The Applicability of Various Frameworks and Models for Assessing the Effects of Hydropeaking on the Productivity of Aquatic Ecosystems

H.A. Morrison[1] and K. E. Smokorowski[2*]

[1]Aqualink, 4936 Yonge Street, Suite 507, Toronto, Ontario, CANADA

[2] Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences, 1 Canal Drive, Sault Ste. Marie, Ontario, P6A 6W4, CANADA. * Author for correspondence.

2000

Canadian Technical Report of Fisheries and Aquatic Sciences No. 2322

Fisheries and Oceans   Pêches et Océans

Canada

Canadian Technical Report of
Fisheries and Aquatic Sciences

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CANADIAN TECHNICAL REPORT

OF FISHERIES AND AQUATIC SCIENCES

May 2000

The applicability of various frameworks and models for assessing the effects of hydropeaking on the productivity of aquatic ecosystems.

By

H.A. Morrison and K.E. Smokorowski[1]

[1]Great Lakes Laboratory for Fisheries and Aquatic Sciences

Fisheries and Oceans Canada

1 Canal Drive

Sault Ste. Marie, Ontario

P6A 6W4

Cat. No. Fs 97-6/2322E ISSN 0706-6457

Correct citation for this publication:

Morrison, H.A., and K.E. Smokorowski. 2000. The applicability of various frameworks and models for assessing the effects of hydropeaking on the productivity of aquatic ecosystems. Can. Tech. Rep. Fish. Aquat. Sci. No. 2322: x + 57 p.

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

A deregulated marketplace for electricity favours companies that can respond rapidly to demands for electricity that occur within the span of a day. Rapid changes in the rate of release of water from dams, a process referred to as hydropeaking, is required to adjust the rate of production of electricity rapidly. Hydropeaking results in dramatic changes in downstream habitat. As such, methods for assessing the effects of hydropeaking on aquatic ecosystems are being developed.

Environmental impact assessment frameworks for instream flow issues represent approaches to addressing the problem of assessing the effects of instream flow (IF) on aquatic ecosystems. A framework is a format for breaking down a complex problem into manageable parts. Most instream flow frameworks have been developed to address the effects of ‘changed’, but stable, hydraulic conditions (i.e. Instream Flow Incremental Methodology). These steady-flow frameworks are not applicable to hydropeaking regimes because they do not account for the potential effects of large, and rapid, changes in flow on downstream habitats and aquatic biota.

The Dual Flow Method (DFM) is an instream flow assessment framework that attempts to assess hydropeaking by considering two extremes, namely, base flow and peak flow. The DFM is able to account for some effects of hydropeaking on aquatic habitat by comparing the two extreme conditions but the methodology does not address the effects of rapid changes in flow on aquatic ecosystems. A validation of DFM suggested that assumptions of the framework resulted in inadequate protection of fish populations.

The environmental impact assessment frameworks provide structure to organize the various models used to predict the impacts of changes in flow on aquatic ecosystems. Fish-Habitat Preference Models, Discharge-Habitat Models and Effects Models are needed to assess the effects of hydropeaking on aquatic ecosystems. Together, these models relate discharge rates to the productivity of aquatic communities. Fish-Habitat Preference Models are based on the relationship between microhabitat features and fish productivity developed for the site of interest. The accuracy with which Fish-Habitat Preference Models describe the site of interest, has the greatest impact on the validity of the outcome of an IF assessment. Fish-Habitat Preference models are species-, site-, and situation-specific. Although there are prescribed steps for developing site-specific Fish-Habitat Preference Models, there is no 'universally applicable' model for relating microhabitat features to the productivity of fish populations in streams.

There are several Discharge-Habitat Models applicable to hydropeaking regimes. Of these, a 2- and 3-dimensional hydraulic model called SSIIM has been used most frequently to predict the relationship between rate of discharge and hydraulic parameters such as velocity, depth and sediment transport. SSIIM can simulate flow that is subcritical, critical, supercritical, and unsteady. The model is also capable of simulating flow through alluvial channels. Of the hydraulic models used commonly for discharge-habitat assessments, SSIIM is most capable of accurately simulating hydropeaking regimes. In the context of creating an environmental assessment framework for hydropeaking, the incomplete understanding of the effects of hydropeaking on fish productivity is problematic. Several effects models are currently being developed by researchers in Norway.

SOMMAIRE

La déréglementation du marché dans le secteur de l'électricité est à l'avantage des entreprises car celles-ci peuvent plus rapidement répondre aux demandes d'énergie au cours de la journée. Des changements rapides au niveau de la vitesse d'écoulement des eaux d'une écluse, processus appelé éclusée hydroélectrique, sont nécessaires pour régler rapidement le rythme de production de l'énergie électrique. Les éclusées entraînent des changements importants de l'habitat en aval. C'est pourquoi les spécialistes élaborent des méthodes permettant d'évaluer les effets des éclusées sur les écosystèmes aquatiques.

Les cadres de travail relatifs à l'évaluation de l'impact environnemental pour les questions touchant le débit en aval constituent des approches qui permettent d'aborder le problème de l'évaluation des effets du débit en aval (DA) sur les écosystèmes aquatiques. Un cadre de travail est un modèle qui permet de décomposer un problème complexe en éléments traitables. La plupart des cadres de travail visant les débits en aval ont été élaborés pour traiter les effets de conditions hydrauliques « modifiées » mais stables (notamment la méthode des microhabitats). Ces cadres de travail sur le débit régulier ne s'appliquent pas aux régimes d'éclusées parce qu'ils ne tiennent pas compte des effets éventuels des changements importants et rapides du débit sur les habitats en aval et le biote aquatique.

La méthode du double débit (DFM pour Dual Flow Method) est un cadre d'évaluation du débit en aval qui vise à évaluer les éclusées en tenant compte de deux

extrêmes, soit le débit de base et le débit de pointe. Avec la DFM, il est possible de prendre en compte certains effets des éclusées sur l'habitat aquatique en comparant les deux conditions extrêmes, mais la méthode ne permet pas de traiter les effets des changements rapides du débit sur les écosystèmes aquatiques. Une validation de la DFM laisse croire que les hypothèses du cadre de travail ont débouché sur une protection inadéquate de la population ichtyologique.

Les cadres de travail d'évaluation d'impact environnemental constituent une structure qui permet d'organiser les divers modèles utilisés pour prédire l'incidence des changements du débit sur les écosystèmes aquatiques. Les modèles de préférences d'habitat du poisson, les modèles d'habitat en fonction du débit et les modèles d'effets sont nécessaires pour évaluer l'impact des éclusées sur les écosystèmes aquatiques. Mis ensemble, ces modèles associent les vitesses de débit à la productivité des communautés aquatiques. Les modèles de préférences d'habitat du poisson sont basés sur la relation entre les caractéristiques du microhabitat et la productivité du poisson, pour un site d'intérêt donné. La précision avec laquelle les modèles de préférences d'habitat du poisson décrivent le site d'intérêt a l'impact le plus élevé sur la validité de l'issue de l'évaluation du DA. Les modèles de préférences d'habitat du poisson sont spécifiques aux espèces, au site et à la situation. Même si le développement des modèles de préférences d'habitat du poisson comporte des étapes précises, il n'y a pas de modèle « universel » permettant d'associer les caractéristiques du microhabitat à la productivité des populations de poissons dans les cours d'eau.

Il existe plusieurs modèles d’habitat en fonction du débit applicables aux régimes d’éclusée. Parmi ceux-ci, le modèle hydraulique bi et tridimensionnel appelé SSIIM a été le plus souvent utilisé pour prédire la relation entre le vitesse de décharge et les paramètres hydrauliques comme la vélocité, la profondeur et le transport des sédiments. Le SSIIM peut simuler un débit sous-critique, critique, hypercritique et non permanent. Le modèle peut aussi simuler le débit dans des lits à fond mobile. Parmi les modèles hydrauliques utilisés couramment pour l’évaluation des habitats en fonction du débit, le SSIIM est le mieux en mesure de simuler adéquatement les régimes d’éclusée. Dans le contexte de la création d’un cadre de travail portant sur l’évaluation environnementale en situation d’éclusée, la compréhension incomplète des effets des éclusées sur la productivité des poissons est problématique. Plusieurs modèles d’effets sont en cours de développement par des chercheurs en Norvège.

1.0 INTRODUCTION

For more than 100 years, North Americans have constructed hydrodams and water impoundment structures to control the flow of water in streams for electricity generation, irrigation, flood control, recreation, and municipal and industrial uses. Alteration of natural stream flow, from the operation of these structures, has been associated with effects on resident fish populations (Hagen and Roberts, 1973; Peters, 1982; Tyus, 1990). Concern about effects of dams on fisheries has lead to regulation of the amount and timing of water release from dams.

The negative effects of dams on fisheries have been attributed primarily to disruption of downstream aquatic habitats (CEA, 1985). Disruption of downstream habitats results from reductions in the flow of water due to diversion, or frequent large-scale changes in flow that result from peaking regimes (CEA, 1985). The availability of habitat for fish has been demonstrated to significantly affect the productivity of fish populations (Loar and Sale, 1981; Jowett, 1992). Habitat attributes are easier to measure than fish populations; hence, the tools that have evolved to relate changes in flow to fishes have focused on relating flow to the availability and amount of habitat suitable for fishes.

These tools, or Instream Flow Methodologies (IFMs), have generally been designed to predict the effects of reductions, or gradual changes, in flow on habitats. As such, most IFMs are designed to predict optimum minimum flow of water to sustain resident fish populations under steady hydraulic regimes or regimes where changes in rate of flow occur gradually over periods of days to months. The primary assumption of these instream flow methodologies is that aquatic biota respond to changes in the amount of habitat at the same rate at which habitat changes. This temporal resolution has generally been compatible with the flow rates of hydro dams generating electricity for a regulated marketplace.

Recently, Canada and other western countries have moved towards deregulation of the marketplace for electric energy. A deregulated marketplace places pressure on providers to be as efficient as possible and hence to respond rapidly to demands for electricity that change within a day. Rapid changes in the rate of release of water from dams, a process referred to as **hydropeaking**, is used to rapidly adjust the rate of production of electricity. Hence, hydropower operators may require or request different restrictions on the amount and timing of release of water from dams in order to compete effectively in the deregulated marketplace.

Concern about the potential negative effects of hydropeaking on aquatic ecosystems has lead researchers to pursue scientifically-defensible tools for quantifying these effects. To effectively assess the environmental impacts of hydropeaking, methodologies specific to hydropeaking are necessary because this process places unique pressures on aquatic ecosystems compared to other water release regimes.

Consequently, the objectives of this report are to; i) review models that can be used to predict the effects of changes in flow on the habitat attributes of a stream; ii) review frameworks for approaching the problem of assessing the effects of hydropeaking on streams; iii) identify knowledge gaps that impede our ability to effectively predict the effects of hydropeaking on abundance of fishes and; iv) outline the steps that precede an ‘instream flow’ assessment.

2.0 DISCHARGE-HABITAT MODELS

One of the steps towards developing an effective environmental impact assessment methodology for hydropeaking is to establish relationships between discharge rates and microhabitat features relevant to the species (or community) of interest. Discharge-habitat models describe relationships between discharge and various microhabitat features. In general, discharge-habitat models are designed to predict the relationship between discharge and a specific microhabitat feature or group of microhabitat features. For example, some models relate discharge to hydraulic features such as velocity and depth. Other models relate discharge to water quality parameters such as suspended sediment concentrations, dissolved oxygen or temperature. Some models address the relationship between discharge and bottom substrate composition while others predict the effects of discharge on aquatic vegetation. When the relationship between discharge and a variety of hydraulic parameters is required, a suite of different discharge-habitat models may be used at a single site. Discharge-habitat models can be grouped into three categories namely, Hydraulic Models, Water Quality Models, and Effects Models The following sections describe models that fall under each of these categories.

2.1 HYDRAULIC MODELS

Hydraulic models were developed to predict hydraulic parameters of a stream such as flow velocities, depth and sediment transport and deposition using information on discharge rates and the topography of the watershed. The appropriate selection of a hydraulic model(s), for analysis of discharge-habitat relationships, requires recognition and understanding of the processes governing stream systems. There are two basic qualities of a stream that must be considered when selecting an appropriate hydraulic model. These qualities are; 1) the geomorphic characteristics of the river channel and; 2) the characteristics of flow (USACE, 1993a).

The geomorphic characteristics of the river channel are divided into two categories namely, rigid boundary and alluvial. Rigid boundary models assume that the boundaries of the stream do not change with flow or time. Alluvial models assume that the boundaries of a stream are movable. Alluvial streams often exhibit significant bed and bank mobility during and after large changes in discharge rates (USACE, 1993a). For these erodible channels, hydraulic models that account for sediment transport and deposition may be necessary to accurately describe changes to downstream habitats resulting from different discharge regimes.

Characteristics of flow can be described according to the dimensionality of flow; type of channel; presense or absense of turbulence; regime of flow and; state of flow (USACE, 1993a). The dimensionality of flow refers to the direction of movement of water through a stream channel. One-dimensional (1-D) hydraulic models assume that water travels in one direction only, namely, along the main axis of the stream (Fig. 1). Changes in the movement of water, in response to objects in the stream, are not considered. Two-dimensional (2-D) models consider movement of water in any direction along a horizontal plane (Fig. 2). These models simulate movement of water around objects but do not consider changes in the direction of flow in an upward or downward direction. Three-dimensional (3-D) models consider the movement of water along horizontal and vertical planes (Fig. 3). As such, these models provide the most ‘realistic’ simulation of the flow of water in streams.

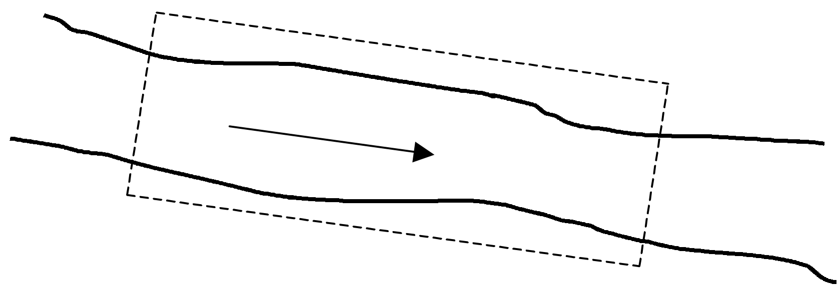


Figure 1: A one-dimensional hydraulic model simulates the flow of water in one direction. Generally, this direction is along the main axis of the stream.

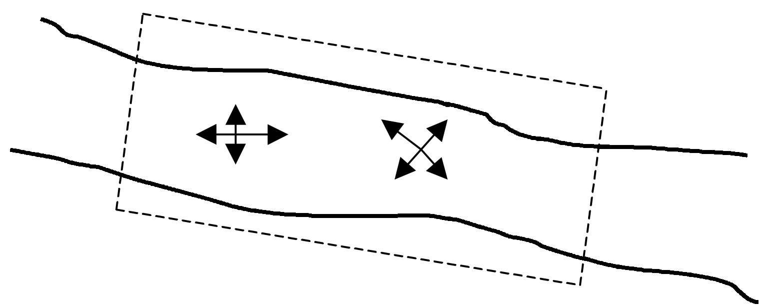


Figure 2: A horizontal, two-dimensional hydraulic model simulates the flow of water in any direction along the horizontal plane.

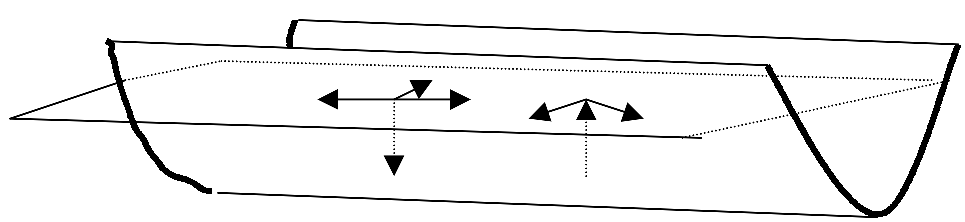


Figure 3: A three-dimensional hydraulic model simulates the flow of water in any direction along the horizontal and vertical plane.

Movement of water is also affected by the type of channel. Channel types may be described as open or closed depending on whether the channel is open to the atmosphere (i.e. water flowing through a stream) or closed to the atmosphere (i.e. water flowing through a pipe). Natural streams are open to the atmosphere, hence, they are categorized as open channels.

Flow is also described as turbulent or laminar. When all water molecules are moving in the same direction, the flow is laminar. Laminar flows occur in smooth channels only. When water molecules move in different directions but generally flow in the same direction, the flow is turbulent. All natural streams have turbulent flow.

The regime of flow can be described as subcritical, critical and, supercritical. The flow regime is defined by the ratio of inertial to gravitational forces (i.e. as represented by the Froude number; see report of USACE, 1993a). When the effects of gravitational forces on water are greater than inertial forces, the regime of flow is referred to as subcritical or tranquil. In subcritical flow, ripples of a shallow water wave can move upstream at a velocity greater than the mean channel velocity. Furthermore, the water surface profile of this type of reach is controlled by channel characteristics at the downstream end of the stream. In these flow conditions, backwaters can form. A backwater is still water that can exist in shallow areas or small sheltered recesses in the shoreline (Vollmer, 1967).

When inertial and gravitational forces are equal, the regime of flow is described as critical. Under these conditions, the ripples of a shallow water wave remain approximately stationary in the river flow relative to the banks.

The regime of flow is supercritical or rapid, when inertial forces exceed gravitational forces. In this state, flow velocity is high and shallow water waves are immediately carried downstream. It is possible to have subcritical, critical and supercritical states of flow at different points along a stream at a single discharge rate.

The final characteristic of flow is described as steady or unsteady. A flow is steady, if the velocity at a specific location does not change in magnitude or direction with time (turbulent movements are not considered in these definitions). A flow is considered unsteady, if the velocity at a point changes with time.

Hydraulic models may be based on different assumptions regarding the characteristics of flow and the geomorphic behaviour of a stream channel. The robustness of a hydraulic model for a stream will depend on how well the assumptions of the model represent the conditions of the system. In general, most streams with hydropeaking facilities are in alluvial basins with flows that are three-dimensional, open-channel, turbulent and unsteady. Additionally, these streams will be comprised of reaches characterized by subcritical, critical and supercritical flow regimes. Most hydraulic model applications assume that stream flow is ‘simpler’ than the description of flow described for hydropeaking regimes.

Hydraulic models are generally categorized according to the dimensionality of flow. Consequently, reviews of 1-, 2- and 3-D hydraulic models, applicable to IF assessments, are presented. Appendix 1 summarizes the features of each of the hydraulic models.

2.11 One Dimensional Models

One-Dimensional (1-D) models assume that water flowing through a stream travels in one direction only, namely, along the main axis of the stream. Within the stream, flow of water in any direction, other than along the main axis, is considered to be negligible. These models view a stream as being comprised of a number of cross-sections or transects (Fig. 4), each of which is characterized by a single depth, stage or water surface elevation, and velocity. The depth and velocity, predicted by 1-D models, represent an average value for the transect. Various mathematical relationships are used to estimate the average value of depth and velocity for a particular cross-section and, to relate the hydraulic parameters of one cross-section to another.

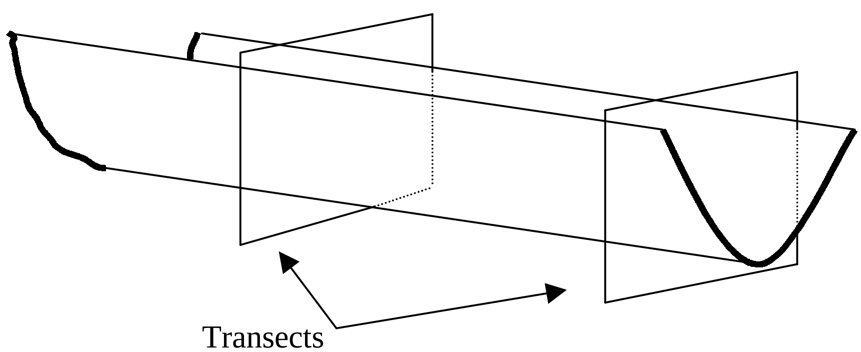


Figure 4: A representation of two transects along a reach of stream.

Most steady flow environmental impact assessment frameworks (otherwise known as Instream Flow (IF) assessments, for example Instream Flow Incremental Methodology see section 4.11) use 1-D hydraulic models. The hydraulic models referred to as IFG-4, MANSQ, WSP and HEC-2 are used most often. When these models are used in an IF assessment, it is assumed that aquatic biota select habitat based on mean cross-sectional attributes of the habitat, flow is turbulent and, channel boundaries are rigid (i.e. they assume that movement of the bed and banks of the stream are negligable during the time period of interest). With few exceptions, these models also assume that flow is steady.

Because hydropeaking flows are characterized as alluvial and unsteady, many 1-D models will not provide realistic simulations of the effects of hydropeaking regimes on stream habitats.

2.111 *One-Dimensional Models that Relate Discharge to Depth*

2.1111 IFG-4

IFG-4 (Bovee et al., 1982) is a steady-flow model designed to predict the average depth of water at a particular cross-section of a stream using a field measured relationship between discharge and depth. A least-squares regression is fitted to three or more pairs of log-transformed discharge-depth data. The depth that corresponds to a discharge, that is intermediate to or outside of the range of measured discharges, is estimated by interpolating or extrapolating along the regression line (Fig. 5). The regression relationship between discharge and depth for a cross-section of stream is referred to as a rating curve. Because a rating curve is based on measured values, this modelling approach is applicable to most stream reaches.

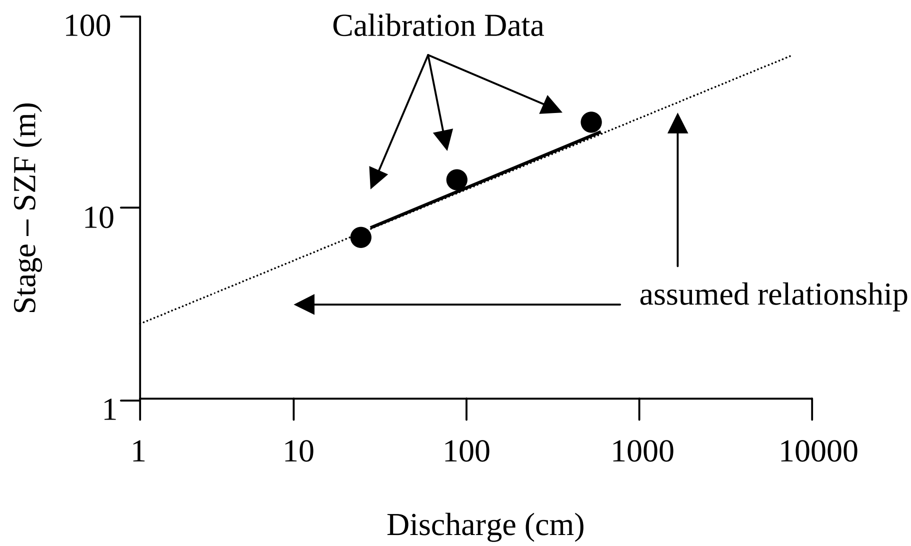


Figure 5: Log-transformed rating curve used to predict water surface elevations at unmeasured discharges in IFG-4. The algorithm in IFG-4 relates the discharge to water surface elevation minus the stage of zero flow (SZF) to ensure that pools will have standing water at zero discharge (from Bovee et al., 1998).

The generality and simplicity of the IFG-4 are considered the best attributes of this model (Bovee et al., 1998). Weaknesses of IFG-4 include the assumption of a linear relationship between log-transformed depths and discharges. Stream researchers have found that this assumption is rarely supported (Bovee et al., 1998). Another weakness of the model is the requirement of large amounts of field measured data for parameterization and calibration. IFG-4 is available as freeware at: http://www.mesc.nbs.gov/rsm/rsm_download.html#PHABSIM.

2.1112 MANSQ

The MANSQ is also a steady-flow model. This model uses the Manning equation to determine the average depth of a cross-section of stream at various discharges. A cross-sectional profile of the stream, along with a discharge and a corresponding depth measurement, are required to parameterize MANSQ. The model also requires calibration. To calibrate the model, additional discharge rates along with corresponding field measured depths are entered into the model and one of the parameters in the model is adjusted until the output of MANSQ corresponds to measured depths. MANSQ uses consecutive iterations to calculate depth based on a simulated discharge.

MANSQ is considered to be superior to IFG-4 because it simulates discharge-depth relationships that are non-linear. One of the limitations of MANSQ is that it is only applicable to channel cross-sections that have a regime of flow that is critical or supercritical. Because MANSQ is not applicable to subcritical flow regimes, the model is most suitable for use at riffles and other types of habitat that do not exhibit backwaters (Bovee et al., 1998). The primary use of MANSQ is to provide initial conditions for WSP and HEC-2 models by calculating depth at control transects (Bovee et al., 1998). The model is available as freeware at: http://www.mesc.nbs.gov/rsm/rsm_download.html#PHABSIM.

2.1113 Water Surface Profile (WSP) and HEC-2

Water Surface Profile (WSP, Milhous et al., 1989) and HEC-2 (USACE, 1982) are steady flow models that are similar to the MANSQ model with the exception that these models are designed for subcritical applications but are not suitable for supercritical applications. As such, these models are frequently referred to as “step-backwater” models. WSP and HEC-2 predict water surface elevation at a transect based on the water surface elevation of the adjacent transect downstream. Consequently, these models require input of a water surface elevation measurement at the downstream-most transect

(Transect 1) to parameterize the model. In most cases, the water surface elevation required to parameterize these models must be predicted. MANSQ is generally used for this purpose (Bovee et al., 1998).

WSP and HEC-2 also require information on the rate of discharge at Transect 1 and the first transect upstream from Transect 1 (i.e.Transect 2). Using these input data, these models calculate cross-sectional area, and the mean channel velocity for each transect. WSP and HEC-2 require calibration to accurately predict the hydraulic parameters of a cross-section of stream. Initial simulations of the models are used to compare predicted water surface elevations to field measured water surface elevations. If there are discrepancies between predicted and measured values, the Manning's n value is raised or lowered to minimize these discrepancies and, thus improve the predictability of the models.

Following the first calibration, the models are rerun and the new outputs are compared to measured data to determine whether the models are accurately predicting water surface elevations at different discharge rates. In this case, measured and predicted water surface elevations, corresponding to various discharge rates, are compared. In the event that model predictions fail to correspond to measured data, a variable that represents channel roughness is modified until the discrepancies are minimized. Once the models have been calibrated to predict water surface elevations corresponding to different discharge rates at the two 'control' transects (i.e. Transects 1 and 2), the model can be used to predict water surface elevations corresponding to various rates of discharge at each transect.

WSP and HEC-2 are based on fundamental hydraulic principles of 1-D flow through open channels and, as such, can provide reliable estimates for the water surface elevation at each cross-section for unmeasured flows if the underlying assumptions are met (Ghanem et al., 1996). Furthermore, these models generally provide better predictions of water surface elevations over a wide range of conditions and discharges than either IFG-4 or MANSQ (Bovee et al., 1998).

Disadvantages of WSP and HEC-2, compared to IFG-4 and MANSQ, are that need to be calibrated extensively and this requires a large commitment of time and attention (Bovee et al., 1998). Furthermore, these models are not suitable to subcritical flow regimes (Bovee et al, 1998) and they require large amounts of field measured data for parameterization and calibration. These models are available as freeware at: http://www.mesc.nbs.gov/rsm/ rsm_download.html#PHABSIM.

2.1114 UNET

UNET is a one-dimensional hydraulic model developed by the US Army Corp of Engineers (Barkau, 1985). The model is similar to HEC-2 except it can simulate unsteady flow regimes. Like HEC-2, UNET is not applicable to reaches of stream with subcritical flow regimes. To date, no references to the use of UNET to predict hydraulic variables in habitat assessments have been found. The program and user manuals are available at a cost from licenced distributors.

2.112 *One-Dimensional Models that Relate Discharge to Velocity*

2.1121 IFG-4

The same IFG-4 model that has been described previously (Section 2.1111) is also the model used most commonly in 1-D analyses to predict velocity (Bovee et al., 1998). A velocity measurement, taken at one of the transects, is used to calibrate the model and the calibrated model is subsequently used to calculate mean velocities corresponding with various discharges at each transect.

An advantage of the IFG-4 approach to calculating velocity is its conceptual simplicity. Disadvantages of using the model include the fact that it is not suitable for modelling velocities at discharges that result in depths that are greater than the ones at which the calibration velocities were measured. Like other one-dimensional models, IFG-4 assumes that the stream is straight hence, the effects of bottom substrate and channel irregularities on the velocity of water are not considered. Milhous et al (1989) state that calcuations of habitat suitable to aquatic biota are considerably more sensitive to errors in velocity measurements compared to errors in depth measurements. Thus, it has been suggested that an approach, more rigorous than IFG-4, should be adopted for the determination of velocities (Ghanem et al, 1996).

2.113 *One-Dimensional Models that relate Discharge to Sediment Transport and Deposition*

2.1131 HEC-6

HEC-6 (U.S. Army Corp of Engineers, 1993b) is an alluvial model designed to predict sediment transport and deposition in a stream. This model is an extension of the

HEC-2 model and, as such, treats stream flow as one-dimensional and steady. The model requires information on the slope of the channel bottom and inflow of sediment to calculate reaches that will be subject to sedimentation or channel scour. The output of HEC-6 is the average dimensions of a channel cross-section. This output can be used directly in one-dimensional water temperature and water quality models but the resolution of the model is not adequate for use in habitat assessment frameworks such as PHABSIM (section 4.1111) (Bovee et al., 1998). The model is available at a cost from licenced distributors.

2.12 Two- and Three-Dimensional Hydraulic Models

Two- and three-dimensional models have evolved to address many of the weaknesses of 1-D models. These multi-dimensional models incorporate hydraulic equations that enable more accurate predictions of hydraulics of water flowing through streams. Two- and 3-D models predict depth and velocity in two- and three-dimensions which enables the identification of back eddies, shear currents and in the case of 3-D models, areas with vertical water circulation (Alfredsen and Harby, 1999). These models view a stream as a continuum rather than a number of cross-sections. As a result, the spatial resolution of simulations with these models is very high. Because aquatic biota respond to microhabitat features, the advantage of using a 2- or 3-D model, as opposed to a 1-D model, is the capacity of these models to predict microhabitat attributes of a stream. Furthermore, the detailed representation of a stream, provided by multi-dimensional models, may allow researchers to develop better relationships between aquatic biota and habitat features (Bovee, 1996).

Other advantages of using 2- and 3-D models is that they generally require less calibration and less field measured data compared to 1-D models (Alfredsen and Harby, 1999). Two- and 3-dimensional models do not use velocity measurements as input data and do not require detailed velocity measurements at several discharges. Instead, a limited amount of velocity data is collected to verify the model output. These models do require topographic data and information about channel roughness for parameterization. Typically, these data are easier and less expensive to collect than velocity data.

Alfredsen and Harby (1999) reviewed various applications of 2- and 3-D models in habitat assessment studies and categorized these applications as follows:

- Practical Applications of 2-D models in Habitat Assessments - Two-D models were used exclusively in these studies because traditional methods for habitat assessments do not use the additional hydraulic data provided by 3-D models (Leclerc et al., 1994; Bartsch et al., 1996; Boudreau et al., 1996).
- Comparisons of the Utility of 1- and 2-D Models in Habitat Assessments – Studies of this type compare the accuracy of habitat assessments based on 1-D models to those based on 2-D models. For example, Ghanem et al. (1994), Olsen and Alfredsen (1994), Waddle et al. (1996) and Tarbet and Hardy (1996) examined differences in hydraulic output from 1- and 2-D models. Leclerc et al. (1995) examined the validity of a 2-D hydraulic model. Leclerc (1997) and Alfredsen et al. (1997) compared weighted usable areas based on 1-D and 2-D hydraulic data.
- Development of New Methods for Habitat Assessment Utilizing Multi-Dimensional Models – These studies focus on developing new methods for habitat assessment that utilize the added information available from 2- and 3-D hydraulic models. This

includes the use of new data like snout-velocity combined with traditional assessment methods (Heggenes et al., 1996) and combinations of new methods for classiflying the spatial environment and utilizing of new data for habitat assessment (Bovee, 1996; Harby and Alfredsen, 1998; Borsanyi, 1998; Waddle et al., 1998; Wentzel, 1999).

Two-D hydraulic models have been demonstrated to provide significantly more accurate representations of the hydraulic features of a stream (Ghanem et al., 1996). The primary advantage of 2- and 3-D models is that they rely on fewer assumptions than 1-D models and therefore provide a more realistic representation of stream hydraulics. The primary disadvantage of 2- and 3-D models is the complexity of the model formulations. Like 1-D models, 2- and 3-D models should be used only by experts trained to use hydraulic models.

Different versions of 2- and 3-D models exist (King, 1990; LeClerc et al., 1995; Ghanem et al., 1996; Olsen, 1996; Habersack and Mayr, 1999). These models differ mostly in terms of accepted format of input data and, ability to simulate supercritical and subcritical states of flow. Many of the 2-D models, that have been used in habitat assessments, are not readily available in pre-packaged software but are described in detail in associated publications (see LeClerc et al., 1995; Ghanem et al., 1996; Habersack and Mayr, 1999). Two- and three-D models that are available in pre-packaged software and have been used in IF assessments are RMA-2, AquaDyn and SSIIM.

2.121 *Rigid-Boundary, Two-Dimensional Hydraulic Models*

2.1211 RMA-2

RMA-2 is a horizontal, depth-averaged, 2-D hydraulic model developed by Resource Management Associates (RMA) for the US Army Corps of Engineers (USACE) (King, 1990). This 2-D hydraulic model calculates vertically- (i.e. depth-) averaged values of water velocity in any direction on a horizontal plane. RMA-2 is capable of calculating velocity under steady- and unsteady-state conditions but is strictly applicable to rigid boundary situations. RMA-2 is not capable of modelling velocity for supercritical flows. Hydropeaking is very likely to result in rapid changes in the regime of flow (i.e. critical, subcritical and supercritical) along the impacted stream reach. The inability of RMA-2 to predict velocity under supercritical flow conditions limits the applicability of the model to hydropeaking regimes. The ability of RMA-2 to predict areas that will go dry or be re-wet, in response to changes in discharge, is considered to be superior to other 2-D hydraulic models (Wentzel, 1999).

2.1212 AquaDyn

AquaDyn is a depth-averaged, 2-D, rigid boundary, hydraulic model for calculating water velocity and depth under steady- and unsteady-state conditions. AquaDyn is better suited to hydropeaking applications compared to RMA-2 because it is capable of modelling hydraulic parameters for sub- and super-critical flow conditions. A study comparing the use of AquaDyn and two other 2- and 3-D models, for the quantification of instream flow needs of fish, is being undertaken in Norway (http://www.sintef.no/units/civil/water/ iahr/oeyvoll.htm). Preliminary work suggests that, compared to SSIIM (see section 2.1231), AquaDyn is less accurate for calcuating the effect of discharge on the depth and shoreline boundaries (Alfredsen and Harby, 1999). Because shallow areas are often the most important to maintenance of fish populations, this model is not appropriate for many habitat assessments. No other references to the use of the model in habitat assessments have been found. AquaDyn software and reference manuals are available commercially.

2.122 *Alluvial, Two-Dimensional Hydraulic Models*

2.1221 TABS-2

TABS-2 (Thomas and McAnally, 1985) is an extension of RMA-2 designed to calculate water surface elevations, current patterns, dispersive transport, sediment erosion, transport and deposition, resulting bed surface elevations and feedback to hydraulics. Like RMA-2, TABS-2 is not applicable to supercritical flow regimes. The ability of TABS-2 to calculate velocity patterns around structures and islands is considered to be very good (USACE, 1993). There are no known references to the application of this software to habitat analyses. TABS-2 is available commercially from licenced distributors.

2.123 *Alluvial, Two- and Three-Dimensional Hydraulic Models*

2.1231 SSIIM

SSIIM (Olsen, 1996) is a hydraulic model designed to calculate the velocity, depth, and sediment transport and deposition in 2- and 3-dimensions based on discharge and topographic features of a stream. SSIIM appears to be the hydraulic model of choice for hydropeaking applications (Halleraker et al., 1999; Alfredsen and Harby, 1999; Harby et al., 1999). SSIIM is appropriate for steady and unsteady flows and can handle subcritical, critical, and supercritical flow regimes. As such, SSIIM is the hydraulic model most capable of accurately simulating hydraulic parameters in streams subject to hydropeaking.

Methodologies for applying the model to habitat assessments are described by Alfredsen and Harby (1999). Data requirements of the model include geo-referenced bathymetry measurements, velocity measurements (for model verification) and, bottom substrate composition (or ‘roughness’). The model uses this information to divide the stream into a series of cells, each of which, is characterized by a particular bathymetry and bottom substrate composition.

With respect to the validity of SSIIM (version 1.4) for hydropeaking applications, preliminary evidence indicates that the model is reasonably accurate at predicting depth and velocity in areas of the stream that are not subject to drying and wetting during a hydropeaking cycle (Alfredsen et al., 1999). The model did have problems accurately predicting depth and velocity in the drying and wetting zones. Because these zones are particularly important to fish, a new version of the program is being developed to resolve this short-coming (Alfredsen et al., 1999). SSIIM is available as freeware at: http://www.sintef.no/units/ civil/water/vass/ssiim.html.

2.13 Hydraulic Models that Consider Vegetation

1-D, steady flow, rigid-boundary hydraulic models (Darby and Thorne, 1996; Tsihrintzis and Madiedo, 1999) and a 2-D, alluvial model (Shimizu and Tsujimoto, 1994) have been developed to estimate the effect of vegetation on the flow of water. These models are useful for predicting depth and velocity in vegetated areas of a stream. These models are hydraulic models, not effects models; hence, a primary assumption of these models is that aquatic vegetation, present in the stream, is adapted to flow conditions. Hydropeaking has been observed to affect, significantly, the composition and density of aquatic vegetation located downstream from a dam (Johansen and Fjeldstad, unpubl.). Consequently, these models may not be applicable to instream flow assessments of hydropeaking.

2.2 WATER QUALITY MODELS

2.21 QUAL-2E

The water quality model used most commonly in IF assessments is QUAL-2E (Brown and Barnwell, 1987). QUAL-2E is capable of simulating temperature, dissolved oxygen, BOD, nutrient kinetics, iron, manganese and, coliform bacteria. QUAL-2E is a one-dimensional, steady-state model designed for steady flow conditions. As such, QUAL-2E is only appropriate for assessing water quality conditions in steady flow regimes.

2.22 CE-QUAL-RIV1

CE-QUAL-RIV1 (USACE, 1990) is a one-dimensional, unsteady flow, hydraulic and water quality model that has been designed for application to hydropeaking regimes. Like QUAL-2E, CE-QUAL-RIV1 is capable of simulating temperature, dissolved oxygen, BOD, nutrient kinetics, iron, manganese and, coliform bacteria. The primary difference between the two models is that CE-QUAL-RIV1 is dynamic and can simulate dramatic changes in stream flow and the effects of these flow changes on water quality parameters. The model is sophisticated, difficult to use, and considered to be in the developmental stages (Bovee et al., 1998). The model is available as freeware from: Environmental Laboratory: Waterways Experimental Station, US Army Corp of Engineers, 3909 Halls Ferry Road, Vicksburg, MS, 39180-6199.

2.23 Stream Network Temperature Model

The Stream Network Temperature Model (SNTEMP; Theurer et al., 1984) is the water temperature model that has been used most often in IF habitat assessments (Bovee et al., 1998). SNTEMP is a one-dimensional, steady flow model. The model is not capable of calculating water temperatures in streams subject to rapid changes in flow (i.e. hydropeaking regimes) (Bovee et al., 1998). The utility of SNTEMP, for assessing the effects of stable discharge rates on aquatic habitat, is described by Bovee et al. (1998). The model is available as freeware at http://www.mesc.nbs.gov/rsm/ rsm_software.html.

2.3 EFFECTS MODELS

2.31 Aquatic Vegetation

Models designed to describe the effects of hydropeaking on aquatic vegetation are being developed by Norwegian researchers (http://www.sintef.no/units/civil/water/effekt/wat-veg.htm). These models are being developed to work with the SSIIM model. Preliminary results of field studies indicate that hydropeaking (min. flow 1.3 m^3/sec. max. flow 80 m^3/sec.) can significantly affect the composition and density of aquatic vegetation located downstream from a dam (Johansen and Fjeldstad, unpubl.).

2.32 Stranding Index

The 'Stranding Index' was developed by Milhous (1990) and intended for use in the Dual Flow Methodology (see section 4.212). The Stranding Index is designed to predict the likelihood that fish would be stranded during the 'ramping down' phase of a peaking cycle. The index is based on the assumptions that aquatic species will be distributed in proportion to the distribution of physical habitat at the generation flow; then, as the flow rate decreases rapidly to base flow, species will escape to suitable habitat only if the conditions at base flow are suitable for escape. For the Dual Flow Methodology, a stream reach is divided into cells. A cell is considered to be suitable for escape if the depth of that cell remains greater than one-half the dorso-ventral height of the aquatic species of interest. Stranding Areas (SAs) are those areas unsuitable for escape at base flow but that are suitable to aquatic species at generation flow. The Stranding Index (SI) is defined as:

$$SI = \sum_{i=1}^{n} SA(i) / WUA(Q_G)$$

Where,

- $SA_{(i)} = 0$ if conditions are suitable for escape or equals the weighted usable area for the cell if the conditions are not suitable for escape and;
- WUA (Q_G) is the total weighted useable area at the generation flow (Q_G).

Milhous (1990; 1992) applied the Stranding Index to salmon inhabiting a river in New York but the validity of the technique has not been verified.

2.33 Salmonid Population Model

The following description of the Salmonid Population Model (SALMOD) is an exerpt from the Instream Flow Incremental Methodology website published by the U.S. Geological Service (http://www.mesc.nbs.gov/rsm/more_salmod.html).

“SALMOD is a computer model that simulates the dynamics of freshwater salmonid populations, both anadromous and resident. The model’s premise is that egg and fish mortality are directly related to spatially and temporally variable micro- and macrohabitat limitations, which themselves are related to the timing and amount of streamflow. Habitat quality and capacity are characterized by the hydraulic and thermal properties of individual mesohabitats, which we use as spatial "computation units" in the model. The model tracks a population of spatially distinct cohorts that originate as eggs and grow from one life stage to another as a function of local water temperature. Individual cohorts either remain in the computational unit in which they emerged or move, in whole or in part, to nearby units. Model processes include spawning (with redd superimposition), growth (including egg maturation), mortality, and movement (freshet-induced, habitat-induced, and seasonal). Model processes are implemented such that the user (modeler) has the ability to more-or-less "program" the model on the fly to create the dynamics thought to animate the population."

To date, SALMOD has been applied to a fall chinook population in a portion of the Trinity River, California only. Researchers are in the process of collecting data sufficient to begin an application on the Klamath River, California, and there is another trial underway with rainbow and brown trout on the Poudre River, Colorado.

SALMOD is a steady flow model designed to 1) determine the population consequences of alternative flow (and temperature) regimes, 2) predict the relative magnitude of mortality in determining the timing and degree of habitat "bottlenecks", and 3) design flow regimes to mitigate those bottlenecks.

SALMOD employs a weekly time step for one or more biological years. Biological years typically (but not always) start with the first week of spawning. All rate parameters (e.g., growth, mortality) and physical state variables (e.g., streamflow, water temperature) are represented by mean weekly values. As such, the model is not suitable to water release regimes where stream flow and water temperatures can change dramatically over the course of a day (i.e. hydropeaking). More information on SALMOD, along with the software, is available at: http://www.mesc.nbs.gov/rsm/rsm_software.html.

2.34 Other Research Efforts

Currently, researchers at the SINTEF Research Institute in Norway are working to develop models to predict:

- The effects of hydropeaking on the stranding of juvenile salmonids (Saltveit et al., 1999);
- The effects of hydropeaking on fish activities (i.e. swimming, feeding etc.) (Vehanen et al, and Perry et al., 1999) and;
- The effects of hydropeaking on the bioenergetics of fish (Harby et al., 1999). These studies are in the preliminary phases.

3.0 FISH HABITAT PREFERENCE MODELS

Another step toward developing an effective environmental assessment methodology for hydropeaking is to determine the microhabitat preferences of fish and other aquatic biota inhabiting the stream of interest. The microhabitat features, that most significantly influence the presense or absense of a species, will drive the selection of the discharge-habitat model needed to quantify the effect of hydropeaking on aquatic habitat. For instance, if brook trout are one of the species of interest in the impacted stream; and temperature, velocity and depth are the microhabitat features that most significantly influence the suitability of the stream to trout; then a discharge-habitat model that relates discharge from the dam to temperature, velocity and depth in the stream will be needed in the IF methodology. In other cases, vegetation and temperature might be the microhabitat features that most significantly affect the suitability of a stream to the aquatic species of interest. In this case, a discharge-habitat model that relates discharge from a dam to downstream vegetation and temperature would be needed to adequately assess the impact of hydropeaking on aquatic biota.

As mentioned previously, hydropeaking places unique demands on aquatic biota and as a result many biota may require specific habitat features to adapt to hydropeaking regimes. For instance in Norway, preliminary results of a fish stranding study indicated that temperature and/or season and light conditions have the most profound effect on stranding of juvenile salmonids (Halleraker et al., 1999). Consequently, discharge-habitat models that account for temperature and/or season and light would be needed to accurately assess the effects of hydropeaking on these fish. In the West Salmon River in Newfoundland, researchers found that Atlantic salmon and brook trout preferred different combinations of microhabitat features depending on the rate of discharge (Perry et al., 1999). To accurately assess the effects of hydropeaking on salmon and brook trout, a fish habitat preference model that accounts for changes in habitat preferences with changes in discharge rates would be necessary.

In light of this, it becomes apparent that fish habitat preference models are species-, site- and sometimes situation-specific. Before one can proceed with an instream flow assessment one needs to identify the species of interest and then develop relationships between microhabitat features and suitability. These relationships are generally based on field observations, literature surveys of field observations and/or expert opinion.

Fish-habitat preference models generally take the form of habitat suitability indices (HSIs). HSIs are based on fish habitat preference data. Fish habitat preference data should be based on observations obtained during different seasons, times of day, discharge rates and at various locations within a stream. Methods of observation include snorkelling, SCUBA, electrofishing or radiotelemetry. Snorkelling, SCUBA and electrofishing are considered to be inferior methods for obtaining fish habitat preference information because the accuracy and reliability of these methods can be compromised by turbidity, water depth, water conductivity, water velocity, debris (Perry et al., 1999) and biased selection of sampling sites. Radiotelemetry is considered to be the best method of data collection because it provides detailed information on fish movements on both large and small spatial scales and provides a means of continuously monitoring fish position relative to biotic and abiotic conditions (Perry et al., 1999).

To develop an HSI from fish habitat preference information, the preference of a fish for a range of conditions within a microhabitat type (i.e. temperature, % cover, depth etc.) is rated on a scale from 0 to 1 where, 1 indicates the highest preference for a particular condition within the range (Fig. 6). The ratings for each microhabitat type are combined to form a matrix of all possible combinations of microhabitat types (Fig. 7). The ratings for each microhabitat type are cross-multiplied and divided by the sum across all matrix combinations to produce suitability values between 0 and 1 for each of the various combinations of microhabitat features. The final HSI is used in conjunction with the microhabitat features of a site to calculate the weighted usable or suitable area (WUA or WSA) of that site to the lifestage or species of interest.

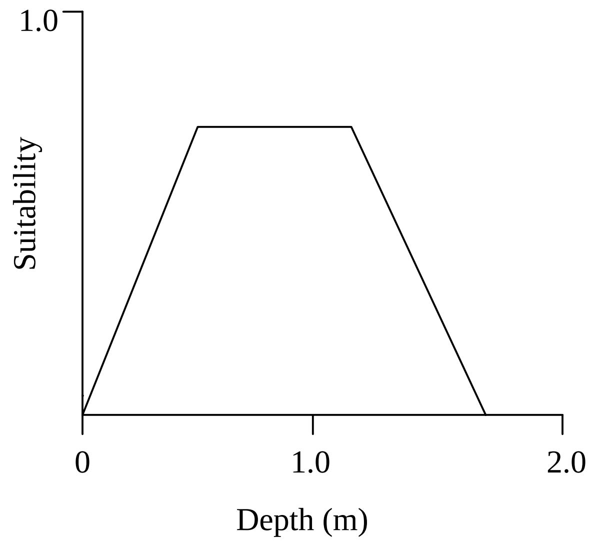


Figure 6: An example of a habitat suitability curve for an aquatic organism.

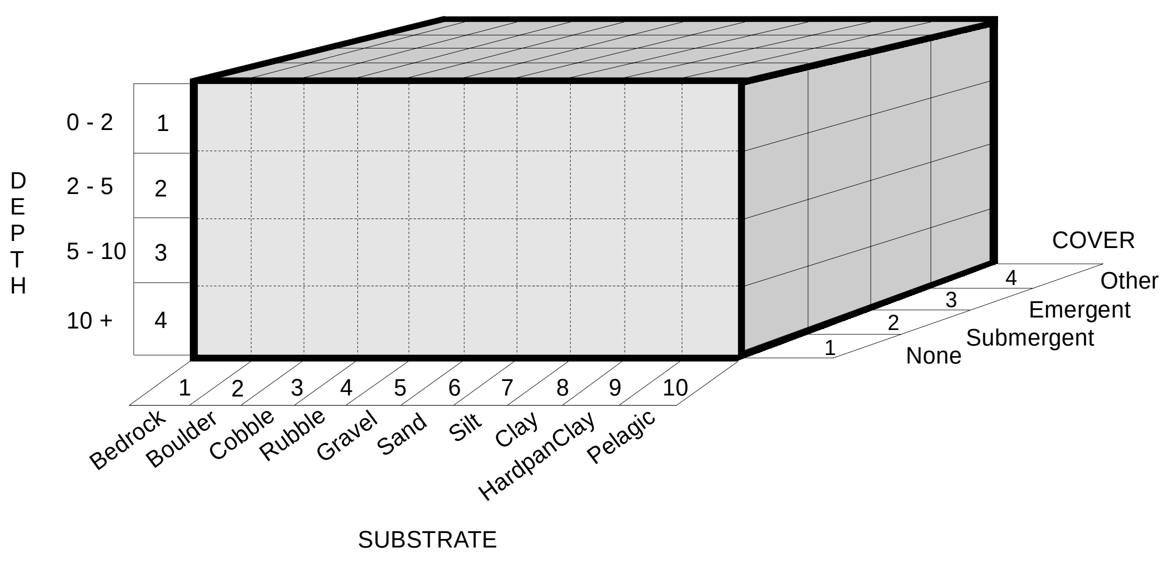


Figure 7: A three-dimensional matrix of fish habitat suitability with depth, substrate, and cover axes (from Minns and Bakelaar, 1999).

The U.S. Fish and Wildlife Service has published a set of standards for the development of HSI models (USFWS, 1981; Terrell et al., 1982) and developed a series of HSI models for selected fish and wildlife species (http://webmesc.mesc.nbs.gov/hsi/HSI_models_available.html). Bovee et al. (1998) reviews many of the techniques used to develop HSI models. It should be noted that the guidelines and models are not specifically intended for application to hydropeaking regimes and, therefore, will require modifications before they can be applied to impact assessments of hydropeaking. The HSI model is one of the most important components of an instream flow assessment. It is imperative that the HSI model accurately represent the habitat preferences of the species of interest at the site of interest. Application in an assessment of HSI models developed for streams and species, other than the ones of interest, can result in a high degree of uncertainty in the outcome of the assessment.

4.0 INSTREAM FLOW ASSESSMENT FRAMEWORKS

Instream flow methodologies provide structure to organize the various models used to predict the impacts of changes in flow on aquatic ecosystems. The models that comprise a methodology can take the form of complex deterministic models or simple qualitative relationships. A framework that fully addresses the potential impacts of hydropeaking on downstream ecosystems would include the following types of models;

1) Fish Habitat Preference Models – Models that relate the microhabitat features of a site to the microhabitat preferences of species and lifestages of fish during different seasons and times of day;

2) Discharge/Habitat Models – Models that relate changes in flow through time to microhabitat features such as depth, velocity, temperature, water quality, vegetation etc. under various climatic conditions.
3) Effect Models – Models that account for the capacity of lifestages and species to respond to changes in microhabitat features through time and the bioenergetic costs associated with living in an artificially unstable environment.

4.1 STABLE HYDRAULIC REGIMES

4.11 IFIM – Instream Flow Incremental Methodology

Instream flow assessment frameworks have been developed to approach the problem of assessing the effects of instream flow on habitat for fish under changed, but stable, hydraulic conditions. The most popular framework is the Instream Flow Incremental Methodology (IFIM). The intended use of IFIM is to elucidate the factors that most significantly affect the productivity of fishes so that the minimum instream flow necessary to sustain maximum productivity can be determined. IFIM provides structure to organize the use of hydraulic models and fish-habitat preference models in order to quantify the amount of habitat potentially available to species and lifestages of fish, in a given reach of a stream, under different flow regimes. The IFIM approach to assessing the effects of 'changed', but steady, instream flows is the basis of the software programs PHABSIM (section 4.1111) and HABITAT (4.1112). IFIM is generally comprised of four component models. These models have been developed to;

1) simulate the microhabitat features of a stream;
2) allow the determination of depths, velocities, substrates and cover objects by area;

3) determine the composite probability of use for each combination of depth, velocity, substrate, and cover found within the study reach for each species and lifestage under investigation and;
4) calculate a 'weighted usable area' (WUA) (defined as "a habitat's carrying capacity based on physical conditions alone" (Bovee, 1978)) for each discharge, species and lifestage under investigation in order to facilitate the development of flow versus habitat relationships.

The scope of IFIM has the potential to change as models are added to the framework and the ability of component models to accurately predict the WUA improves. In its present state, the primary assumptions of IFIM are that:

- discharge from the dam is constant over time;
- the abundance of fish is related directly to the amount of habitat suitable to fish (habitat that would support a particular lifestage of a fish species, defined at the outset of the study by the participants);
- depth, velocity, substrate and cover characteristics are the microhabitat features that affect most strongly the suitability of habitat to fish and;
- the methodology is universally applicable to any stream.

Several comprehensive reviews of the validity and applicability of IFIM are available (i.e. Orth and Maughan, 1982; Stein, 1997). The methodology has been used extensively but rarely tested, particularly in relation to the biological output. The IFIM approach to assessing the relationship between discharge and habitat is designed to predict responses of fish to average microhabitat conditions under steady flow conditions. The methodology is not applicable to hydropeaking regimes because it does not account for the potential effects of large and rapid changes in flow on downstream habitats and aquatic biota.

4.111 *Software that Combines Fish-Habitat Preference Models and Discharge-Habitat Models*

4.1111 PHABSIM

Combining Habitat Suitability Indices (HSIs) with measurements of site-specific microhabitat availability is the basis of PHABSIM Software. PHABSIM (Physical Habitat Simulation System; Bovee, 1982) is based on IFIM. PHABSIM is designed to simulate the relationship between stream flow and physical habitat for a predetermined selection of lifestages and species of aquatic biota under steady flow conditions. PHABSIM requires information on the velocity, depth, cover and substrate characteristics of a stream. Information about cover and substrate is usually obtained from field observations. Hydraulic simulation models are used to forecast changes in depth and velocity in response to changes in discharge.

PHABSIM software contains 1-dimensional hydraulic models to predict the mean depth and velocity of water at transects within a stream (i.e. IFG-4, MANSQ, WSP, and HEC-2). The software also includes models to predict channel geomorphology (i.e. HEC-6) and water quality including temperature (i.e. SNTEMP, SSTEMP and QUAL-2E). The output of discharge-habitat models are used, in conjunction with HSI models, to determine the weighted usable area of a stream to the lifestages and species of interest.

PHABSIM has been used in the Dual Flow Method (see section 4.212) to determine the weighted usable area (WUA) of habitat during base flow and generation flow.

PHABSIM is based on the assumptions that there is a direct relationship between physical habitat conditions and fish production; the population is limited by a lack of appropriate habitat at some stage in the life history of the species and biological factors such as predation and competition are not limiting. It should be noted that component models of PHABSIM have been developed primarily for salmonids that inhabit cold water and high gradient streams. As such, the models commonly used within the framework have been found to be unsuitable for use under warm water and low gradient conditions (Zorn and Seelbach, 1995)

PHABSIM is available as freeware by USGS (http://webmesc.mesc.nbs.gov/rsm/rsm_download.html#PHABSIM). User manuals for the software can be ordered at a cost from the same website. It is recommended that only trained experts use the PHABSIM software.

4.1112 HABITAT

Combining Habitat Suitability Indices (HSIs) with measurements of site-specific microhabitat availability is also the basis of HABITAT Software. HABITAT software is very similar to PHABSIM. The software uses the HEC-2 hydraulic model to calculate relationship between discharge, depth and velocity but is also compatible with 2- and 3-D versions of SSIIM.

Like PHABSIM, HABITAT is based on the assumptions that there is a direct relationship between physical habitat conditions and fish production; the population is limited by a lack of appropriate habitat at some stage in the life history of the species and; biological factors such as predation and competition are not limiting.

A description of the methodology is available at: (http://www.sintef.no/units/civil/water/rss/interact/habitat/habi-met.htm).

4.2 HYDROPEAKING REGIMES

4.21 Requirements to Develop an IFM for Hydropeaking Regimes

An effective IFM for hydropeaking situations should account for;

1) the seasonal relationship between rate of release of water from a dam and microhabitat features that might affect aquatic biota such as: depth, velocity, temperature, oxygen, surface area and vegetation;
2) the seasonal and possibly diurnal relationship between microhabitat features and microhabitat preferences of life stages and species of fish;
3) the capacity of lifestages and species of fish to respond to changes in microhabitat features through time and;
4) fitness costs associated with living in an artificially unstable environment.

To date, no formal methodology has been developed to assess these four aspects for hydropeaking on downstream ecosystems. A methodology has been proposed to assess some of the effects of hydropeaking. This methodology is adapted from IFIM and is called the Dual Flow Method (Milhous, 1992).

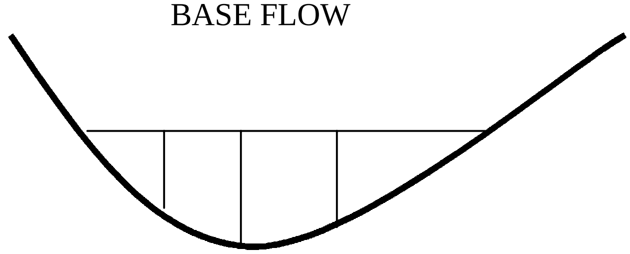
4.212 *Dual Flow Method or Effective Habitat Method*

In its present state, the Dual Flow Method (DFM), otherwise known as the Effective Habitat Method (HABEF; Milhous, 1992), is designed to account for:

- the relationship between rate of release of water from a dam and microhabitat features of the affected site;
- the relationship between microhabitat features and microhabitat preferences of life stages and species of aquatic biota and;
- some aspects of the capacity of species and lifestages of fish to respond to changes in microhabitat features through time.

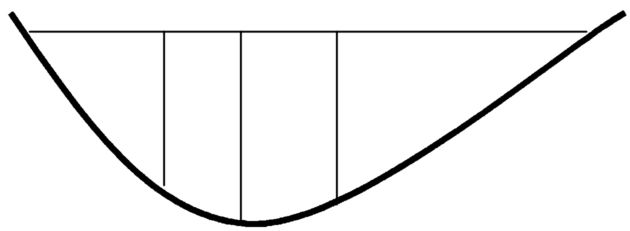
DFM simplifies the problem of considering the incremental changes in habitat that occur as rates of flow change by assuming that hydropeaking regimes are characterized by only two flows namely, a base flow (the lowest flow) and a generation flow (the highest flow). As such, the microhabitat features of various locations in the impact zone of a stream are predicted at base flow and generation flow using a discharge-habitat model that is designed for steady-flow conditions. Outputs of the discharge-habitat model at base flow and generation flow are used in conjunction with information on the microhabitat preferences of various species and lifestages of aquatic biota to estimate the amount of habitat suitable to biota. A ‘Stranding Index’ (see section 2.32) estimates the capacity of lifestages and species of biota to respond to changes in microhabitat features through time. The amount of habitat suitable to a particular aquatic species is calculated as the sum of the minimum habitat occurring at a series of locations in the impact zone during base flow and generation flow as illustrated in Figure 8.

BASE FLOW



WUA for Base Flow = $\sum$ 3 + 2 + 5 + 1 = 11

GENERATION FLOW



WUA for Generation Flow = $\sum$ 1 + 4 + 2 + 6 = 13

Dual Flow WUA = $\sum$ 1 + 2 + 2 + 1 = 6

Figure 8: Calculation of Weighted Usable Area (WUA) for non-motile aquatic biota inhabiting a stream subject to hydropeaking using the Dual Flow Methodology (from Milhous, 1990). The sum of the WUA of each section of the transect is the total WUA for the entire transect at a particular discharge rate.

Primary assumptions inherent to DFM are:

- Abundance of fish is directly related to the sum of the minimum amount of habitat suitable to fish, in a series of reaches that characterize a stream, during a hydropeaking cycle that consists of a period of base flow and generation flow;
- Flow rates that are intermediate to base flow and generation flow do not result in amounts of WUA that are smaller than amounts that are available at base flow or generation flow in each reach of the stream;
- Ramping rates do not affect the productivity of populations of aquatic biota;
- For nonmotile animals, the available habitat is the minimum habitat available in each reach of stream. For motile animals, the minimum habitat is based on the habitat in a reach of stream and in adjacent reaches within a distance that the animal can move;
- Aquatic organisms will be distributed in proportion to the distribution of suitable physical habitat at the generation flow. As the rate of flow decreases rapidly to base flow, organisms will escape to suitable habitat only if conditions at base flow are suitable for escape (i.e. maintain a depth greater than one-half the dorso-ventral height of the fish of interest) and;
- Preferences of aquatic biota for particular microhabitat features during hydropeaking regimes will be the same as the preferences for habitat exhibited during steady flow regimes.

There is evidence to suggest that some of the assumptions of the DFM framework are invalid. Several researchers have found that fish prefer different combinations of microhabitat features depending on the rate of discharge (Holm et al., 1999; Perry et al., 1999). This finding contradicts the last assumption of the framework, namely, ‘Preferences of aquatic biota for particular microhabitat features during hydropeaking regimes will be the same as the preferences for habitat exhibited during steady flow regimes’. If preferences for microhabitat features differ depending on the rate of discharge, it is likely that rates of flow intermediate to base flow and generation flow will result in amounts of WUA that are smaller than amounts available at base flow and generation flow.

DFM was used by Parasiewicz et al. (1998) to develop a flow management system for a river in western Austria that is subject to hydropeaking. DF analysis suggested that fish and invertebrates would benefit from increased base flow and reduced peak flow. DFM does not address ramping rate, hence, this was not changed. The modified peaking regime resulted in an increase in the biomass of benthic invertebrates but did not result in an increase in fish biomass. Parasiewicz et al. (1998) suggest that unaltered ramping rates may have inhibited growth of fish populations. This study suggests that the assumption of the DFM, stating that ramping rate does not affect the productivity of populations of aquatic biota, is invalid.

DFM has also been criticized for using the ‘stranding’ of fish as an endpoint for assessing the effect of hydropeaking on ecosystem productivity (V. Cairns, pers. comm.). ‘Stranding’ is an extreme, and therefore poor, measure of impact. Sublethal effects of changes in flow on fishes is a more sensitive, and therefore, more desirable indicator of change.

DFM must be used to simulate conditions at base flow and generation flow at different times of the year in order to account for seasonal differences in habitat availability. In its present state, the methodology does not account for diurnal relationships between microhabitat features and microhabitat preferences of biota nor does it account for diurnal differences in the capacity of fish to respond to rapid changes in flow rates. Furthermore, DFM does not address the bioenergetic costs of living in an unstable environment.

DFM is an environmental impact assessment framework. As such, models could potentially be added to account for some of the other effects associated with hydropeaking such as diurnal differences in habitat use and behaviour, bioenergetics etc.

4.213 *Other Efforts to Develop Frameworks*

Currently, researchers at SINTEF Research Institute in Norway are working towards the development of a framework for addressing the ecological impacts of hydropeaking (Harby et al., 1999). This research team is in the third year of a four year research program designed to lead to the development of new methods and simulation models to assess environmental impacts of hydropeaking. The program is comprised of the following 5 subprojects:

1) Stranding of Juvenile Salmonids – A field study is being used to quantify stranding of juvenile fish under various climatic, diurnal and hydraulic conditions.
2) Habitat Utilization by Fish during Hydropeaking Cycles – A three-dimensional hydraulic model is being used to simulate variations in the composition and distribution of habitats available during a hydropeaking cycle. Field studies are being performed to determine habitat utilization by fish and invertebrates during a hydropeaking cycle. This information is being used to develop habitat and bioenergetic models for fish.

3) Fish Behaviour during Hydropeaking – Fish behaviour and shelter-type selection during a hydropeaking cycle is being investigated using laboratory and field studies (DFO is collaborating on the field study).
4) The Effect of Hydropeaking on Aquatic Vegetation – Field studies are being carried out to assess the impact of hydropeaking on aquatic vegetation. A 3-D hydraulic model is being calibrated to predict the impacts of hydropeaking on aquatic vegetation.
5) Fish Bioenergetic Studies – Laboratory and field studies along with bioenergetic models are being used to quantify the energetic costs and, the effect on growth of fish, resulting from inhabiting an artificially unstable environment. Laboratory tests will be used to measure stress responses in the physiology of fish exposed to hydropeaking conditions.

The Norwegian study addresses some of the major gaps in our understanding of the effects of hydropeaking on productivity of aquatic ecosystems namely, effects on the structure of habitat, fish behaviour during unsteady discharge regimes and, fitness costs associated with this regime. Results of this study will be used to develop tools to assess the impacts of hydropeaking on aquatic ecosystems and to establish management guidelines to limit damage (Harby et al., 1999).

5.0 GAPS

There are many significant gaps in our understanding of the effects of hydropeaking on productivity of aquatic ecosystems in general and with respect to Canada. General knowledge gaps pertain to:

- effects on the structure of habitat (shifts in substrate type, vegetation, and water quality);
- fish behaviour during unsteady discharge regimes and;
- fitness costs associated with this regime.

Gaps specific to Canada include:

- effects of hydropeaking on the stranding of various lifestages and species of fishes. These studies should consider season and time of day because these factors have been demonstrated to effect stranding of juvenile salmonids (Saltveit et al., 1999).
- Effects of hydropeaking on the activities, behaviours and bioenergetics of different lifestages and species of fish. The work of Perry et al. (1999) could be extended to other habitats in Canada and other species and lifestages of fishes.
- Calibration of 3-D hydraulic models in Canadian streams.
- Development of discharge/habitat models for temperature, vegetation and water quality relevant to the hydrogeology of Canadian streams.
- Studies on the seasonal and diurnal relationships between microhabitat features and microhabitat preferences of lifestages and species of fishes.

6.0 STEPS PRECEEDING AN INSTREAM FLOW ASSESSMENT

Preceding the application of all IF assessment frameworks is a ‘Problem Definition’ phase and a ‘Study Planning’ phase (Bovee et al., 1998). These phases are described in detail at: http://www.mesc.nbs.gov/rsm/IFIM_5phases.html. The following is a summary of the steps involved in each phase.

6.1 PROBLEM DEFINITION PHASE

The Problem Definition phase is comprised of the following steps;

1) all stakeholders involved in or affected by a project are identified and consulted;
2) concerns and information needs of stakeholders are identified;
3) the role of each of the stakeholders in the decision-making process is formalized;
4) the location and geographic extent of the probable impact of the water impoundment project is estimated;
5) locations and/or aquatic species located within the likely impact zone that are deemed to be of special importance are identified;
6) management objectives for the impact zone and species within the zone are formalized.
7) the hydrologic time series (i.e. amount and timing of release of water) of the proposed project is presented and;
8) a baseline hydrologic time series representing either the *status quo* or another baseline that is mutually acceptable is jointly agreed upon.

6.2 STUDY PLANNING PHASE

The Study Planning phase is comprised of the following steps:

1) the temporal and spatial scale of evaluations are identified;
2) important information gaps are identified;
3) a strategy for addressing information gaps is developed;

4) criteria, for evaluating the acceptability of a discharge regime, are developed and agreed upon;
5) the agency responsible for fisheries must describe the biological reference or benchmark conditions;
6) the agency responsible for fisheries should also identify the size of the impact zone; times of the year that are critical in evaluating different life history phases of the fish populations and; aquatic species, communities or food webs of interest.

A written study plan should be developed to:

1) Determine when data collection must be completed in the field;
2) Synchronize the collection of data needed for model input, calibration, and testing;
3) Estimate the labour, equipment, travel, and other costs required to produce the needed information by the agreed study deadline.

An interdisciplinary planning effort, representing all the major interest groups, can result in considerable savings of time and effort during the conflict resolution phase.

7.0 CONCLUSION

Several environmental impact assessment frameworks have been developed to assess the effects of instream flow on aquatic ecosystems. Most of these frameworks have been developed to assess changed, but stable hydraulic conditions (i.e. IFIM, PHABSIM). These steady-flow frameworks are not applicable to hydropeaking regimes because they do not account for the potential effects of large, and rapid, changes in flow on downstream habitats and aquatic biota.

The Dual Flow Method (DFM) is an instream flow assessment framework that attempts to assess hydropeaking by considering two extremes, namely, base flow and peak flow. The DFM is able to account for some effects of hydropeaking on aquatic habitat by comparing the two extreme conditions but the methodology does not address the effects of rapid changes in flow on aquatic ecosystems. A validation of DFM suggested that assumptions of the framework resulted in inadequate protection of fish populations.

All frameworks for assessing instream flow are based on Fish-Habitat Preference Models, Discharge-Habitat Models and, in the case of hydropeaking, Effects Models. Fish-Habitat Preference Models are based on the relationship between microhabitat features and fish productivity. The accuracy of Fish-Habitat Preference Models, to the site of interest, has the greatest impact on the validity of the outcome of an IF assessment.

There are several Discharge-Habitat Models applicable to hydropeaking regimes. Of these, a 2- and 3-dimensional hydraulic model called SSIIM is the model of choice. In the context of creating an environmental assessment framework for hydropeaking, the incomplete understanding of the effects of hydropeaking on fish productivity is problematic. Several effects models are currently being developed by researchers in Norway.

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9.0 APPENDIX 1 - Summary of the Features of Various Hydraulic Models (See Section 2 of Report for Advantages and Disadvantages of each Model).

	Channel Boundaries		Dimensionality of Flow			Regime of Flow			State of Flow		Other Features				
Model	Allu vial	Rigid-Boundary	1-D	2-D	3-D	Sub-Critical	Critical	Super-Critical	Steady	Un-steady	Depth	Velocity	Sediment Transport and Deposition	Water Quality Parameters	Vegetation
Actual Features of Hydropeaking	✓				✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
IFG-4		✓	✓			✓	✓	✓	✓		✓	✓			
MANSQ		✓	✓				✓	✓	✓		✓				
WSP		✓	✓			✓	✓		✓		✓				
HEC-2		✓	✓			✓	✓		✓		✓				
UNET		✓	✓			✓	✓			✓	✓				
HEC-6	✓		✓			✓	✓		✓				✓		
RMA-2		✓		✓		✓	✓			✓	✓	✓			
AquaDyn		✓		✓		✓	✓	✓		✓	✓	✓			
TABS-2		✓		✓		✓	✓			✓	✓	✓	✓		
SSIIM	✓			✓	✓	✓	✓	✓		✓	✓	✓	✓		
1-D Veg.[1]	✓		✓						✓		✓	✓			✓
2-D Veg.[2]		✓		✓					✓		✓	✓			✓
QUAL-2E	✓		✓						✓					✓	
CE-QUAL-RIV1		✓	✓							✓				✓	
SNTEMP		✓	✓						✓					✓	

1 – Darby and Thorne, 1996 and Tsihrintzis and Madiedo, 1999; 2 – Shimizu and Tsujimoto, 1994

10.0 APPENDIX 2

DISCHARGE METHODS

Discharge Methods are based solely on historical streamflow records and do not incorporate information on the microhabitat features of a site. Instream flow needs may be determined as fixed percentages of mean or median annual flow, as constant yield factors (runoff per unit watershed area), or on the basis of an analysis of flow duration. Discharge Methods do not allow the development of discharge-habitat relationships and as such are not suitable for evaluating the potential effects of hydropeaking on fish habitat and productivity. Table 1 provides reference to various comprehensive reviews of the methods and their utilities.

Table 1: List of commonly used discharge methods*.

Fixed Percentage Methods:

Tennant or Montana Method (Tennant, 1976; Bayha, 1978)
Utah Water Records Methodology (Geer, 1980)
25% of the Mean Annual Flow (25% MAF) (Cassie and El-Jabi, 1995)
Median Monthly Flow (Q_{50}) and Aquatic Base Flow (ABF) Method (Cassie and El-Jabi, 1995)
90% Flow Duration Method (Q_{90})
Statistical Low Flow Frequency Method (7Q10) (Cassie and El-Jabi, 1995)
Constant Yield Methods:
The New England Flow Recommendation Policy (NEFRP) Guidelines (U.S. Fish and Wildlife Service, 1981)

Flow Duration Curves:
Northern Great Plains Resource Program (NGPRP, 1974)
Alberta Variation of NGPRP Method (Alberta Environment, 1983)
The Hoppe Method (Hope, 1975; Stalnaker and Arnette, 1976)
One Flow Method (Sams and Pearson, 1963)

Review of Methodologies:
Canadian Electrical Association, 1985; Wesche and Rechard, 1980; Cassie and El-Jabi, 1995

* Note: Basic assumption of all of these methodologies is that habitat availability is a dominant limiting factor for fish populations.