexed	Yes (National - Canada)	Contiguous Hydrologic Regions with representative MAR-indexed FDC / Target MAR Derived from regional maps and drainage area	No	N/A	N/A	No	No
US-DOE [101, 102]	2004	MAF, Regression Equations based on area, precip. and temperature	Yes (National – USA)	National (USA) - 20 hydrologic regions.	No*	N/A	N/A	No (for flow estimates)	No
KWL [49, 62]	2007	MAF - MAR Maps and Drainage Area Calculations	Yes (Provincial – British Columbia)	N/A	No	N/A	N/A	No***	No
NRC-CHC [71]	2008	Mean monthly flow from Area Ratio	No	N/A	Yes	NHN Database for width, Assumed Depth, Rectangular Channel	Estimated global, static value	No	No
Rojanamon, et. al. [81]	2009	FDC, Q_{30} – Parametric, Indexed to MAD	Yes (Single drainage basin, Nan River)	Regional regression to estimate MAD from drainage area.	No	N/A	N/A	No	No

* - The US-DOE study identifies hydrokinetic energy as a resource, but the calculation channel velocities or hydrokinetic energy was not conducted.
**- The Acres study proposed methodology for estimating hydrokinetic potential but the methodology was not regionalized and required site field data acquisition
*** - KWL reported validating streamflow estimates but the validation results were not presented in any publicly available documents.

6 RECOMMENDED APPROACH

The recommended approach for Phase II of this project is outlined in this section. Here the technological scope is defined including the types of regionalization and estimation techniques recommended considering the available data sources.

Upon reviewing the literature, no one study has yet been employed that accounts for all the required components to estimate hydrokinetic power regionally across Canada. However, a number of studies have examined individual components of the required approach that, when integrated, could lead to a successful regional hydrokinetic potential estimate in Canada.

The regionalization approaches listed below will not be evaluated against stream gauges on regulated rivers. Regionalization techniques assume natural conditions and adjustments for regulation require some knowledge of the regulation rules applied at control structures within the river network. The impact of regulation may be considered in Phase III.

Average channel flow velocities will be considered in Phase II, meaning that spatial variability of flow velocities over a river cross section will not be considered in the regionalization approaches. However, as part of the analysis of the EC Water Survey Measurement Database, the hydrokinetic power at the stations will be determined considering the velocity profiles as well as the average velocity. These data will not play a role in the technique validation but could inform the resource quantification conducted in Phase III.

The regionalization methodology of choice in this study is Canonical Correlation Analysis (CCA) and will be applied in a number of the regionalization methods outlined below. It is a preferred method considering the multivariate approach implicit in CCA that allows for the prediction of multiple variables lending itself to graphical FDC regionalization analysis. For the regionalisation, a number of validation regions will be selected based on physiographic and hydrologic regions, and the regionalisation will be applied within each of these regions.

A point worth noting is the consideration of non-stationarity in this era of climate change. Stationarity is the principle that natural processes operate within static bounds of variability that can be determined using historical records. With mounting evidence of the effects of climate change and a general scientific consensus, the principle of stationarity as a design guideline is believed no longer to be tenable [59]. Nevertheless all the FDC regionalization studies in the literature that were identified as part of this report did not account for pattern changes in flow frequency distribution in predicting FDC curves. Some considerations made for changes in climactic patterns have been accounted for in some studies of flood frequency [22], and techniques such as these could be considered in future investigations.

It should be mentioned that Phase II involves a research-based approaches into hydrokinetic estimation techniques and it is recommended that during the course of the investigation techniques other than those listed below be considered as necessary. For example, the Region of Influence (ROI) FCD regionalization approach may be considered should the CCA approach prove to be unsatisfactory early in the investigation.

6.1 Flow Duration Curve Estimation at Ungauged Basins

The selection of a suite of suitable methods for FDC estimation for this study requires that we examine a number of factors. The methods must be applicable using available data, easily automated, and with evidence of some practical success in previous studies or in the literature.

It is recommended that the following techniques be employed to estimate flow duration curves:

1. **Mean Annual Flow (RETScreen and CCA)**

The first method will be employed to estimate Mean Annual Flow (MAF) and use it to estimate the kinetic energy at a location. The inclusion of MAF represents a relatively easy flow rate to estimate when compared to a complete FDC and has been used in a number of national scale studies [49, 102, 97]. It is recommended that two approaches be applied to estimate MAF at ungauged basins: the RETScreen MAF approach (see item 2 below) and estimation through CCA.

2. **Area Index Method with Defined Contiguous Hydrologic Regions (RETScreen)**

This method, developed by NRCan, is a simple but well-established and fairly widely - used technique for flow estimation. Its inclusion in this study is recommended. The delineations are available, as are the representative flow duration curves. This method has been in use for several years, it accompanies an established national energy planning and cost estimation tool, and it was designed specifically for FDC estimation at ungauged sites. Its inclusion in the analysis will be important in validating this established method and it will act as a benchmark for comparison of other methods.

This method will not require any data for preparation other than what is already provided by the RETScreen procedure. The method may be validated against established WSC gauges within the selected study regions.

3. **Area Ratio Method with CCA**

The area ratio method represents a very simple and commonly-employed approach for estimating streamflow at ungauged basins. It was employed in a large number of studies in FDC transposition, including the method employed by NRC-CHC [71]. This method, unlike some other parametric and statistical techniques, can regenerate the entire FDC curve.

The CCA approach as described by Shu and Ouarda [84] is recommended for use with the area ratio method. This method has been employed already in Quebec and the Upper Great Lakes by Environment Canada as part of the IJC Upper Great Lakes study for flow determination in ungauged basins.

To validate the method, a jack-knife validation approach is recommended for each region of study.

4. **Graphical FDC Transposition with CCA**

The graphical FDC transposition method was developed by Hughes and Smakhtin [44] for flow time series transposition in ungauged basins, and then adapted for FDC transposition use in Canada by Metcalfe [57], and by Shu and Ouarda [84]. This method takes advantage of the complete FDC curve, whereas many parametric and statistical methods of FDC representation tend to focus on a particular section of the FDC. The CCA regionalization approach is recommended for this method as well, based on the reasons described above.

To validate the method, a jack-knife validation approach is recommended for each region of study.

6.2 Slope Estimation

Of particular interest in this study is the use of DEM to calculate the channel slope, which in turn is employed directly in the velocity estimation equation and the calculation of the drainage area (which may be used tangentially to determine channel characteristics using empirical equations).

All of the methods listed in Section 3.6 employ DEM data to estimate the slope. They tend to vary primarily based on the techniques for interpolation. Two techniques are recommended; one is to use a local slope calculation based on the upstream and downstream slope as derived from the calculated DEM channel as identified by NRC-CHC [71] and Lunetta et al. [54]. The other is to investigate fitting the curve outlined by Peckham [78], because it is suspected to have utility in the Canadian prairies, or in other areas of low relief.

No slope data database has been found to validate these approaches. As such, the methods will be employed as they are, and the ultimate velocity calculations that derive from the estimated slope can be compared with measured values.

6.3 Channel Geometry Estimation

For channel geometry it is recommended that the approach by Ames et al. [6] be employed. This method uses a stepwise regression analysis for estimating the channel geometry from known watershed parameters and it was used to estimate bank full widths and depths.

There are two recommended approaches to geometry estimation for channel widths. Widths may be calculated by extracting a channel width from the NHN database if mapped channel widths are available. Alternatively the approach employed by Ames et al. [6], relating the width to known physiographic characteristics, will be employed.

A channel geometric shape must be assumed for power generation calculations. It is recommended for this study that a rectangular shape be assumed. This can be a reasonable estimate for larger rivers, and assumptions such as this are often used in other studies.

Geometry estimates may be validated through comparisons with the WSC database widths and depths via a jack-knife validation technique.

6.4 Roughness Estimation

No regional estimates of channel roughness were found in the literature for Canadian streams, nor were any databases discovered that could validate estimates or be used in a regional regression analysis. A study by Mohamoud and Parmar [61] estimated roughness by back-calculating (through use of the Manning equation) all other values in the equation either known or estimated. Some empirical equations have been developed by Dingman and Sharma [25] that relate an estimate of roughness to drainage area, channel slope, and hydraulic radius.

It is recommended that roughness estimation be conducted as an estimated published range based on standard physical descriptors in references like Barnes [7] or Chow [18] and the Dingman and Sharma regression equation. No roughness measurements were discovered and as such no direct validation of the roughness estimates will be possible in Phase II. However, as with slope estimates, the resulting flow velocity estimates may be compared.

6.5 Hydrokinetic Energy Calculation

The energy resource calculation will require the solution of the Manning equation for the entire FDC curve at each ungauged location, similar to what was conducted by both the UMA Group [97] and NRC-CHC [71] in their resource assessment studies. For the validation study (Phase II) this will be conducted at each WSC gauge location within the selected study sites. It is recommended that uniform velocity be assumed in the calculation and errors associated with variable flow velocity not be considered. This is largely because the characterization of the in-stream velocity profiles is impractical to characterize at a regional scale. However, the relationships between hydrokinetic energy calculations based on average and distributed velocities will be considered through the examination of the EC Water Survey Measurement Database (see Section 6.7).

It is proposed that flows only up to bank-full flow be considered when performing the energy calculations. That is, any flow in excess of bank-full will be considered at the bankfull level both in terms of flow and cross section for the purposes of velocity calculations. Flows above bank-full will be characterised by inundation of the flood plain and average velocities across the section would drop in these circumstances, not being representative of the flow velocities in the main channel.

6.6 Uncertainty Considerations

In order to assess the degree of uncertainty in the estimates, a number of approaches will be considered. For the FDC estimation techniques (other than the RETScreen method) a bootstrap approach could be considered when applying the methods that will generate confidence limits on the estimates being conducted. For channel geometry estimates a similar bootstrap approach could be considered for the regional regression approach. For the NHN estimate of channel width a standard error could be employed based on consultation with the NHN developers. Roughness uncertainty must be judiciously selected as a possible range for a region. Slope uncertainty estimates could be estimated using a localized Monte Carlo analysis using the RMSE error published with the DEM data. Implementing spatial auto-correlation is not recommended considering the relatively greater importance assigned to the RMSE error as compared to auto-correlation errors.

Considering the effort possibly required developing uncertainty estimates, the implementation of a bootstrap technique for FDC and channel geometry estimates is recommended if time permits at the end of Phase II.

6.7 Cross-sectional Velocity Distribution Considerations

Although cross-sectional velocity distribution is not to be considered in the evaluation of the regional estimation techniques conducted in Phase II, it is seen as an important consideration when assessing the total hydrokinetic resource in Canada. Consequently some investigation will be conducted into the analysis of the EC Water Survey Measurement Database to investigate the relationships between hydrokinetic power based on average velocity and the measured velocity profile. It is hoped that this investigation will provide some insight into the impact of velocity variability on hydrokinetic energy relationships in natural streams.

7 PROPOSED PHASE II TASKS

The tasks of the second phase of this project follow from the recommendations in the previous section. This section provides a summary of the anticipated tasks to complete a validation study.

7.1 Study Region Selection

Region selection will be finalized at the outset of the second phase of this study and will involve the selection of a particular region in Quebec, Ontario, BC, Manitoba and in one of the Territories for analysis. The regions may be as large as the province itself, but may be restricted to a sub-region of the province. The regions will be selected in collaboration with EC, NRCan and other researchers familiar with the data and the regionalization methods.

Our review of the various techniques has identified some regions that have been investigated previously, including the province of Quebec and the areas of the Upper Great Lakes as part of other studies. It is anticipated that data gleaned from these studies will prove advantageous in judicious region selection. At the time of writing, detailed geometry data for the Quebec region was unavailable.

7.2 Dataset Preparation

The dataset preparation will follow the study region selection stage and will involve the processing of the validation dataset. The ultimate goal of this dataset preparation is to identify a number of characteristics associated with each station. This will include flow data (FDC percentiles), channel geometry, and a number of physiographic characteristics. The ultimate product will be a flat table linking a station to a number of these quantifiable parameters which will be used to drive and validate the predictive models.

7.2.1 EC Measurement Database

The following data will be obtained from the EC Measurement database:

1. Channel Width (estimated at bank full)
2. Channel Depth (estimated at bank full)
3. Channel Flow – Mean Velocity – Hydrokinetic Relationships

The EC Measurement database is in Microsoft Access format which will lend itself to a degree of automation.

The width and depth data for each station in the study validation regions will be extracted form the WSC database. This will be done by first determining the channel forming discharge from the flow history at the gauge (2 year flow). Establishment of bank full flow will be calculated by determining the minimum width-depth ratio as a function of channel water depth [19]. This may require some manual investigation to determine this value, although an automated technique may be possible.

Hydrokinetic power calculations will be performed for each station in two ways: using the average flow velocity reported, and by using the cross sectional velocity data. In this way the difference between the average and actual hydrokinetic power estimates can be evaluated.

7.2.2 HYDAT

The HYDAT database will also have to be processed. For each station required in the model, the flow duration curves need to be identified. A software routine will be constructed to automatically process a list of stations and output the flow duration curve values at prescribed percentiles. The routine will be coded to calculate the standard FDC as well as the annualized FDC and a prescribed confidence interval. Additionally, the published drainage areas for each station in the HYDAT database will be extracted for comparison with the calculated drainage area values (see below).

7.2.3 Digital Elevation Data Processing

From the CDED digital elevation data the following data will be required for each station:

1. Drainage Area
2. Centroid of Drainage Area
3. Local channel slope at the gauge location
4. Mean/Median Elevation of Watershed
5. Watershed Elevation Range
6. Watershed Perimeter
7. Main Channel Length
8. Average Channel Slope

For each station location, the upstream drainage area is to be calculated by delineating the contributing area using the available digital elevation models. GreenKenue™ can generate and store the watershed delineations for the stations as polygons, and will be augmented to calculate the centroid of the drainage area polygons. The local channel slope at the gauge location will be estimated by finding the nearest estimated channel and calculating the local slope using a prescribed length with which to estimate the slope (slope calculation at the pixel resolution may not be representative). The GreenKenue™ application has the Jenson and Dominique [47] and Ehlschaeger [27] algorithms for watershed delineation already included in the EnSim software library. The remaining parameters will require development to extract from the DEM data.

7.2.4 Watershed Characteristics Processing

In order to characterise the basins a number of basin characteristics require identification. Most of the important parameters will be acquired directly from pixel-counting or shape-file parsing techniques. The list below summarizes the likely input parameters for regionalization, including the probable data source.

1. Fraction of drainage areas occupied/influenced by lakes – CANSIS
2. Fraction of drainage areas occupied/influenced by wetlands– CANSIS
3. Fraction of drainage areas occupied by forest - CANSIS
4. Mean annual precipitation (MAP) – AAFC, Canadian Ecodistrict Climate Normals

5. Mean annual runoff (MAR) - RETScreen or DFO/EC
6. Mean annual temperature (MAT) - AAFC, Canadian Ecodistrict Climate Normals
7. Potential Evapotranspiration (PET) - AAFC, Canadian Ecodistrict Climate Normals
8. Soil Surface Conductivity / Runoff Coefficients - CANSIS

7.2.5 Channel Widths from NHN

The National Hydro Network (NHN) provides mapped channel boundaries for large rivers throughout Canada and also includes channel centrelines. An automated process will be developed to map channel centrelines to channel widths if available. This method can be conducted only if a programmatic link exists between the channel centreline segments and the width segments in the NHN shape files. This will be investigated as part of Phase II. The validity of the NHN dataset will be evaluated even if the programmatic automation is not possible, as the widths may be extracted in a manual or semi-automatic fashion for the validation exercise. However, should this programmatic link not be available then this technique for estimating channel widths will not be useful for the Phase III national hydrokinetic resource estimate.

7.2.6 RETScreen Map Processing

The inclusion of the RETScreen approach will require the determination of the MAR and hydrologic region for all gauges employed in the second stage of Phase II. These maps have not been found in any geo-corrected format, so that some manual effort will be needed to identify hydrologic regions of the selected stations.

7.3 FDC Estimation and Validation

With the dataset fully developed, the estimate of FDCs will be conducted using the three proposed methods in each study region. Validation of the FDC estimates against measured data will be conducted using a jack-knife validation approach for each method (except the RETScreen method). For the RETScreen method all study site HYDAT stations will be used in the validation, unless details are found that indicate which stations were used in the development of the hydrologic regions, in which case those stations may be excluded. The two other methods will require the development of regional regression equations and will employ watershed parameters as identified above to develop a reasonable predictive dataset.

It is recommended that the validation metrics employed in comparing the methods be taken from Castellarin et al. [15]. In particular, the authors employed a mean relative error calculation for all estimated sites and a particular duration, and also suggested a performance index modelled after the Nash-Sutcliffe [64] efficiency criterion. The various methods will be compared and the preferred method identified.

7.4 Channel Geometry Estimation and Validation

The channel geometry estimation will be conducted using two methods. The first will involve extracting channel widths from the NHN database. The second will involve determining channel bank full width and depths from a step-wise regression analysis as described by Ames et al. [6]. Performance of both methods will be evaluated using a RMSE difference between the two methods.

7.5 Channel Roughness and Slope Estimation

The channel slope will be generated using the DEM data for the study site locations as well as the power-law equation described by Peckham [78] as described in Section 6.2

The range of roughness values for each site will be assigned approximately, based on data from published hydraulics texts as well as an empirical equation developed by Mohamoud and Parmar [61] for bank-full flow levels as described in Section 6.4.

Both of these methods will require the development of some custom code for GreenKenue™ to expedite the estimates. No slope or roughness datasets have been found, so no validation of these techniques appears to be possible. The various approaches will be evaluated in the actual calculation of the calculated velocity and kinetic energy as compared to measured values.

7.6 Channel Velocity and Hydrokinetic Energy Validation

The final task will be to take the estimates of roughness, slope, geometry and flow and estimate the velocity duration curves for each site. These will be compared to the measured velocity duration curves calculated using the EC measurement database. The best-performing results from the FDC estimate and channel geometry estimates will be employed and the roughness and slope estimation methods will also be employed.

7.7 Uncertainty Calculations

Time permitting, the inclusion of an uncertainty estimate may be conducted for several of the FDC estimation techniques and the channel geometry techniques using a bootstrap approach. This will provide uncertainty bounds for the percentile predictions of the FDC curves and the geometry estimates as predicted by the method outlined by Ames et al. [6]. Uncertainty estimates of the RETScreen FDC estimation method and the channel width error estimate may not be easily determined and may have to be estimated (should those methods provide the best results).

Uncertainty in the slope could be estimated from a Monte Carlo method by adjusting DEM values based on the published RMSE value for the DEM. The calculated degree of variability in the slope calculations could be recorded. Errors in the roughness estimate would require some judicious estimation to determine an appropriate range.

With the uncertainty in the estimates of the parameters known, the errors in the estimated velocities could be calculated using the Monte Carlo method described in Section 3.8. This study would provide bounds on the estimate at each location.

Should uncertainty estimates be difficult to obtain on the input parameters a simple sensitivity analysis may be conducted to establish the model's sensitivity to input variable estimation.

7.8 Reporting of Results

Phase II will conclude with a summary report outlining the findings of Phase II and suggesting recommendations for the Phase III investigation.

8 SUMMARY

This report summarizes the findings of Phase I of this study initiated by NRCan to investigate Canada's hydrokinetic power potential. The goal of this report was to report on available methodologies that could be employed in the determination of Canada's hydrokinetic potential, the available data sources and recommendations for Phase II, which includes a methodology validation.

The general approach to estimating the hydrokinetic power suggested in the report involves the solution of the Manning equation to estimate velocity, based in turn on estimates of channel geometry, flow (as flow duration curves), slope and roughness. Each of these four input variables will require individual regionalization and/or approximation methods.

Many techniques were identified in the scientific literature relating to flow regionalization for extreme events, however few studies examined FDC regionalization. Some promising approaches using graphical FDC characterization and employing canonical correlation were identified. Few regional channel geometry and slope estimation techniques were discovered in the literature. Although discharge-based estimates were quite common, other approaches were identified relating channel geometry to drainage area and other physiographic and climatological watershed characteristics. Channel slope calculations at a regional scale are generally accomplished using DEM data, sometimes with power-function smoothing in low-gradient streams. Regional roughness estimation techniques were not discovered and typically roughness values were assumed in the studies examined.

A number of national datasets were identified that could be employed in the next phase of this study. The data sets include measured or calculated physiographic and climatological properties including climate data, hydrometric data, digital soil and land use maps, hydro network maps and digital elevation data. Of particular interest is an internal-use database maintained by WSC for storing water station survey data, which includes cross section, flow and velocity information. This database will be invaluable for validation of the estimation techniques for flow and channel geometry.

The recommended approach for Phase II is to evaluate a number of flow characterization and regionalization techniques including some conceptually simple methods (e.g. Area-Ratio), commonly employed and endorsed methods (e.g. RETScreen) and methods recently developed and employed by the academic community (e.g. CCA with graphical FDC). The recommended approaches for geometry estimation include the use of digital maps of river edges where available, and the use of physiographic and climactic data to drive regression analysis. Channel slope estimation is recommended to be estimated using available DEM data with the investigation of functional smoothing in low-gradient channels. Finally, lacking any regional data or regionalization techniques, roughness is to be estimated as a potential range of values based on published roughness estimates. Validation and uncertainty estimates are to be employed using jack-knife and bootstrap techniques where applicable.

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