Literature Review of Habitat Productivity Models for Pacific Salmon Species

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EXECUTIVE SUMMARY

A literature review was undertaken for the Department of Fisheries and Oceans (DFO) to develop a template for habitat status reports as part of the Conservation Unit reporting requirements under the Wild Salmon Policy. The objective of the literature review was to summarize the current state of knowledge regarding habitat productivity models for the 5 Pacific salmon species. The models included habitat state indicators and habitat pressure indicators, two components of a framework that can link indicators with values and goals to guide management actions under DFO's Wild Salmon Policy.

We searched the literature for documents that included information on candidate habitat status and pressure indicators provided by DFO. Although the focus of this project was Pacific salmon species, habitat productivity models for trout species were also identified in the literature search and considered in the evaluation of candidate indicators. A total of 113 potentially useful documents containing habitat models were identified in the literature search. We identified potentially useful models by comparing them to a list of potential habitat (pressure and state) indicators supplied by DFO. Following this, we characterized the support for the indicators by identifying and describing the literature concerning specific indicators. In addition, the utility of the indicators as estimates of production was investigated by identifying recent models that included the indicators in a quantitative framework that predicted salmon abundance. In general, there was good support for the habitat status indicators (streamflow, water temperature, water chemistry, physical habitat quality, and habitat area) as indicators of salmon abundance or productivity. There was also support for the habitat pressure indicators (terrestrial development (land use), riparian and foreshore development, and water use, though it was less extensive. All 26 of the indicators identified by DFO are supported by the literature to some extent, either directly or through inference from findings that logically support their application. The level and validity of support varies between indicators, with habitat status indicators having a longer history of evaluation and therefore better support, including experimental evidence for some indicators (particularly water temperature, water chemistry, and some aspects of physical habitat (e.g. substrate sediment and suspended sediment)).

As stand-alone tools, individual indicators can provide a valid representation of habitat status and pressure, though there will be a number of challenges in their interpretation, including non-linearity, scale issues, cumulative and synergistic responses, and conflicting habitat requirements among species and their life stages. The resolution of these issues will require a pilot trial and evaluation of a subset of the most promising indicators, preferably organized in a simple model to facilitate interpretation. The confirmation of trial indicators can be informed by this literature review and the attached annotated bibliography of key recent literature during an analysis of technical feasibility by scientists, program and database managers, and stakeholders.

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INTRODUCTION

The objective of this work is to complete a literature search and review summarizing the current state of knowledge regarding habitat productivity models for the 5 Pacific salmon species. This literature review will help in the development of a template for a habitat status report as part of the Conservation Unit's reporting requirements under the Wild Salmon Policy. Habitat status reports prepared by the Department of Fisheries and Oceans (DFO) will describe habitat in variables defined as habitat state indicators and habitat pressure indicators, two components of a framework that can link indicators with values and goals to guide management actions under DFO's Wild Salmon Policy.

This literature review can be used to support current initiatives to develop habitat status indicators. In 2006 a background information review and summary and expert technical workshop were completed by the Pacific Fisheries Resource Conservation Council (PFRCC) to provide advice and support to DFO on potential habitat indicators (G.A. Packman & Associates Inc. & Winsby Environmental Services (GAP&WES 2006). Those efforts provided an overview of habitat indicator development and the proposed candidate indicators identified during a November 2005 workshop with experts in the field from the PCFRCC, DFO, Environment Canada, B.C. Ministries of Forests and Range/Environment/Agriculture and Lands as well as the Skeena Fisheries Commission, Okanagan Nation Alliance, consultants, and non-governmental organizations. The analysis of recommended indicators required that the potential indicators be tested against a list of technical and feasibility criteria that GAP&WES (2006) listed in their report (source of the indicator, indicator type, rationale, and definition). The present document provides a literature review that can support a reassessment of the feasibility of the indicators identified by DFO.

A key finding from the review of background information by GAP&WES (2006) was that considerable work had already been done in reviewing and identifying wild Pacific salmon habitat indicators: they have been developed for salmon in several other jurisdictions and documented in a dozen reports that identify specific indicators. Despite this extensive prior work, GAP&WES (2006) emphasized that additional effort was needed to develop the indicators, specifically: analyze recommended indicators, evaluate the availability of information necessary to implement the indicators, and implement the indicators at a pilot scale in selected watersheds. GAP&WES (2006) recommended that the indicators be examined by experts in relevant disciplines, preferably in a group setting that included stakeholders (particularly where stakeholders are required for successful implementation of the indicator(s)). The literature review provided herein documents the current state of knowledge on the candidate indicators, and provides the available empirical evidence to rationalize their use.

In another effort to support the development of the Wild Salmon Policy, Nelitz *et al.* (2006) cited three groups of evaluation criteria when selecting ecological indicators: technical, management, and ecological relevance. For habitat indicators, habitat relevance is an analogy to ecological relevance, thus among these criteria, we are concerned here with the 'strength' of the cause-effect link. Thus our work focuses on a narrow aspect of the suitability of an indicator (see GAP&WES (2006) and Nelitz *et al.* (2006) for an elaboration of other aspects and a description of other important criteria to consider when selecting indicators).

In a review of environmental indicators for Oregon salmon and watersheds, Dent *et al.* (2005) identified six focal characteristics of an ideal indicator, as follows:

- Quantifiable: The indicator can be described numerically and objectively.
- Relevant: The indicator will be biologically and socially germane to the questions being asked.
- Responsive: The indicator will be sensitive to the stressors of concern.
- Understandable: The indicator can be summarized so as to be intuitively meaningful to a wide range of audiences and pertinent for decision makers.
- Reliable: The indicators will be supported by science. Statistical properties will be well understood and have acceptable levels of accuracy, sensitivity, precision, and robustness.
- Accessible: Data are available or collection of necessary data is feasible in terms of cost, time, and skills.

The literature review herein can help assess if an indicator is quantifiable, responsive, and reliable. Such aspects of utility could be quantified and compared among different indicators, however, this is beyond the scope of a literature review, and typically such detailed quantitative data are not available for the indicators. Note that reliable is not used here in the sense of statistical reliability, i.e., the consistency of a set of measurements, but rather more broadly to indicate how well a measure will represent the state of the indicator, otherwise known as 'validity'. At present, the primary evidence of indicator validity lies in correlations between the indicators and salmonid abundance, and less frequently through experimental evidence.

There are many publications in the scientific grey literature that report relationships between fish abundance and habitat (e.g., the relationship between coho salmon abundance and stream length in Bradford *et al.* 1997), however, not all of these are useful as indicators. A concise and useful definition of an indicator is provided by Cairns *et al.* (1993):

> "An indicator is a characteristic of the environment that, when measured, quantifies the magnitude of stress, habitat characteristics, degree of exposure to the stressor, or degree of ecological response to the exposure."

Dent *et al.* (2005) distinguished between variables (or data parameters or attributes) and indicators, noting that indicators provide overarching quantifiable descriptions, whereas variables describe the specific data collected and are used to support or calculate the indicator. In some cases, an indicator may be a simple physical parameter, such as the measure of stream length, in others more complex, such as a measure of weighted usable area. Good indicators are understandable and simple to communicate to the public or government decision makers, recognizing the role of stakeholders in implementing both the collection of indicator information and management actions. Habitat state indicators and habitat pressure indicators are analogous to habitat quality and impact variables typically used in habitat and impact assessment models and reported on in the literature, but again, would be expected to be simpler and represent the underlying quantitative variables inherent to impact assessment with an index.

We anticipate that in the future the candidate indicators will be examined by experts in relevant disciplines in a group setting that includes stakeholders, as recommended by GAP&WES (2006). This literature review provides a summary of the current state of knowledge on the candidate indicators in literature that documents the available empirical evidence supporting their use.

METHODS

Multiple resources were utilized for the literature search as described below. There were two literature searches conducted using BIOSIS. The search inputs were:

- salm* AND (stream* OR river* OR lake*) AND (habitat* OR product*) AND (model* or simulation*), and
- (salm* OR fish) AND (stream* OR river* OR lake*) AND (habitat* OR product*) AND (model* OR simulation*) AND (abundance* OR densit* OR biomass* OR capacit* OR product*)

DFO's WAVES library was searched using the terms that were applied in the BIOSIS searches. The WAVES site can be accessed at http://inter01.dfo-mpo.gc.ca/waves2/index.html.

Canadian Science Advisory Secretariat (CSAS) publications were searched on the internet at http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/publications/search_e.asp. Searches were conducted in all publication types (Research Documents, Science Advisory Reports and Status Reports, and Proceedings) in the Pacific region for all years of publication. Search options are limited to the following predefined keywords:

- habitat productivity,
- salmon,

- salmon (Pacific), and
- salmon (pacific)

Pacific Scientific Advice Review Committee (PSARC) documents are available on the internet at: http://www.pac.dfo-mpo.gc.ca/sci/psarc/Default_e.htm. Documents in the following categories were browsed for potential papers, including:

- Research documents in the "Diadromous" and "Habitat" categories (all years), and
- Proceedings Series documents (all years)

The search terms used in the BIOSIS search were entered into Google Scholar (beta version) (available at http://scholar.google.com/). These searches were intended to identify pertinent grey literature, however, they also identified some primary literature that was missed in the BIOSIS searches.

In addition to the literature searches, a review of fish productivity models (Fausch *et al.* 1988) and a review of stream and lake habitat capability models (Korman *et al.* 1994) were screened for models pertinent to the current literature review. Note that several studies reviewed in these two papers were grey literature publications (e.g., US State Fish and Game or Fish and Wildlife departments, Ph.D. theses, M.Sc. theses) dating between 1969 and 1988. The collection at the University of Calgary library was searched for all documents identified in Fausch *et al.* (1988) and Korman *et al.* (1994). Identified documents were obtained where possible. For documents not in the U of C library collection, attempts were made to locate them on the internet (e.g., by going to particular State Fish and Wildlife department web pages). However, most documents identified in Fausch *et al.* (1988) and Korman *et al.* (1994) were written in the 1970's or early 1980's, and could not be found on the internet.

After completing the literature review, we submitted an incomplete draft report to DFO for review and comment, to identify any significant publications that had been omitted. DFO staff provided several additional publications for inclusion in our literature review, particularly grey literature publications not readily accessible on the internet or through academic search engines.

Following the literature searches, we compared potentially useful models to a list of habitat (pressure and state) indicators (supplied by DFO in the file "Master Habitat Performance Indicators List Jan30-06.xls") to identify support for the use of specific indicators. The list of candidate indicators supplied by DFO is provided in Table 1. An annotated bibliography of key recent literature examined has been provided (Note: the documents cited in Fausch *et al.* (1988) and Korman *et al.* (1994) that could not be located have not been included in the Annotated Bibliography, but have been included in Table 2 (the list of models identified in the literature) and Table 3 (links between the literature and the list of candidate indicators) – see below).

RESULTS

1.1. Identified Salmon Productivity Habitat Models

A total of 113 documents containing potentially useful models were identified in the literature search and the review of Fausch *et al.* (1988) and Korman *et al.* (1994). Table 2 lists the individual documents identified by author and publication year, the species and life history stage used in the model(s), and the significant independent variable(s) in the model(s). The majority of the models are focussed on trout species; however, the results are broadly applicable to Pacific salmon productivity in some cases because of the overlap in habitat use between these species.

Our literature review began with Fausch *et al.* (1988) and Korman *et al.* (1994), which provide extensive reviews of habitat productivity models, albeit completed over ten years prior. We have reviewed a number of articles published since that time, including several published in 2006.

To identify potentially useful models, we identified where the model might overlap with DFO habitat performance indicators, for both habitat state and habitat pressure indicators. Of the 113 documents reviewed, the majority of overlap occurred with the DFO habitat state indicators (with slightly more overlap for water quantity and quality data habitat state indicators than for highly productive habitat state indicators). Overlap was relatively uncommon for habitat pressure indicators (land and water use), likely due to the difficulty in quantification of these indicators prior to the advent of GIS and widespread availability of such information in digital form. The overlaps are shown in Table 3, which lists the model number and the overlap for each of the three habitat performance indicators. To use the Tables, it is necessary to flip between them, using the reference number

There are a number of literature models that have direct links with the DFO habitat performance indicators. Although most of the models have potential application as comparative indicators, many appear too specific for widespread application. Other may not quantify habitat performance in absolute terms, they may provide relative indicators of performance. In addition, they may with some additional analysis provide more powerful indicators.

1.2. DFO Habitat Performance Indicators

DFO provided us with a list of 26 habitat performance indicators, variables that describe the state of fish habitats (14 variables) and anthropogenic pressures acting on them (12 variables) (Table 1). This list is presented as provided to us by DFO, whose staff developed it for the purposes of habitat status reporting. The variables include both quantitative measures (e.g., decadal mean daily discharge graphs and mean annual discharge (MAD)) and dimensionless ratios (% riparian forest integrity), with two variables (other habitat issues & constraints; future water & land use trends and threats) presenting undefined pressures on habitat. In several of the indicators the notion of a benchmark arises; for example, streamflow relative to a benchmark.

We note that the habitat status indicators provided by DFO fit well within the hierarchical framework identified during a national workshop on the effects of habitat alteration on salmonid stocks two decades ago (Ryder and Kerr 1989). In this framework environmental assessment can be most effectively focussed by considering fundamental ecological determinants (dissolved oxygen concentration, water temperature, light, and nutrient concentrations) acting within the structural framework of physical habitat. The categories of streamflow, physical habitat quality, and habitat area represent habitat, whereas water temperature, water chemistry and food production are, or are direct products of, the fundamental ecological determinants. The power of this organizational hierarchy may be useful in later stages of indicator development, when the indicators are reviewed, evaluated, selected, and confirmed.

Anticipating the utility of such an organizational hierarchy when assessing the indicators, we organized the indicators identified by DFO into a few simple categories. Habitat status is described by six variable catagories: streamflow, water temperature, water chemistry, physical habitat quality, and other habitat quality or quantity indicators. Grouped in with physical habitat quality was the indicator 'macroinvertebrate indices' as it implies food production, which would be a function of both water chemistry and physical habitat quality. Habitat pressure is defined by terrestrial development (land use), riparian and foreshore development, water use, and other habitat pressure indices. Considering the small number of categories, it is most efficient to organize the literature models based on these indicator catagories.

1.3. Discussion of DFO Indicators that Closely Correspond to Productivity Model Variables

To evaluate more fully the support for individual indicators, we identified the literature that best supports the indicator and discussed the findings relevant to the indicator. We have grouped the indicators together in some cases as they often referenced within the same articles. To facilitate this grouping, we used the five catagories discussed above.

1.3.1. Streamflow

Intuitively, biologists believe that streamflow should correlate with habitat conditions for salmon. Streamflow has been described as a 'master variable' (Poff *et al.* 1997) that controls a suite of physical variables that in turn influence fish production. Flow affects stream surface area, velocity, and depth, but also a host of other physical variables such as light penetration, rates of sedimentation and erosion, and water temperature. The evidence for this link is widespread, from simple correlations driven by mechanisms of unknown causality, to more recent results from controlled flow release experiments.

Three indicators have been identified for streamflow as follows:

1) Decadal mean daily discharge graphs and MADs;
2) Annual peak discharge events (frequency, timing, magnitude, duration) relative to some benchmark (e.g., USGS percentile approach); and
3) Annual mean 7-day-low-flow discharge relative to some benchmark (e.g., < 10% MAD).

All of these indicators are measures of the magnitude of streamflow with relevance to salmon biology supported by literature demonstrating links with habitat or fish abundance. MAD, or mean annual discharge, measures the mean annual quantity of streamflow that, when plotted over time, can illustrate long-term trends in flow. Healey (1991) shows that chinook salmon spawning population sizes correlate with river flow over two orders of magnitude (5 to > 500 cms). This relationship reflects the underlying influence of watershed size (and thus habitat quantity) on population size that was used in Parken's (2006) chinook productive capacity model. Although the mechanism linking fish abundance to average flow may be habitat-based, and not directly a result of flow, the correlation may support the use of MAD as an indicator, as changes in flow will result in direct changes in habitat capacity.

In a review of case histories of regulated streamflow, Burt and Mundie (1986) found evidence that the percent of annual flow stage change was an indicator of declines in salmon populations. Bradford (1993) found evidence in patterns of adult chinook salmon returns had low survival in a river reach where flow was reduced, implying that increased (more natural) flows would restore survival. Much earlier, Smoker (1955) found a correlation between the commercial catch of coho salmon and annual runoff, summer flow, and lowest monthly flow in 21 western Washington basins 2 years prior to return. Mathews and Olson (1980) analysed data from Washington and showed that summer baseflows were correlated with total coho production for Puget Sound streams. Rushton (2000) reported a remarkably strong fit ($R^2>0.9$) between numbers of coho smolts produced in Bingham Creek (Washington) over ten years and 60-day mean summer low flows.

Although direct evidence linking Pacific salmon production to flow is rare, among trout there are a number of definitive studies. Baran *et al.* (1995) showed that changes in the percentage of mean annual flow in regulated reaches correlated with changes in brown trout abundance. Wolff *et al.* (1990) found that resident trout responded to flow increases in Douglas Creek (Wyoming) with a four-to-six fold increase in biomass (habitat surveys showed a doubling of stream wetted width and a five-fold increase in weighted usable area for adult fish). Binns and Eiserman (1979) were able to predict standing stocks of trout in Wyoming based on flow and other habitat variables. Rimmer (1985) showed reduced flow decreased the production of rainbow trout fry in semi-natural experimental stream channels in New Zealand.

The mechanisms responsible for the observed link between flow and fish abundance are multiple, but include reductions in insect drift and resultant fish growth (Harvey *et al.* 2006). Lewis (1969) reported high densities of rainbow and brown trout in pools with greater currents and higher insect drift rates from riffles. These mechanisms would apply to both trout and juvenile salmon species rearing in streams. Experimental flow releases have shown promising responses for Pacific salmon on the Bridge and Alouette Rivers (Rosenau and Angelo 2003), and though not necessarily characterizing the mechanism, provide strong support for flow as an indicator of habitat productivity. Such tests may provide findings similar to those among non-salmonid species, such as a recent study that significantly linked a shift in species composition to a minimum flow increase, confirming independent quantitative predictions of an instream habitat model (Lamouroux *et al.* 2006).

Annual peak discharge events relative to a benchmark provide a measure of the flow that could mobilize and transport stream sediments, alter channel morphology, potentially scour incubating eggs, or increase velocities to high levels that displace juveniles from preferred habitats. Flood magnitude and frequency is a strong predictor of salmon freshwater survival for several species. Empirical evidence for the influence of peak flow on salmon abundance is found in numerous publications including Quinn (2004), who showed that sockeye salmon egg-fry survival decreases with increases in the peak flow during egg incubation in the Cedar River (Washington). Greene *et al.* (2005) were able to predict chinook salmon returns using freshwater and marine environmental conditions, with the return period of floods during incubation having the greatest predictive power. Similarly, Seiler *et al.* (2003) found that flood magnitude explained over 80% of the variance in chinook salmon freshwater survival. Smith (2000) suggested that wild steelhead abundance is negatively affected by high summer and autumn flows in northern, snow-melt driven watersheds. More definitive evidence for stream rearing salmonids was provided by Nehring and Anderson (1993), who showed that rainbow and brown trout young of year in 10 Colorado rivers was negatively correlated with mean monthly snowmelt discharge during the month of peak emergence. Latterell *et al.* (1998) had similar findings.

The 7 day-low flow discharge (e.g., 7Q10, the seven day average discharge with a return period of 10 years) is a common statistic for assessing low flow frequencies, however, there are few published studies relating salmon survival to this statistic. However, given that hydrologic indicators are highly correlated, leading to redundancy among groups of statistics (e.g., Olden and Poff 2003), 7Q10 is likely a good correlate of low flow effects. Creque *et al.* (2005) found that chinook salmon density was positively correlated with the low-flow yield (LFY, the ninety percent exceedance flow standardized by drainage area), negatively correlated with mean July temperature at a watershed scale, and negatively correlated with depth at a site. However, significant correlations between streamflow and salmon productivity may be rare because of the high seasonal and interannual variation in streamflow and the numerous variables that correlate with streamflow.

Streamflow data is continuously collected in B.C. in many locations at high intensity, with many long term (> 20 year long) records available. Where stream specific records are lacking or short term, estimates can be derived from a regional analysis using local long-term stations managed by the Water Survey of Canada (e.g., Obedkoff 2003). The quantity of data provides the opportunity to calculate numerous indices that describe flow and flow change. Indicators of hydraulic alteration (IHA) deal with the magnitude, timing, frequency, duration, and rate of change of flow, all attributes of the flow regime that can affect stream ecology and salmon productivity. Richter *et al.* (1996) calculated 32 different parameters, organized into five groups, to statistically characterize annual hydrologic variation. In a recent review 171 such indicators were identified, yet correlations between them created redundancy that, when removed through principle component analysis, allowed dominant hydrologic patterns to be described by as few as two indices (Olden and Poff 2003).

Flow thresholds, i.e., flow indices scaled to mean flow conditions, may prove to be useful indicators of potential impacts to salmon habitat. A recent initiative to develop flow thresholds in British Columbia uses seasonally-adjusted fractions of median monthly flows to set thresholds that are expected to result in low risk to fish, fish habitat, and productive capacity (Hatfield *et al.* 2003). Although there are no published studies that test the efficacy of these thresholds, they were based on a recent review of the instream flow literature and prescribed flows equal to or higher than other methods commonly used in B.C. The review examined alternative thresholds (such as MAD, and other streamflow statistics proposed as indicators by DFO) and current practises in other jurisdictions, hence the thresholds represent current thinking on setting standards for instream flow. Moreover, the flow thresholds were developed collaboratively with the Ministry of Environment (MOE) and DFO science staff and were guided by their experience. The thresholds rely on the historic flow at the site of interest, allowing their effective use in all streams in the province, despite the great hydrological and biological diversity. Accordingly, they could serve as an indicator of flow alteration, providing that both natural and altered flow regimes have been characterized in the streams being monitored.

1.3.2. Water temperature

One indicator was provided regarding water temperature: 4) annual water temperature graphs (daily max, min, and mean) relative to some benchmark. The role of temperature in the growth and production of salmonids has been well documented in the scientific literature, for example Brett (1995), Downing and Plante (1993), and Weatherley and Gill (1995). The operational definition of productive capacity (Minns 1995) is the sum of the annual production (kilograms•hectare^{-1}•year^{-1}) of all fish populations in a given area: since temperature affects fish weight by determining growth rate, it also affects overall habitat productivity. Ryder and Kerr (1989) identified temperature as a fundamental ecological determinant of habitat productivity. Downing and Plante (1993) found that lake fish populations with an average air temperature of 2°C have production rates on average three times greater than populations with an average air temperature of 0°C.

Water temperature has a direct influence on the rate of salmon egg incubation that varies between species and stocks (Murray and McPhail 1988). Temperature measured as thermal input is implicated as a significant habitat status indicator for chinook salmon fry as well as for trout and char species in Rocky Mountain streams, with land use (grazing) identified as a pressure indicator influencing thermal input (Platts and Nelson 1989). Chinook salmon parr-smolt survival in the Snake River (Idaho and Oregon) correlates negatively with the 'Palmer Drought Severity Index (PDSI), an index of temperature, precipitation, and evapotranspiration (Paulsen and Fisher 2001). Chinook salmon and rainbow trout in Oregon streams were found at higher densities where coldwater patches were more common (Ebersole *et al.* 2003). There are many other examples of the relationship between temperature and trout habitat: in Ontario streams, water temperature was the most important factor discriminating trout biomass density, with pools, substrate size, and cover explaining additional variance (Stoneman and Jones 2000).

Water temperature data is typically collected by continuous recorders that allow individual measurements at user-defined frequencies ranging from seconds to days, allowing annual, seasonal, and diurnal variation to be well-characterized. Continuous water temperature data can be characterized by a variety of statistics, from simple annual means to frequency distributions over select seasonal windows, similar to those used for streamflow data (e.g., monthly duration curves). As with streamflow data, numerous indices can be calculated, creating the task of selecting non-redundant indicators that can explain biotic variation. To identify temperature sensitive streams supporting rainbow trout, Nelitz *et al.* (2006) compiled summer temperature records from 104 streams in central B.C., calculating up to 16 indices for some streams. The temperature indices were highly correlated, allowing the selection of a single index to characterize summer temperatures, the seven-day average of the daily mean temperature (or maximum weekly average temperature, MWAT), an index used by the Province (B.C. MWLAP 1998).

Although maximum water temperatures are currently the focus of concern because of climate change issues and loss of riparian vegetation in certain areas, minimum temperature issues are also important, particularly in high altitude or northern ecosystems where mortality from icing may result from increased thermal exchange following forest harvesting (MacDonald *et al.* 2003) or water withdrawal. Simulation modelling predicts cooling would reduce growth and reproductive success for rainbow trout (Van Winkle *et al.* 1997), and presumably also for rearing Pacific salmon. Indices of maximum and minimum temperatures as well as the change in temperature are required to describe thermal conditions relevant to fish, just as hydrologists require minimum and maximum flow statistics.

In summary, the scientific literature supports the use of temperature indices as indicators of effects on salmon habitat productivity. Divergence from natural temperatures can serve as an indicator of effect, particularly for high temperatures. The interpretation of the biotic significance of changes in average temperature or low temperature is less straightforward, as there may positive and negative impacts, though this complexity can be reduced by assuming that divergence from natural temperature regimes represents a negative impact to ecosystems in general.

1.3.3. Water chemistry

Two indicators of water chemistry were provided:

5) lake chemistry (nitrate, nitrite, ammonia, total phosphorous) for sockeye only; and

6) stream chemistry if available.

Total phosphorous is a strong predictor of fish biomass in north temperate lakes (Hanson and Leggett 1982). This predictive ability is owed to the fact that primary production in temperate lakes is generally limited by phosphorus availability, based on empirical relationships between phosphorus loading rates and lake trophic status (Vollenweider 1976). Phosphorus exists in three forms: dissolved inorganic phosphorus (also called orthophosphate), dissolved organic phosphorus, and particulate phosphorus. Total phosphorus (TP) is the sum of all three forms and is typically used to characterize the status of phosphorus in freshwater, for example Downing and Plante (1993).

Primary production in aquatic systems is limited by light, temperature, and nutrient concentrations (Wetzel 2001). Phosphorus and nitrogen may limit aquatic production, however, because phosphorus does not have an atmospheric phase to its biogeochemical cycle, and can be bound with metals such as iron and calcium in lake sediments, its availability is typically more limited. Strong empirical relationships between phosphorus loading rates and lake trophic status demonstrate the importance of phosphorus limitation (Vollenweider 1976). However, nitrogen is often co-limiting to aquatic production: Elser *et al.* (1990) found that substantial algal growth required both N and P enrichment and nitrogen limitation has been observed during some parts of the year in B.C. coastal lakes (Perrin *et al.* 1983). The literature suggests that lakes with N:P ratios greater than 10:1 are not limited by N (Stockner and Shortreed 1985).

Hume *et al.* (1996) examined three methods of predicting sockeye rearing capacity in Fraser River basin lakes and found that daily seasonal average photosynthetic rates were the best predictor. Photosynthetic rates are more difficult to measure than standard nutrient or chemical parameters, but have the advantage of actually measuring lake productivity, thereby integrating the underlying chemical conditions that support lake productivity. The model could effectively predict lake sockeye rearing capacity with only 1 to 2 years of data from a lake collected over the growing season. Shortreed *et al.* (2000) expanded on this model by applying it throughout B.C., and with some slight adjustments to the model, they were able to estimate optimum escapement and smolt production from the lakes. The model allows the prediction of the productive capacity of lakes for rearing sockeye salmon. Shortreed *et al.* (2001) went further still to employ the model to identify enhancement and restoration opportunities in B.C. sockeye lakes.

In addition to direct measures of nutrient concentrations, several chemical variables have been used as indexes of lake or stream biological productivity. The chemical indices most typically used are total dissolved solids (TDS), specific conductivity, total alkalinity, and fixed non-filterable residue (NFR). TDS is the sum of the major ions in a sample of freshwater, including potassium, calcium, magnesium, chloride, sulfate, silicate, nitrate, and phosphate. TDS in both lakes and streams is associated with high production (Ryder *et al.* 1974). Total alkalinity is the sum of all titratable bases, including carbonate, bicarbonate, phosphates, silicates, and borates.

Also pertinent to B.C. waters is an empirically-based model that predicts maximum fish density, primarily for juvenile rainbow trout and steelhead, as a function of nutrients (represented in the model by alkalinity) in clear streams (Ptolemy 1993). To predict theoretical fish density with this model requires observed fish density to be weighted to reflect the density expected in high quality habitat. A more recent variant of the model found cutthroat trout density was highly correlated with alkalinity (Ptolemy 2005).

1.3.4. Habitat quality

Fish habitat is the physical space used directly by fish or relied upon indirectly by fish for survival that can be parameterized as the combination of physical and chemical conditions, essentially a physical subset of the variables that define a niche. Chapman (1966) noted that 'The physical environment only legislates the density and does not react to the biological aspects; thus, setting the framework by within which density is regulated.' Considering the framework of Ryder and Kerr (1989), the quality of fish habitat is a function of fundamental ecological variables acting within the physical structure of fish habitat. Habitat is a relatively fixed physical space within which habitat quality variables, which have wide ranges in level, determine productivity.

Two water quantity and quality indicators of habitat quality were provided for consideration in the literature review:

7) channel stability (e.g., pool:riffle, bankfull channel width:depth ratios); and

8) substrate quality or macroinvertebrate indices if available.

These variables were also found in models reviewed in Fausch *et al.* (1988) – the landmark review paper documenting 99 studies of stream fish that relate number or biomass of fish per unit area or length of stream to habitat variables. Numerous habitat variables were considered in this review spanning a range of spatial scales, including drainage basin, channel morphometry and flow, primary habitat structure: biological, physical, and chemical, combinations of the above factors, and weighted usable area (WUA).

Various habitat quality features correspond with salmonid density in streams. Sharma and Hilborn (2001) examined coho smolt abundance and habitat relationships in Puget Sound (Washington) streams. They found that coho salmon smolt abundance increased with the increasing area of pools and ponds. The quantity of large woody debris (LWD) and pool habitat was correlated with higher abundances of juvenile coho salmon and cutthroat trout parr, and juvenile cutthroat trout and salmon density decreased with increasing stream size (wetted width) (Rosenfeld *et al.* 2000). Rosenfeld *et al.* (2000) emphasized the observation that pools formed by LWD were deeper, suggesting that coho and cutthroat habitat will increase with increasing LWD in streams. Dunham *et al.* (2002) studied cutthroat trout density in streams and found that the channel width:depth ratio explained variance across streams and years, but that other factors were more important, possibly the presence of competitors and habitat connectivity. Jowett (1992) demonstrated that physical habitat measurements can be strongly correlated with brown trout abundance (New Zealand), explaining 88% of the variance with a physical habitat simulation (PHABSIM, the component microhabitat model of the instream flow incremental methodology, or IFIM) type model that scored habitat based on the suitability of depth, velocity, and substrate for brown trout. Food abundance and winter water temperature were also important, however, water quality and flow variability did not influence brown trout abundance. Although the study used detailed data collected at individual sites, the sites were distributed among rivers (89 sites in 82 rivers, such that the data explain between river variance, rather than variance between sites within a river). The study is noteworthy because many previous studies of PHABSIM type models failed to explain fish abundance (Mathur *et al.* 1985). Additional validation of the predictive power of habitat measurements was provided by Baran *et al.* (1995) who showed that physical habitat models (again similar to PHABSIM) could explain significant variation in brown trout density and biomass in regulated streams.

Feist *et al.* (2003) found that watershed scale models outperformed reach scale models in estimating the density of chinook salmon redds. Habitat characteristics did not predict redd abundance well within reaches, but did explain distribution at a watershed scale using the variables percent non-forested riparian wetlands, percent sedimentary geology, and percent hillslope less than 1.5%. In contrast, Montgomery *et al.* (1999) found that channel type described coho and chinook redd abundance well at a reach scale, while within reaches pool spacing was a good predictor. Creque *et al.* (2005) found that more variance in the density of chinook salmon and trout species in Michigan streams was explained by watershed scale variables (termed landscape level in their analysis) than by site scale variables. Using detailed habitat models that quantified habitat usability at a site based on depth, velocity, and substrate (analogous to the PHABSIM model popular for instream flow assessments), Hedger *et al.* (2004) was able to explain significant (r^2 = 0.31 to 0.59) variance in Atlantic salmon density. However, at a regional level these models had poor predictive power (r^2 = 0.13 to 0.31), emphasizing that stream channel predictive measurements are most appropriate for explaining reach-scale abundance patterns. Therefore, although there may be evidence to support the use of a particular indicator (like pool spacing) within reaches, it may not perform well at the broad levels that indicators are expected to perform over.

More specific to Pacific salmon, Parken *et al.* (2002) developed a habitat-based model that provided good predictions of Fraser chinook salmon spawning capacity for some populations. The model was 1) species specific, 2) stratified by lake influence, juvenile life history, and physiography (intra-watershed location), and 3) used gradient as a key habitat attribute. Later, Parken *et al.* (2006) developed a habitat-based approach to generate escapement goals for data limited chinook stocks in B.C.. The model predictions were biologically-based on the demonstrated relationship between watershed area and chinook salmon spawning populations (estimated at replacement and maximum sustainable levels). The model provided reasonably accurate population estimates and performed better than the interim escapement goal method.

Bocking and Peacock (2004) estimated coho smolt productive capacity and spawner density for maximum smolt production for streams in the Nass region. The model was stratified by sub-area within Statistical Area 3, and was built on the assumption that the accessible length of streams greater than 2nd order defined the carrying capacity of coho salmon. Although Bocking and Peacock summarized the existing literature on coho salmon habitat relationships, in their model they used only the relationship between stream length and coho smolt production, in keeping with the conclusion of the most recent detailed review of this issue by Bradford *et al.* (1997). From a database of 474 annual estimates of smolt abundance from 86 streams in western North America, Bradford found that stream length (and to a lesser extent latitude) were useful in predicting mean smolt abundance. Bradford concluded that on average, smolt abundance is limited by spatial habitat, with climate, flow, or other factors creating significant variation in abundance between years. Bradford's recommendation to forecast smolt yield from stream length and latitude at the watershed or regional level suggests that stream length may provide a reasonable habitat indicator for coho salmon, but suggests other attributes of habitat quality may not. However, his observation that interannual abundance may be affected by additional factors suggests that these could be used to track habitat status.

Holtby and Scrivener (1989) developed a model to predict coho and chum escapements in Carnation Creek, B.C.. The model linked sequential regression sub-models that predict survival and or and fish size at various life stages in various physical habitats to ultimately predict adult escapements. The model related salmon survival to water temperature, peak discharge, gravel particle size, and habitat quality indices for stream features affected by logging. Sea surface salinity and temperature were also used as model inputs to incorporate marine effects. They concluded that most of the observed variation in escapements for both species was due to climatic variability in the stream and in the ocean. The primary empirical contribution of the work was the significant correlation between mean spawning substrate size and both egg-fry survival and mean size in chum salmon.

Sediment particle size has a long history of use as an indicator of habitat quality for spawning salmonids, either as a mean value (geometric mean), a composition metric (% fines), or an index of both (Fredle index, Lotspeich and Everest 1981). Tappel and Bjornn (1983) report the survival and emergence of salmonid eggs and alevins in response to increased levels of fine sediment. Chapman (1988) and Kondolf (2000) provide literature reviews that show fine sediment thresholds determine incubation success, and identify experimental evidence to support the use of levels of fine sediment in stream gravels as indicators of survival. Suspended sediment has a similar long history of use, with field empirical and experimental studies quantifying the effects of specific sediment concentrations on each life stage of Pacific salmon. Newcombe and Jensen (1991) provide a meta-analysis of 80 reports on the subject to derive an equation that calculates an index of severity related to the duration of exposure and concentration of suspended sediment.

1.3.5. Other habitat quantity and quality indicators

An additional indicator provided was: 9) other freshwater or marine water quality information if available and relevant to limiting factors, which we have interpreted as a general other category in which to identify additional indicators. A number of environmental variables measured during aquatic assessments provide additional opportunities to develop alternative indicators of habitat status and pressure. Of these, thalweg metrics stand out as particularly powerful indicators for streams. Thalweg metrics are a number of different measures derived from longitudinal profiles of the streambed elevation measured along the deepest portion of the stream. Mossop and Bradford (2006) measured and derived two useful measures (length in residual pool and mean maximum residual pool depth) that correlated with juvenile chinook salmon abundance. An advantage of these indicators is that they are flow independent, reducing the variance caused by the seasonal timing of sampling. Drawbacks are that the indicators may only give strong indications of habitat quality in small streams, may apply to only some species, and may not be easily quantified in larger rivers.

Studies of juvenile salmonid habitat use in large rivers are rare, and only recently have classification systems been published identifying habitat features distinct to large rivers, such as edge habitats (Beechie *et al.* 2006). Historically, challenges in main-stem river area sampling have created uncertainty in estimates of salmon production (e.g., Beechie *et al.* 1994), therefore models relating salmon production to habitat features in large rivers are rare, and the literature on habitat – productivity relationships is probably biased towards results obtained from small streams. Given this, we are uncertain if available salmon habitat productivity relationships will apply to larger streams. We know that habitat relationships change with stream size: Hatfield and Bruce (2000) showed how stream size affects estimates of optimum streamflow in PHABSIM studies; Rosenfeld *et al.* (2000) showed how stream size affects the abundance of cutthroat trout; and Bradford *et al.*'s (1997) finding that stream length, but not stream size (flow) was correlated with coho smolt production implies that production per unit flow decreases with increasing flow. Accordingly, stream size may provide an important indicator for salmon production, either in the form of a continuous variable, or as a stratum within which to apply other habitat indicator relationships.

1.3.6. Habitat area

DFO provided five indicators of habitat area:

10) # kms accessible stream length (to adults, to juveniles);
11) # hectares accessible and inaccessible off-channel habitat;
12) # hectares estuarine habitat;
13) conservation unit (CU) specific high value or limiting habitat at different life history stages; and
14) productivity model variables and outputs.

Habitat area is an obvious indicator because fish habitat is typically defined on an areal basis in the scientific literature, where it has been used as a convenient index of the spatial extent of an ecosystem. The mechanism underlying the primacy of area as a habitat descriptor is well described by Minns (1995): "Since nearly all biological productivity is ultimately derived from photosynthetic activity which depends on the areal interception of sunlight energy, area is the logical spatial basis for assessing biotic productivity." Furthermore, fish numbers or biomass can be compared between locations only if the spatial bounds of the sites are quantified, and that requires their measurement. Particularly in quantifying lake productivity, area has been the standard. For example, Ranta and Lindstrom (1989), predicted lake specific fish yield by correlating fish catch with lake area. Downing and Plante (1993) and Randall *et al.* (1995) compiled estimates of production and standing stock for lake fish populations and used surface area to scale production.

As discussed in section 1.3.4, area is a key component of standard habitat definitions and metrics. Area is a component of the weighted usable area metric that has been strongly correlated with fish standing density or abundance in many streams (e.g., Baran *et al.* (1996), Jowett (1992), and others: see Fausch (1988) for a detailed review of studies correlating abundance and weighted useable area). There are fewer papers that correlate abundance with simple area, but not because these correlations are rare, but rather because the connection between area and abundance is a considered so fundamental that the reporting of such is trivial. Burns (1971) found a strong correlation (r = 0.898) between stream surface area and salmonid biomass in seven streams in northern California, and similar additional correlations can be sifted from the literature.

Stream habitat area is not always the most appropriate spatial metric. Bradford *et al.*'s (1997) finding that stream length, rather than area, was the best predictor of coho smolt production illustrates the noisy relationships that can be expected from stream area, which covaries with streamflow such that salmon abundance versus area relationships may be obscured. Bradford's finding contrasts with the use of weighted usable area to quantify trout and steelhead abundance in B.C. (Tautz *et al.* 1992, Ptolemy 1993). This difference may reflect the different habitat preferences and life histories of steelhead/rainbow trout and coho salmon, but also methodological differences in measuring habitat. Bradford compiled data over multiple ecosystems, jurisdictions, and stream sizes across which methods of area calculation varied. In contrast, models of steelhead carrying capacity developed by MOE and used for estimating freshwater habitat in B.C. rely on habitat data generated through a single methodology, in the same jurisdiction, applied by a consistent group of researchers.

Dauble *et al.* (2003) estimated the lineal distance of current and historic (pre-dam) chinook spawning habitat in the Columbia and Snake Rivers (Washington). They used a geomorphic model to identify river reaches downstream of present migration barriers and categorized habitat based on geologic composition of the riverbank (consolidation and bedrock), longitudinal gradient of water surface, presence or absence of channel bars or islands, and shoreline length. This approach allowed the authors to determine that historic spawning areas for fall chinook occurred mainly within wide alluvial floodplains that were common prior to dam construction.

Regardless of whether stream length or area is used to characterize habitat, the quantity of accessible habitat is an important indicator of productivity. Natural and anthropogenic barriers to migration severely limit salmon habitat, and indicators that measure this attribute are essential for effective monitoring of wild fish habitat. For example, Beechie *et al.* (1994) calculated coho salmon smolt production in a large river basin (8,270 km^2 Skagit River basin, Washington), estimating habitat losses by habitat type from different habitat pressures, primarily hydromodification (diking, ditching, dredging). Hydromodification reduced the length of channel accessible to fish. Harper and Quigley (2000) audited 46 stream crossings in two forest districts in British Columbia, and found that of 12 corrugated metal pipes (CMPs), 4 were impassable, resulting in a 6 km loss of potential upstream habitat.

Off-channel habitats are important for salmonids, particularly coho salmon. Indicators representing the area of these habitats are justified for the same reasons as for stream habitats given above. Similarly, estuarine habitats are key to salmon production and their area is also expected to be correlated with production. Conservation unit (CU) specific high value or limiting habitat will be important in identifying the appropriate indicator to be applied, and area or stream length may be the most appropriate metric, depending on species and life history stage.

Productivity model variables and outputs are described throughout this document, and include measures of habitat area or length. Additional discussion of the most current models is provided in section 1.4.

1.3.7. Land development

DFO identified four indicators relevant to land development:

15) %watershed road surface area (and a separate measure of all impervious surfaces area if available);
16) %watershed urban development;
17) %watershed agricultural development; and
18) %watershed logged in past 20 years.

There are a number of documented relationships between land development indicators and salmon abundance. Bradford and Irvine (2000) published a study of watershed level habitat pressure indicators associated with changes in the interannual productivity of 40 coho salmon stocks over the period from 1988 to 1998. The proportion of land used and road density were significantly correlated with the decline in coho salmon productivity, though the proportion of land logged was not. Furthermore, an index of habitat concerns comprised of 10 major categories of land and water use was also significantly correlated with the decline in coho salmon productivity (prepared as part of the salmon watershed planning profiles and included forestry, agriculture, urbanization, recreation, mining, industrial development, linear development, hydro development, cumulative impacts, and special biophysical concerns, Department of Fisheries and Oceans 1998). This study provides significant evidence that watershed level land and water use indicators can be expected to accurately predict changes in habitat status. This finding was echoed in a later study in Washington where adult coho abundance was higher in forest dominated areas than in areas with rural, urban, and agricultural development (Pess *et al.* 2002). This study showed that both habitat pressure indicators (land use) and status indicators (wetland occurrence, local geology, stream gradient) correlate with coho abundance. Furthermore, the study demonstrated that an index integrating professional judgement and habitat pressure information was well correlated with salmon productivity, highlighting the utility of the current effort to develop habitat indicators in a group context using experts in the field.

Other salmon species also show links to land development indicators. Chinook salmon parr-smolt survival in the Snake River (Washington) is lower in streams with high road densities and in those surrounded by 'young dry forests' (intensively managed timber lands), additional evidence of habitat pressure indicators (Paulsen and Fisher 2001). This study also found a significant negative relationship between parr-smolt survival and the 'Palmer Drought Severity Index (PDSI), an index of temperature, precipitation, and evapotranspiration. Again looking at the watershed level, Thompson and Lee (2000) found that and index of chinook salmon parr abundance was negatively correlated to road density and positively related to mean annual precipitation, whereas and index of steelhead parr abundance was negatively correlated to percent unconsolidated lithology (an indicator of sedimentation).

The intensity of grazing was identified as a pressure indicator influencing thermal input in a study that showed significant links between temperature and chinook salmon fry biomass as well as trout and char biomass in Rocky Mountain streams (Platts and Nelson 1989).

Opperman *et al.* (2005) report relationships between land use or land cover and embeddedness, the habitat status indicator used by McHugh *et al.* 2004 to predict chinook salmon abundance. Although data collection was limited to the Russian River Basin in California, Opperman *et al.* (2005) sampled 54 streams, and a large proportion of the variability in embeddedness was explained with coarse-scale measures of watershed land use. Interestingly, the variance explained increased as the scale of influence assessed increased, with little variance in embeddedness explained by activities in the local riparian corridor. This reflects the fact that stream channel conditions integrate the effects of upstream land use practices in all tributaries that may mask local effects. Further, regardless of assessment scale, less variance was explained in small watersheds, possibly because small watersheds have more variable sediment fluxes. This emphasizes the importance of scale when calculating habitat pressure indicators.

1.3.8. Riparian and foreshore development

Three indicators were provided as follows:

19) % riparian forest integrity;

20) % lake foreshore altered (defer unless analysis already done); and

21) % estuarine foreshore altered (defer unless analysis already done).

All three indicators are ratios of areas, though they could also be expressed as lengths, e.g., riparian zone can be expressed as a lineal distance, or as a lineal distance and zone width. The ratios contrast the altered area with the sum of the altered and unaltered areas (the total area), providing a percentage value that is an analog of the measure of impact, either the loss rate or 1 minus the loss rate.

A few studies relating riparian habitat indicators to measures of salmon habitat or productivity were identified. In developing an index of biological integrity (IBI) for fish and amphibian assemblages in coastal Oregon and Washington, Hughes *et al.* (2004) found the IBI was strongly correlated with watershed and riparian disturbance. MacDonald *et al.* (2003) found forest cover removal increased temperatures 4 to 6°C with higher diurnal temperature variation. The indicators suggested by DFO (% riparian forest integrity) were not reported on in this study, however, treatments with higher levels of riparian harvesting had greater changes in temperature. The response of fish populations to the treatments was not recorded, however, the authors noted that temperature changes could alter insect production, egg incubation, fish rearing, migration timing, and susceptibility to disease. Elliot (2004) examined three Fraser Valley streams and found that % forest cover in the riparian corridor was correlated with dissolved oxygen concentration, temperature, habitat complexity, and large woody debris. In contrast, Vadas (1997) found that stream habitat characteristics in the Salmon and Nicola Rivers such as pool:riffle ratio and habitat diversity, were not consistent along a riparian-intactness gradient, possibly because the effects of sedimentation were not considered.

The response of fish populations to riparian habitat removal has been documented in some studies. Fausch and Northcote (1992) found that densities of juvenile coho salmon and cutthroat trout were higher in sections where forested areas contributed large woody debris to the stream channel than in those where they did not.

In southeast Alaska, timber harvesting and associated road building were associated with fewer pools in an examination of 23 stream reaches (Wood-Smith and Buffington 1996). Eaglin and Hubert (1993) found the number of stream crossings and intensity of logging correlated with the amount of fine substrate and embeddedness, with trout biomass being lower in basins with many culverts. Bradford and Irvine (2000) were unable to detect a significant effect from logging on coho salmon in the Thompson River watershed, though this may have been because they used an index of recent logging that excluded historic logging.

The area of estuarine foreshore altered is expected to show similar relationships to salmon productivity as riparian forest integrity does. Reimers (1973) examined juvenile chinook growth and found that those which reared the longest in the estuary comprised the bulk of the adult population, and that density may limit growth, implying that estuary area controls growth and therefore the production of juvenile chinook. Magnusson and Hilborn (2003) showed that survival of ocean type chinook released from hatcheries increased with percentage of the estuary in natural condition, however, the survival of coho salmon survival did not. This study highlights the wide variation in juvenile life history that would affect the relevance of a particular habitat indicator. Similarly, MacFarlane and Norton (2002) found that juvenile chinook salmon did not use the San Francisco estuary significantly, instead relying on coastal waters.

1.3.9. Water use

An indicator for water use was identified; 22) water extraction data. Records of water use are available across the Province, primarily in the volume of licensed annual amounts for irrigation purposes, but rarely are the actual volumes extracted each year recorded. A few large municipal and industrial extractions are metered directly, and flow withdrawals associated with major hydroelectric projects have continuous records of flow withdrawal. Two key types of use should be differentiated when examining water ‘extraction’: consumptive versus non-consumptive. Consumptive water use describes most municipal, industrial, and domestic water withdrawals, where water is removed from the channel and not returned, except in reduced volumes in the form of effluent discharge. Hydroelectric uses are typically non-consumptive in that they return the water to the channel, although in cases many kilometres distant from the point of diversion and other cases in another water basin altogether. We found little direct evidence linking water extraction data to fish abundance, however, indirect links can be imputed from the instream flow literature relating fish abundance to the instream flows remaining post development.

The literature on fish flow versus abundance relationships is substantial (see section 1.3.1), providing the rationale for using water extraction as a habitat pressure indicator. Burt and Mundie (1986) reviewed a large number of hydroelectric impact assessments and concluded that impacts were significant when flow removal exceeded a threshold value (30% MAD). This suggests that water extraction, scaled to MAD, could serve as a predictor of impact. This could be effective in a few cases, however, in practise it is difficult to detect the effect of water withdrawals on streamflow (other than in the case of major diversions from hydro projects). For example, a summary of instream flow information on the Nicola basin, where numerous extractions are licensed, found no temporal signal from water withdrawal in records of instream flow, possibly because of insensitive gauging or because of the influence of groundwater inputs (Hatfield 2006). This suggests that quantitative evidence of links between water extraction and salmon abundance will be difficult to detect, despite the logical quantitative link between water extraction and streamflow.

1.3.10. Other

DFO provided two other habitat pressure indicators for consideration:

23) other habitat issues and constraints (e.g., water quality issues, dredging, aquaculture, etc.); and

24) future water and land use trends and threats and climate change issues.

There are numerous other indicators that could be developed from the literature. Water quality parameters can be modelled and related to salmon survival and growth and there is a large body of literature dealing with this subject that was not examined here. The extent of dredging and aquaculture can be quantified and related to salmonid production to provide logical indices of effect. For example, sea lice infection pressure on juvenile pink and chum salmon increases with proximity to farm sites (Krkosek *et al.* 2006), suggesting that an indicator could be constructed that includes both the proximity to and the number of farms.

Indices of proposed development can be constructed as used as indicators of habitat pressure. The evidence supporting the use of temperature as an indicator is sufficient (as discussed in section 1.3.2) to warrant its use in estimates of future climate change, providing guidance on anticipated habitat pressures. Estimates of climate change can be readily obtained for discrete locations within BC through internet accessible models (e.g. the ClimateBC model available from UBC, Wang *et al.* 2006), allowing site-specific indices of anticipated mean temperatures to be calculated and integrated into habitat indicators. As the magnitude of temperature change indices, such as mean annual temperature, varies with elevation and location, such climate change indices will affect indicator values and may influence site-specific habitat management decisions.

1.4. Assessment of DFO Indicators as Estimators of Production

The concept of fish habitat productivity is central to the management of fish and habitat in Canada. The no net loss principle of the Policy for the Management of Fish and Fish Habitat requires no net loss of 'productive capacity of fish habitats', defined as "the maximum natural capability of habitats to produce healthy fish, safe for human consumption, or to support aquatic organisms on which fish depend." Although a clear definition of productive capacity has been elusive, Minns (1995) adopts Ricker's (1975) definition of production (new body mass per unit time, per unit area) and refines this for fish as "the sum of all production rates for all co-occurring fish stocks with a defined area of ecosystem."

It is difficult to measure fish production even in simple situations, such as a single stock in a small lake. By comparison, the task of estimating the production of multi-species assemblages of anadromous fish appears daunting. To overcome this challenge, Minns (1995) identifies biomass and other biological indices as well as surrogate habitat variables as alternatives to measuring fish production. Production is commonly inferred from standing stocks of fish, assuming consistent ratios of production to biomass (e.g., Waters 1992), but these and all other surrogate measures require supporting work to validate their utility. In the preceding sections on individual indicators, support was found for the indicators as estimators of production, survival, or habitat attributes that are known or expected to be correlated with production. The indicators link with production with varying closeness, from indirect indicators that correlate to habitat indicators that in turn are expected link to production (e.g., the correlation between forest cover and coho productivity) to experimental tests of the effects of indicators (e.g., temperature regimes and egg incubation rate).

A few more recently developed models demonstrate how indicators could be used in habitat productivity models. These models typically integrate several indicators and may use population dynamic models to predict survival and reproduction, allowing estimates of annual production to be generated for one or more life stages. The models show that the indicators identified by DFO can be used to estimate salmon production, as illustrated by the following examples.

Using published salmon–habitat relationships, McHugh *et al.* (2004) were able to predict chinook salmon egg-smolt survival in both degraded and pristine streams. The model combined the effect of habitat parameters on survival at different life stages, including the effects of fine sediment and water temperature on egg-fry survival, the effect of substrate embeddedness on summer and overwinter rearing capacity, and the effect of mean daily temperature during the growing season. The model was intended to be used to prioritize restoration sites and evaluate habitat status, but did not link habitat pressure indicators to the habitat indicators.

In developing an index of biological integrity (IBI) for fish and amphibian assemblages in coastal Oregon and Washington, Hughes *et al.* (2004) achieved good precision using variables at both the watershed and reach scales. The number of coldwater species and individuals (including Pacific salmon) were most correlated with the IBI, which in turn was strongly correlated with watershed and riparian disturbance. Watershed road density was the strongest single-variable predictor of the IBI: the best model also included an interaction of road density with stream power (watershed area x gradient), boulder fish cover, and the percent of the reach with broadleaf deciduous canopy. A key point demonstrated by Hughes *et al.* (2004) was the importance of choosing habitat pressure indicators that are not, or are only weakly, associated with habitat status indicators, to ensure that natural limitations to fish habitat are not confused with the effects of development. Alternatively, indicators can be adjusted for natural gradients in abundance. For example, Hughes *et al.* (2004) adjusted the number of cold water individuals by watershed area to remove the effect of stream power and gradient, to create what is analogous to a response variable against which habitat pressure indicators can be correlated. An IBI has promise for widespread application to salmon streams, and could be developed for Pacific salmon through the general seven-step process defined by Hughes *et al.* (2004).

Fight *et al.* (1990) developed a multiresource model for fisheries (and other resources) for watersheds in southeast Alaska ranging in size from ~20 to 80 km^2. The fisheries submodel considers fisheries regulations, logging related parameters (percentage of bank cut, area logged), road parameters (length of road used, length of road constructed), total sediment load, fine sediment concentration in gravel, amount of large organic debris, bedload shift, water temperature (summer mean and maximum, fall mean, and winter degree-days), flow (summer and winter lows), stream velocity, and canopy cover. Available spawning gravel area was also required as an input. The model allows the prediction of egg deposition, egg survival, rearing success, smolting success, and harvest in stream reaches for pink, chum, and coho salmon. The model was not validated with empirical data, but it provides a logical approach consistent with other more recent habitat models for salmon.

Jager and Rose (2003) developed the Oak Ridge Chinook Salmon model that combined habitat and stock-recruitment relationships to predict chinook recruitment (number of smolts produced) under different flow regimes in a regulated river. The model consists of a spatial representation of river habitat and a biotic model of chinook salmon reproduction, development, growth, and mortality. The key habitat features for chinook salmon that are included in the model are weighted usable area and water temperature. The biotic model simulates development and mortality of egg and alevin life stage, daily development, growth, mortality, and downstream movement of individual juveniles, as well as predation. The model has not been empirically validated but demonstrates how to combine habitat and life history parameters derived locally and from the literature into a productivity model.

Greene *et al.* (2005) predicted 22 years of return rates for Skagit River (Washington) chinook using a regression model relating return rates with environmental conditions in four different habitats (freshwater, tidal delta, bay, and ocean) and egg production (indicator of density dependence). Environmental parameters considered included flood recurrence interval (frequency at which a flood of a given magnitude will occur) during intragravel development, sea surface temperature, sea level pressure, sea level, and coastal upwelling during non-freshwater residency. Up to 90% of the variation in return rate could be explained, with the best predictors being the magnitude of floods during incubation, the principal habitat component for bay residency, the principal habitat factor for the third ocean year, and an estimate of egg production.

Knowler *et al.* (2003) showed how empirically derived models relating habitat quality to coho recruitment rates (from Bradford and Irvine 2000) could be amplified to estimate habitat value through various assumptions about exploitation rates, stock composition in the catch, and smolt-adult survival rates.

Lestelle *et al.* (2004) developed the Ecosystem Diagnosis and Treatment (EDT) model to diagnose current environmental constraints and model the effectiveness of habitat restoration strategies for chinook, coho, chum, and steelhead (it is under development for bull trout, cutthroat trout, and interior rainbow trout; it is also being considered for sturgeon). Habitat rating rules for chinook, coho, and steelhead rated both the quality and quantity of stream habitat by assuming that biological capacity and productivity are functions of the environment. A multi-stage Beverton-Holt production function was calculated at the reach scale and integrated to create an overall estimate of capacity and productivity. Habitat quality was described with 35 Environmental Quality Attributes that were formed into 17 Habitat Attributes. These attributes were used to weight the area of each reach by life stage, analogous to the habitat suitability weighting used in stream physical modelling.

A multistage Beverton-Holt model was also used by Scheuerell *et al.* (2006) who provide a framework (the Shiraz model) for combining habitat attributes with other key information to predict chinook salmon returns in a river basin. Density-dependent population growth, hatchery operations, and harvest management are incorporated into the model, which operates in a time-varying, spatially explicit manner. Just as the indicators evaluated here rely on scientific literature to support their use, this model embeds literature values to form the quantitative relationships between the physical environment and the necessary productivity and capacity parameters for the model. The model used few functional relationships: prespawn adult survival as a function of water temperature, egg-fry survival as a function of normalized mean flow, and percent fine sediment in the spawning gravel. Bartz *et al.* (2006) developed these functional relationships for Snohomish basin chinook, as habitat inputs to the Shiraz model. Few functional relationships were used, primarily because habitat-specific data (e.g., temperature, fine sediment) were limited to a few parameters, although Scheuerell *et al.* (2006) note that simpler models tend to be more generally applicable to other systems, which is the objective for this model.

An analysis of historic and current use of the Columbia River estuary by chinook salmon used modelling techniques to calculate habitat under historic and current conditions (Bottom *et al.* 2005). Estuary bathymetry and river flow were the key inputs to the model, which integrated changes in estuary area when calculating habitat. The loss of forested and emergent wetlands and alterations in river flow were identified as the most important factors influencing estuarine habitat, supporting the use of an indicator of estuarine foreshore alteration. The complexity of modelling estuary habitat was apparent in the finding that changes in habitat capacity from losses in wetlands had been offset by an unknown extent by gains in shallow and flats. Shifts in the food web were also considered important to estuary productive capacity, again there were offsetting effects identified over time precluding an objective quantification of impact.

A characteristic of the recent published models is the specificity of information they require. Although parameters from the literature (e.g., growth-temperature relationships) are employed, the models typically rely on stream specific data (e.g., habitat area versus flow relationships). Moreover, the models are typically specific to a single river or basin, and though they could be adapted to other watersheds (e.g., the Shiraz model provides a modelling framework), they are typically species specific. The sensitivity of the indicators will also depend on the relative importance of the habitat they represent to the life history of the species of interest. Greene *et al.* (2003) found that the relative importance of habitats depends greatly on the form of density dependence influencing salmon stocks, such that simple habitat indicators may not be sensitive to changes in production. Modelling of habitat-related and density dependent population responses in chinook salmon revealed no correlation between apparent survival (return rate) and estuarine environmental conditions, yet Greene *et al.* (2003) suggested that this may indicate that residency in the delta was an important population buffer, i.e. the delta may be "a relatively stable zone within a series of habitats characterized by large environmental variation". Clearly the interpretation of the results of complex habitat production models is not a simple matter.

1.5. Discussion

We have reviewed the literature for salmonids that describes relationships between habitat status/pressure indicators and the fish abundance/production. In summary, there was good support within the habitat status variable catagories (streamflow, water temperature, water chemistry, physical habitat quality, and habitat area) for indicators of salmon abundance. There was also support for the habitat pressure catagories (terrestrial development (land use), riparian and foreshore development and water use, and water chemistry), though it was less extensive. All 26 of the indicators identified by DFO are supported by the literature to some extent, either directly or through inference from work that logically supports their application. The level and validity of support varies between indicators, with habitat status indicators having a longer history of evaluation and therefore better support, including experimental evidence for some indicators (particularly water temperature, substrate sediment, and suspended sediment). Support for some indicators was less definitive: water flow shows surprisingly few correlations with fish abundance considering the number of attempts to draw these, reflecting the indirect relationship between flow and fish abundance.

As stand-alone tools, individual indicators can provide a valid representation of habitat status or pressure that may be consistent and responsive over large ranges in indicator value. For example, percent sediment in stream gravels is a valid indicator of salmonid egg-fry survival with published equations available to allow prediction from stream-specific data. Assuming the detailed spatially-explicit data required to calculate this indicator can be collected over time, mean values could be tracked to document time trends, compared to nearby watersheds in a BACI (before-after-control-index) framework, or compared to a threshold value (e.g. 15% fines) to determine habitat status. Alternatively if site-specific status data on sediment are not available, one could rely on relationships between habitat pressure indicators and survival from published studies, with the caveat that the confidence in estimates of the effect on production would likely be large.

Several features of potential habitat indicators complicate their interpretation. Non-linear responses are inherent to many indicators. For example, increases in mean temperature suggest negative impacts during warm months in streams in arid climates, yet in the shoulder seasons temperature increases may promote greater growth and production. In winter temperature increases may reduce icing and increase overwinter survival, or could cue inappropriate foraging activity, leading to increased predation and energy deficits. Adoption of an indicator that reflects only the change over natural conditions could incorporate these non-linear effects, but may inappropriately suggest impacts where temperatures do not exceed thresholds of effect and would not capture the potential benefits of changes in naturally limiting conditions. Another complicating aspect are cumulative and synergistic effects among individual indicators. For example, the actual impact of extreme temperatures will be complicated by the presence of thermal refugia in deep pools and tributaries, which in turn may be driven by land use, riparian development, and water use. The extent to which streams differ in these features both naturally and from anthropogenic effects will modify the severity of an individual effect, highlighting the complexity of response and the difficulty in interpretation. Such observations suggest that indicators should at least be region-specific, reflecting the hydrology and climate of a region: the consequences of an increase in annual mean temperature in an arid climate may be more severe than in a boreal climate.

Differences in habitat requirements between species and life stages will also complicate interpretation. Some indicators can be readily calculated but may not clearly indicate habitat status. For example, flow expressed as % of the long term MAD could theoretically provide an indicator of status that, when adjusted to reflect water withdrawal, would also indicate habitat pressure. However, critical thresholds for the indicator will vary between species and their life stages. This aspect is incorporated in detailed stream habitat models which calculate habitat as a function of different indicators for each species and life stage. Interpreting the net effect of a combination of habitat indicators is complex, relying on site-specific understanding of the local ecosystem, the species of interest, and the factors limiting production. Despite this complexity, key indicators may emerge through detailed ongoing study, that can provide a valid representation of habitat – production relationships.

A key design feature of a habitat reporting system will be the spatial and temporal scale on which habitat performance indicators are calculated. Effective indicators will reflect underlying functional relationships, and in local settings should correlate highly with fish abundance, providing that high quality long-term data sets are available, and that populations are not limited by factors outside of the stream setting (e.g. adult recruitment). The predictive power of these indicators will partly depend on the scale over which they are calculated. GAP&WES (2006) discussed the factors/criteria that should be considered when forming a candidate indicator shortlist, noting that data must be are available at the appropriate geographic scale to support decisions at both the strategic and site specific scale. Scale issues are particularly important when calculating habitat pressure indicators, where effects that accrue across a watershed may be concentrated in specific locations distant from the apparent point of impact.

The selection of valid indicators can be informed by the literature provided in this review in an analysis of technical feasibility by scientists, program and database managers, and stakeholders as recommended by GAP&WES 2006. Assuming that there is agreement on the most appropriate indicators, and that the data to calculate these indicators are available, scientists, managers and stakeholders can implement a sub-set of indicators in a pilot trial. GAP&WES (2006) suggested this subset include the habitat status variables of temperature, flow, sediment and barriers to fish movement, with phytoplankton and chlorophyll *a* for lakes. Interpretation of this small set of indicators seems tractable, however, as described above, there are difficulties in interpretation because of non-linearity and differences in effect between regions. The interpretation of multiple, stand-alone indicators will be difficult, since they interact. It is for that reason that models have been used to integrate the effects of the indicators, allowing complex, non-linear, and synergistic effects to be accounted for.

Recent models of salmon production combine some of these indicators with a population model to estimate production in a highly data intensive, spatially explicit framework. The models integrate external processes, represented by habitat status and pressure indicators, with internal processes such as density dependence to better explain the observed variation in salmon production. The models typically include aspects of the marine life history including smolt-adult survival rates and harvest, to estimate adult returns. The models are species specific, and rely on considerable site-specific data to provide accurate predictions of production. Although the general framework of some of the models (e.g. the Shiraz model) can apply to an entire species, and with modification be applied to other salmon species, data input needs are substantial. These needs can be filled by river-specific indicators, with some indicators or functional relationships derived from the literature.

A compromise between model complexity and general applicability may be struck by selecting the most valid indicators and developing a simple model that reflects function during only the first few phases of life history. Simple models apply generally and are easier to understand (Scheurell *et al.* 2006), an important consideration for a Province-wide habitat status report with a broad audience of stakeholders. The subset of indicators identified for pilot trial could be integrated in simple models specific to the species and region, using the available habitat status and pressure indicators. Functional relationships between status indicators and salmon productivity can be drawn form the literature identified herein and refined through the pilot trial.

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TABLES

Table 1. List of habitat performance indicators provided by DFO for comparison to the literature.

Habitat Performance Indicators:		No.	Description
Habitat State Indicators	**Water Quantity & Quality Data::**		
		1	Decadal mean daily discharge graphs & MAD's
		2	Annual peak discharge events (frequency, timing, magnitude, duration) relative to some benchmark (e.g. USGS percentile approach)
		3	Annual mean 7-day-low-flow discharge relative to some benchmark (e.g. < 10% MAD)
		4	Annual water temperature graphs (daily max, min & mean temps) relative to some benchmark
		5	Lake chemistry (nitrate, nitrite, ammonia, total phosphorous) for SK only
		6	Stream chemistry if available
		7	Channel Stability (e.g. pool:riffle, bankfull channel width:depth ratios)
		8	Substrate quality or macroinvertebrate indices if available
		9	Other freshwater or marine water quality info if available and relevant to limiting factors outlined in table below
	Highly Productive Habitats:		
		10	# kms accessible stream length (to adults, to juveniles)
		11	# hectares accessible and inaccessible off-channel habitat
		12	# hectares estuarine habitat
		13	CU-specific high value or limiting habitat at different life history stages
		14	Productivity model variables & outputs
Habitat Pressure Indicators:	**Land & Water Use:**		
		15	%watershed road surface area (and a separate measure of all impervious surfaces area if available)
		16	%watershed urban development
		17	%watershed agricultural development
		18	%watershed logged in past 20 years
		19	%riparian forest integrity
		20	%lake foreshore altered (defer unless analysis already done)
		21	%estuarine foreshore altered (defer unless analysis already done)
		22	water extraction data
		23	other habitat issues & constraints (e.g. WQ issues, dredging, aquaculture, etc.)
		24	future water & land use trends & threats, climate change issues

Table 2. **Salmon habitat productivity models, by author and year, showing model output by species, age class, and unit, and the significant independent variables in the model.**

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
1a	Lanka (1985)	Trout in rangeland streams (kg/ha)	Basin Perimeter, logReach Gradient from map, mean basin elevation rating, rating of width:depth ratio
1b	Lanka (1985)	Trout in forest streams (kg/ha)	Drainage density, elevation rating, logrelief ratio, log mean width
2	Ziemer (1973)	Pink salmon (log escapement)	drainage density, mean basin elevation, mean basin length, mean basin slope
3	Wesche *et al.* (1977)	Cutthroat trout (> 6") (#/mi)	drainage area, mean basin elevation, mean basin length, mean basin slope, total stream length
4	Burton and Wesche (1974)	Trout (log #/acre)	Drainage area, forested area, mean basin elevation, total stream length
5	Randolph and White (1984)	Rainbow trout (# remaining/section)	Flow 11 days previous
6	Kraft (1972)	Age 1 and older brook trout (#/pool)	Flow, mean pool depth, mean pool velocity, pool area, max pool veloctiy, area of all cover
7	Chisholm and Hubert (1986)	Brook trout (kg/km)	mean depth, mean width, section gradient measured in field, width:depth ratio
8	Nelson (1980)	Age 2^+ trout (#/1000 ft)	minimum summer flow
9	Hunt (1979)	Brook Trout - all stages (#/mi)	mean summer flow

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
10a	Nehring and Anderson (1981)	Age 1^+ rainbow trout (log #/ha)	maximum summer flow 1 yr previous
10a	Nehring and Anderson (1981)	Age 0^+ brown trout (log #/ha)	maximum summer flow
10a	Nehring and Anderson (1981)	Age 2^+ brown trout (#/ha)	difference between 7 day maximum and 7 day minimum winter flows 3 yrs previous
11a	Nehring and Anderson (1982)	Age 1^+ rainbow trout (log #/ha)	maximum summer flow 1 yr previous
11b	Nehring and Anderson (1982)	Age 0^+ brown trout (log #/ha)	maximum summer flow
11c	Nehring and Anderson (1982)	Age 2^+ brown trout (#/ha)	difference between 7 day maximum and 7 day minimum winter flows 3 yrs previous
12a	Nehring and Anderson (1983)	Age 1^+ rainbow trout (log #/ha)	maximum summer flow 1 yr previous
12b	Nehring and Anderson (1983)	Age 0^+ brown trout (log #/ha)	maximum summer flow
12c	Nehring and Anderson (1983)	Age 2^+ brown trout (#/ha)	difference between 7 day maximum and 7 day minimum winter flows 3 yrs previous
12d	Nehring and Anderson (1983)	Age 1^+ brown trout (#/ha)	weighted usable area
12e	Nehring and Anderson (1983)	Age 1^+ rainbow (#/ha)	weighted usable area
13a	Nehring and Anderson (1984)	Age 1^+ rainbow trout (log #/ha)	maximum summer flow 1 yr previous
13b	Nehring and Anderson (1984)	Age 2^+ brown trout (#/ha)	difference between 7 day maximum and 7 day minimum winter flows 3 yrs previous
13c	Nehring and Anderson (1984)	Age 0^+ brown trout (log #/ha)	maximum summer flow
13d	Nehring and Anderson (1984)	Age 1^+ brown trout (#/ha)	weighted usable area
13e	Nehring and Anderson (1984)	Age 1^+ rainbow (#/ha)	weighted usable area
14	Frenette *et al.* (1984)	Atlantic Salmon parr (#/ha)	mean summer flow 2 yrs previous, minimum spring flow 1 year previous, minimum spring flow 2 yrs previous
15a	White *et al.* (1976)	Age 0^+ brook and brown trout (#/km)	mean summer flow, mean winter flow, maximum spring flow
15b	White *et al.* (1976)	Brook and brown trout (kg/km)	mean summmer flow, previous standing crop
16	Hunt (1971)	Brook Trout <6" long and >6" long (lb/100 yd)	mean depth, mean pool depth, pool area, surface area, channel volume, length of undercut bank
17	Burns (1971)	Juvenile coho, steelhead, and cutthroat (kg)	surface area

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
18	White (1975)	Brook and brown trout (kg/100 m)	mean winter flow
19	Solomon and Paterson (1980)	Age 0 brown trout (log #)	mean spring flow
20	Barber *et al.* (1981)	Age 0 coho (log #/30 m)	Age 0 coho: Area of overhanging riparian vegetation, days from June 1, log area with suitable spawning substrate
21	Harshbarger and Bhattacharyya (1981)	Age 2 trout (biomass)	area of all cover, area of overhanging veg less than 1 m above water, area of overhanging veg between 1 and 2 m above water, number of rocks, percentage of pool area as bruch cover, percentage of area as instream bank vegetation
22a	Barber *et al.* (1981)	Coastal cutthroat (log #/30 m)	channel width at bankfull flow, bank stability rating
22b	Barber *et al.* (1981)	Dolly Varden (log #/30 m)	log pool width, log riffle width
22c	Barber *et al.* (1981)	Age 1 and older coho (log #/30 m)	section gradient measured in the field, area of overhanging riparian vegetation, area of undercut bank, log shallow slow area
23a	Stowell *et al.* (1983)	Age 0 chinook (log #/m^2)	percentage of substrate embeddedness
23b	Stowell *et al.* (1983)	Age 1 steelhead (#/m^2)	(percentage of substrate embeddedness)^2, (percentage of substrate embeddedness)^3
23c	Stowell *et al.* (1983)	Age 0 chinook (#/m^2)	percentage of substrate embeddedness, (percentage of substrate embeddedness)^2
23d	Stowell *et al.* (1983)	Age 0 steelhead (log #/m^2)	percentage of substrate embeddedness
23e	Stowell *et al.* (1983)	Age 0 steelhead (#/m^2)	percentage of substrate embeddedness, (percentage of substrate embeddedness)^2
24	Gordon and MacCrimmon (1982)	Juvenile rainbow trout, brown trout, and coho salmon (combined #/m^2)	percentage of area as instream cover
25	Wesche (1980)	Brown trout (lb/acre)	area of deep water > 1.5 ft, area of rubble, boulder, and aquatic vegetation substrate, length of undercut bank, preference factor for rubble, boulder and aquatic vegetation substrate, preference factor for undercut banks

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
26	Wesche (1980)	Brown trout (lb)	weighted usable area
27	Enk (1977)	Brook trout ≥ 100 mm (kg/100 m)	length of undercut bank
28	Hawkins *et al.* (1983)	Rainbow, cutthroat, and coho combined (#/m^2)	percentage of fine sediment <1 mm
29	Eifert and Wesche (1982)	Trout (kg/ha)	area of rubble, boulder and aquatic vegetation substrate
30	Ward and Slaney (1980)	Steelhead parr (#)	number of rocks > 30 cm
31	Klamt (1976)	Salmonids (primarily age 0 chinook) (#/m^2)	inverebrate drift abundance, percentage of area as boulder and log cover
32	Binns (1979)	Trout (brook trout, brown trout, rainbow trout, and cutthroat trout) standing crop (log kg/ha)	log annual flow variation rating, log late summer flow rating, log stream width rating, log velocity rating, log rating of cover, log rating of eroding banks, log nitrate nitrogen rating, log substrate rating, log maximum summer water temperature rating
33	Binns and Eiserman (1979)	Trout (brook trout, brown trout, cutthroat trout, rainbow trout) standing crop (log kg/ha)	log annual flow variation rating, log late summer flow rating, log stream width rating, log velocity rating, log rating of cover, log rating of eroding banks, log nitrate nitrogen rating, log substrate rating, log maximum summer water temperature rating
34a	Nickelson *et al.* (1979)	Age 1$^+$ and older cutthroat (g/section)	frequency of depth 46-60 cm, frequency of depth > 60 cm, velocity rating, surface area, frequency of cover in water > 5cm deep, frequency of overhanging cover in water >5cm deep, frequency of turbulence in water > 5 cm deep, frequency of velocity refuge in water > 5 cm deep
34b	Nickelson *et al.* (1979)	Steelhead (g/section)	weighted usable area
34c	Nickelson *et al.* (1979)	Juvenile steelhead (g/section)	surface area, frequency of cover in water > 5cm deep, frequency of overhanging cover in water >5cm deep, frequency of turbulance in water > 5cm deep, frequency of velocity refuge in water > 5cm deep, depth and velocity preference factors

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
34d	Nickelson *et al.* (1979)	Cutthroat (g/section)	weighted usable area
34e	Nickelson *et al.* (1979)	Juvenile coho (g/section)	pool volume
35	Sekulich (1980)	Age 0 chinook in pools (g/m^2)	flow, estimate of eggs deposited/m^2, minimum water temp of 5 previous days
36	Marshall (1985)	Age 0 brown trout (kg/ha)	mean depth, surface area, area of overhanging riparian veg, deep slow area
37	Konopacky (1984)	Age 0 chinook (g/pool)	log pool area, riffle area, mean riffle particle size
38	Leathe and Enk (1985)	Bull trout $\geq$ 75 mm (#/100 m^2)	drainage area, maximum pool depth, area of all cover, channel debris, substrate score
39	Leathe and Enk (1985)	Westslope cutthroat $\geq$ 75 mm (#/100 m^2)	drainage area, maximum depth, area of all cover
40	Rinne (1978)	Gila trout (g/100 m)	mean pool depth, pool area, pool volume, maximum pool depth, area of all cover, percentage of area as cover
41	Hendrickson *et al.* (1973b)	Trout (log lb/acre)	log mean flow per unit area, log velocity index, log mean annual maximum water temp, log percentage of area as aquatic vegetation
42a	Stewart (1970)	Rainbow trout > 18 cm (g/m)	mean depth, rock cover < 0.1 m^2, rock cover > 0.3 m^2
42b	Stewart (1970)	Brook trout > 18 cm (g/m)	mean depth, total cover rating
43	Fraley and Graham (1981)	Age 1 and older trout (#/100 m^2)	stream order, area of all cover, 90th percentile substrate size
44	Platts (1974)	Rainbow trout (#/section)	reach elevation, watershed condition, mean depth, percentage of pool, percentage of riffle, section gradient measured in field, percentage of boulder substrate, pool feature (2*), percentage of fine substrate, percentage of gravel substrate, percentage of rubble substrate, pool rating (2*), stream bank condition (5*)
45	Platts (1976)	Rainbow trout (#/section)	reach elevation, watershed condition, mean depth, percentage of pool, percentage of riffle, section gradient measured in field, percentage of boulder substrate, pool feature (2*), percentage of fine substrate, percentage of gravel substrate, percentage of rubble substrate, pool rating (2*), stream bank condition (5*)
46	Leathe and Erick (1985)	Brook trout $\geq$ 75 mm (#/100 m^2)	area of all cover

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
47	White *et al.* (1983)	Trout (brook, brown, and rainbow) ≥ 200 mm (log #/km)	log annual flow variation, log critical period flow as percentage of mean flow, log mean velocity, log nitrate nitrogen, log percentage of eroding banks, log pool and turbulance cover, log substrate rating, log maximum summer water temperature
48a	Scarnecchia (1983)	Trout (brook, brown, rainbow, cutthroat) (g/m^2/yr)	reach elevation, mean width, width to depth ration, sulfate
48b	Scarnecchia (1983)	Trout (brook, brown, rainbow, cutthroat) (g/m^2)	reach elevation, nitrate nitrogen, percentage of zero velocity, sulfate
49	Hendrickson *et al.* (1973a)	Trout (log lb/acre)	log mean flow per unit area, log width to depth ratio, log percentage of area as aquatic vegetation
50	Lewis (1969)	Trout (brown, rainbow, brook) ≥ 7" (#/pool)	mean pool velocity, area of all cover
51	Hendrickson and Doonan (1972)	Trout (log lb/acre)	mean annual maximum water temperature
52	Gowan (1984)	Trout (brook and brown) (#/section)	weighted usable area
53	Stalnaker (1979)	Brown trout (kg/km)	weighted usable area
54	Nehring (1979)	Brown trout > 13 cm (lb/acre)	weighted usable area
55	Loar *et al.* (1985)	Age 0 rainbow in allopatry (#/km)	weighted usable area
56	Loar *et al.* (1985)	Age 2$^+$ and older brown trout (g/km)	weighted usable area
57	Loar *et al.* (1985)	Age 1$^+$ brown trout (#/km)	weighted usable area
58a	Ptolemy *et al.* (1991)	Salmonid (steelhead, rainbow, cutthroat, brown trout, Dolly Varden, brook trout, and chinook salmon) density (# / 100 m^2) by size class or age group	fish weight, alkalinity, fixed nonfilterable residue
58b	Ptolemy *et al.* (1991)	Juvenile coho density (# / 100 m^2)	fish weight, alkalinity
59a	Oswood and Barber (1982)	Coho (age 0) abundance in 30 m long stream sections	spawning area, area of overhanging riparian vegetation, season
59b	Oswood and Barber (1982)	Dolly Varden abundance in 30 m long stream sections	stream area, area with forest debris in riffles

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
59c	Oswood and Barber (1982)	Coho (age 1^+) abundance in 30 m long stream sections	gradient, area with depth <0.5 m velocity < 0.3 m/s, area of overhanging riparian vegetation, area undercut banks
59d	Oswood and Barber (1982)	Trout (rainbow and cutthroat) abundance in 30 m long stream sections	area with forest debris in riffles, area with depth >0.5 m velocity >0.3 m/s, area with forest debris in pools, area of overhanging vegetation
60	Lanka *et al.* (1987)	Trout (brown, rainbow, brook, and cutthroat) standing stock (kg/ha for fish > 100 mm)	reach elevation, relief ratio, drainage density, average reach width
61a	Jowett (1992)	Brown trout abundance (# > 200 mm total length per ha)	water temp, mean:median flow, % lake area, % flat slope
61b	Jowett (1992)	Brown trout abundance (# > 200 mm total length per ha)	water temp, total benthic invertebrate biomass
61c	Jowett (1992)	Brown trout abundance (# > 200 mm total length per ha)	water temp, % WUA, % lake area, % sand in substrate, instream trout cover grade, river gradient, elevation, % developed (pasture, crop, horticulture)
61d	Jowett (1992)	Brown trout abundance (# > 200 mm total length per ha)	water temp, total benthic invertebrate biomass, % WUA
62	Rosenau and Slaney (1983)	Trout and char sustained standing crop (i.e., standing crop remaining after moderate fishing pressure)	area of cover/total area, nitrate
63a	Milner *et al.* (1985)	Brown trout (10.1-20 cm)density (# / 100 m^2) at hard water sites	altitude, average depth, depth variance, % of depth of 0-15 cm, % of depth of 46-60 cm, cover index
63b	Milner *et al.* (1985)	Brown trout (> 20 cm) density (# / 100 m^2) at hard water sites	water hardness, average depth, depth variance, % of depth of 46-60 cm, % boulders, % cobble, cover index
64	Marshall and Britton (1990)	Coho smolt yield (biomass)	stream length
65	Godbout and Peters (1988)	Stable brook trout catch in lakes	Several models, best and most relevant to BC had inputs of total phosphorus, fishing effort, and lake area
66a	Baran *et al.* (1996)	Brown trout density (juvenile and adult) (#/ha)	Froude number, area of cover, area of shelter, elevation

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
66b	Baran *et al.* (1996)	Brown trout density (juvenile and adult) (kg/ha)	Froude number, area of shelter, coefficient of variation of depth
67a	Creque *et al.* (2005)	Chinook (fry/smolts) (#/ha) - landscape scale	log 90% exceedence flow yield, mean July temp^2
67b	Creque *et al.* (2005)	Chinook (fry/smolts) (#/ha) - site scale	depth
67c	Creque *et al.* (2005)	Steelhead (0-2 yrs) (#/ha) - landscape scale	log Drainage Area, 90% exceedence flow yield
67d	Creque *et al.* (2005)	Steelhead (0-2 yrs) (#/ha) - site scale	depth
67e	Creque *et al.* (2005)	Brook trout (juvenile and adult) (#/ha) - landscape scale	mean July temp^2
67f	Creque *et al.* (2005)	Brook trout (juvenile and adult) (#/ha) - site scale	depth
67g	Creque *et al.* (2005)	Brown trout (juvenile and adult) (#/ha) - landscape scale	mean July temp^2
67h	Creque *et al.* (2005)	Brown trout (juvenile and adult) (#/ha) - site scale	depth
68	Dunham *et al.* (2002)	Cutthroat (# juveniles & adults/m)	width:depth
69a	Ebersole *et al.* (2003) best model	Chinook (#/100 m^2)	width:depth, proportional pool area, subbasin location, cold water patch frequency
69b	Ebersole *et al.* (2003) variables in other models	Chinook (#/100 m^2)	channel sinuosity, mean substrate embeddedness, large wood frequency, and maximum 7-day mean maximum daily temperature, cold water patch area
69c	Ebersole *et al.* (2003) best model	Rainbow (#/100 m^2)	proportional pool area, mean substrate embeddedness, maximum 7-day mean maximum daily temperature, riparian canopy density, subbasin location, and cold water patch frequency

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
69d	Ebersole *et al.* (2003) variables in other models	Rainbow (#/100 m^2)	width:depth ratio, channel sinuosity, large wood frequency, cold water patch area
70a	Feist *et al.* (2003)	Chinook redds (redds/km) - watershed scale	Hillslope less than 1.5%, major lithology, USGS Land Use and Land Cover, GAP Land Use and Land Cover, Mean daily mean, maximum and minimum air temperature, cumulative annual precipitation, Livestock grazing allotments, mining claims, water diversions; BEST MODEL INCLUDED percent non-forested riparian wetlands, percent sedimentary geology, and percent hillslope less than 1.5%
70b	Feist *et al.* (2003)	Chinook redds (redds/km) - reach scale	Network distance, channel sinuoisity, channel gradient, Hillslope less than 1.5%, major lithology, USGS Land Use and Land Cover, GAP Land Use and Land Cover, Mean daily mean, maximum and minimum air temperature, cumulative annual precipitation, Livestock grazing allotments, mining claims, water diversions; the best model maximum air temperature and lithology.
71	Greene *et al.* (2005)	Chinook return rate (spawners per spawner in the previous cohort or recruits per spawner)	egg producton, flood recurrence index (FRI), tidal delta PCA factor, Bay PCA factor, 1st ocean year PCA factor score, 2nd ocean year PCA factor score, 3rd ocean year PCA factor score, 4th ocean year PCA factor score (PCA scores based on sea surface temperature, sea level pressure, sea level, and coastal upwelling). Best model (spawners per spawner) included the Bay PCA factor, FRI, 3rd ocean year PCA factor score, egg producton, tidal delta PCA factor, and 2nd ocean year PCA factor score
72	Hedger *et al.* (2004)	Atlantic salmon fry and parr (#/m^2)	HQI (velocity, depth, and granulometric index)

Document	**Author(s)**	**Species (Model Output)**	**Significant Independent Variable(s) in Model**
73	Hughes *et al.* (2004)	Fish IBI (an index measuring stream condition based on fish assemblage data)	residual pools > 1 m, % sand and fines, bed stability, log total N, log total P, riparian human disturbance, riparian condition index, catchment road density, and catchment and riparian condition index
74	Inoue and Nakano (2001)	Masou salmon fry (#/100 m^2)	water temperature, mean depth, woody debris cover
75	McHugh *et al.* (2004)	Chinook (egg to smolt survival)	% fines in spawning gravel, incubation temperature, riffle-run embeddedness, summer parr rearing temperature, and pool embeddedness
76	Opperman *et al.* (2005)	Embeddedness index (concentration or level of fine sediment within gravel and cobble substrate at each potential spawning site on a four-level ordinal scale, from 1 (very low levels of fine sediment) to 4 (very high levels of fine sediment)) for salmonid (coho, chinook, pink, and chum salmon and steelhead) spawning substrates	agriculture, urban landuse, road density, forest cover
77	Paulsen and Fisher (2001)	Chinook juvenile overwinter survival; 3 models: land use, no land use, and road density	Landuse: 5 land use categories (based on land use, land ownership, elevation, and vegetation pattern), fish length, month of tagging, and the Palmer drought severity index; No Land Use: fish length, month of tagging, and the Palmer drought severity index; Road Density: road density, fish length, month of tagging, and the Palmer drought severity index.
78	Pess *et al.* (2002)	Adult coho abundance index (in fish days, which were calculated by multiplying the live fish observed on each survey date by the number of days between surveys; the values from individual surverys were then summed for the entire observation period to generate a relative index of spawner abundance at each reach for any given year)	wetland occurance, local geology, stream gradient, landuse

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
79a	Platts and Nelson (1989)	Total salmonid biomass regardless of age or species (per unit area). Species included chinook fry, rainbow, steelhead, cutthroat, bull, and brook trout	none
79b	Platts and Nelson (1989)	Total salmonid biomass regardless of age or species (per unit area). Species included chinook fry, rainbow, steelhead, cutthroat, bull, and brook trout	canopy density, light intensity, average potential daily thermal input, unobstructed sun-arc (in the Great Basin area only)
80	Rosenfeld *et al.* (2000)	Juvenile coho (#/m^2)	bankfull width, reach gradient
81	Sharma and Hilborn (2001)	Coho smolt density (smolts/km)	individual models: pool density, ponds density, valley slopes, road density, stream gradients, LWD density, drainage density, lake density (pool and pond densities were best predictors of smolt density)
82a	Stoneman and Jones (2000)	Juvenile and adult brook and brown trout, and juvenile rainbow trout (biomass density in g/m^2 for all species combined)	water temperature, percent pools, substrate size, and cover
82b	Stoneman and Jones (2000)	Juvenile and adult brook and brown trout, and juvenile rainbow trout (biomass density in g/m^2 for individual species)	water temperatures, percent pools, substrate size, average competitor biomass, and cover
83a	Thompson and Lee (2000)	Chinook parr (snorkel count category at index sites, original counts expressed per m^2)	geometric mean road density, mean annual percipitation
83b	Thompson and Lee (2000)	Steelhead parr (snorkel count category at index sites, original counts expressed per m^2)	% unconsolidated lithology

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
84	Bradford and Irvine (2000)	Instantaneous average annual rate of change in Thompson River watershed coho recruitment (slope of the regression of ln(R+1) on year for the years 1988–1998)	Separate correlations for each of: a) Proportion of land under agricultural and urban use, b) density of roads, c) habitat concerns index (factors in forestry, agriculture, urbanization, recreation, mining, industrial development, linear development, hydro development, cumulative impacts, and special biophysical concerns), and c) proportion of land recently logged or burned in last 20-25 years
85	Hume *et al.* (1996)	Sockeye maximum smolt output in Fraser River lakes and the corresponding optimum escapement required	Photosynthetic rates (kg C/d) in lakes, lake surface area
86	Parken *et al.* (2006, DRAFT)	The number of spawners required to produce the maximum sustained yield and the number of spawners required for replacement for a given stock	watershed area, spawner escapements of known accuracy and reliability
87	Parken *et al.* (2002)	Spawner Capability Models (predict the number of spawners a system would contain based on maximum observed densities) including Habitat Suitability Models and Spawner Density Models; and Spawner Capacity Models (predict the spawner carrying capacity) including Scaled Habitat Suitability Models and Scale Spawner Density Models - all for Fraser River chinook	annual escapement, spawner counts, stream length, stream area (from length combined with wetted width estimated from late summer low flow which were calculated from MAD), and gradient

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
88	Bocking and Peacock (2004)	Maximum coho smolt abundance and the associated number of required spawners (used two models to estimate # smolts/km: 1) a log linear predictive regression of smolt yield from stream length for Alaskan and BC streams; and 2) used recent decadal smolt yield and stream length for 3 northern BC coho indicator streams)	accessible stream length, relationship between smolt yield and stream length, survival estimates by life stage, fecundity estimates
89	Holtby and Scrivener (1989)	Coho and chum escapements in Carnation Creek	peak discharge, stream temperature, gravel particle size, habitat quality index (logging activity related), sea surface temperature, and sea surface salinity; several other non-habitat related parameters also required as inputs
90	Bradford *et al.* (1997)	Coho smolt abundance at the watershed or regional level	stream length and latitude (to a lesser degree) were found to be significant; note: they also examined valley slope, discharge (mean annual, minimum monthly mean, and maximum monthly mean), and water yield (mean annual discharge/drainage area) as potential predictors of smolt abundance
91	Shortreed *et al.* (2000)	Maximum sockeye smolt numbers and biomass in individual lakes and optimum adult escapement to individual lakes	Total seasonal (May to October) lake carbon production (metric tons), lake surface area
92	Ptolemy 1981	Juvenile coho biomass density (g/m^2)	mean cross-sectional velocity
93	Beechie *et al.* (2006)	Number of chinook spawners per population (separately in small streams and large channels)	Small streams: stream length in pool-riffle and forced pool riffle channels, redd frequency, and number of adults per redd; Large channels: total wetted area, proportion of that area that is suitable for chinook spawning, redd area, and number of adults per redd

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
94	Fight *et al.* (1990)	For coho, chum, and pink: escapement to a particular stream reach, egg deposition, egg survival, rearing success, smolting success, and harvest	fisheries regulations, logging related parameters (percentage of bank cut, area logged), road parameters (length of road used, length of road constructed), total sediment load, fine sediment concentration in gravel, amount of large organic debris, bedload shift, water temperature (summer mean and maximum, fall mean, and winter degree-days), flow (summer and winter lows), stream velocity, canopy cover, and available spawning gravel area
95	Downing *et al.* (1990)	Fish production in lakes (kg/ha/yr) - not species specific	many potential regression models examined, the best three being the models that predict fish production from annual phytoplankton production, mean total phosphorus concentration, and average annual fish standing stock
96	Knowler *et al.* (2003)	Coho recruitment (South Thompson and Georgia Strait fishery), habitat value ($)	habitat quality factor, habitat capacity factor, and Habitat Concerns Index as per Bradford and Irvine (2000) - it is based on indicators of human activity in forestry, agriculture, urbanization, recreation, mining, industrial development, roads and other linear development, hydro development, cumulative impacts, and special biophysical concerns
97	Ptolemy (2005)	Coastal cutthroat biomass (g/100 m^2)	alkalinity, unit runoff (latter not presented)
98	Tautz *et al.* (1992)	Number of adult steelhead produced at carrying capacity in the Skeena River and its tributaries per stream or stream section	3 models: 1) linear based, 2) area based (2 versions), and 3) process based. See below (Parken (1997)) for a summary of the model inputs
99	Bocking and English (1992)	Number of adult steelhead produced at carrying capacity, minimum escapement, and allowable harvest rate in the Skeena River and its tributaries per stream or stream section	Modification of Tautz et al. (1992) model in that they rolled the different components of the 3 models (linear-based, area-based, and process-based – or biological-based as per the review of Parken (1997)) presented in Tautz et al. (1992) into one model (with slight modifications in that they used fry density at capacity in conjunction with fry-smolt and smolt-adult survival instead of smolt density at capacity and smolt-adult survival; they also used a different estimate of smolt-adult survival). The model was extended in that a minimum escapement and allowable harvest rate are estimated

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
100	Parken (1997)	Number of adult steelhead produced at carrying capacity in the Skeena River and its tributaries per stream or stream section	Reviewed 3 models from Tautz *et al.* (1992): 1) linear based, 2) area based (2 versions), and 3) biological based (referred to as process based in Tautz *et al.* (1992). 1) Linear based model has inputs of accessible stream length and adult capacity/km in the Keogh River; 2) Area based model has inputs of total area of stream available to steelhead, smolt density at capacity (Keogh River), and smolt-adult survival (Keogh River) (note the second version of this model differs in that it uses total useable stream area available to steelhead); 3) Biological based model has inputs of total useable stream area available to steelhead, smolt density at capacity adjusted to better suit Skeena tributaries (based on higher alkalinity), and smolt-adult survival (Keogh). NOTE: in all models smolt density was estimated using alkalinity, water temperature (for growing season length), and the required rearing area to produce 1 smolt.
101	Bocking *et al.* (2005)	Amount of suitable habitat for fry rearing, production estimates for smolts, and the minimum escapement required to fully seed available habitat for summer and winter steelhead in Nass River tributaries (6 versions using combinations of parameters given in adjacent cell and using biolgical parameters from different steelhead populations) in the Nass River and its tributaries per stream or stream section	alkalinity, water temperature, mean annual discharge, gradient, stream order, mean size at age (smolts), life history parameters, accessible stream length, useable stream area

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
102	Lestelle *et al.* (2004)	Chinook, coho, & steelhead: abundance (i.e., habitat capacity) and productivity (defined as density independent survival rate) for various life stages; done at a stream reach scale then integrated to estimate the overall population capacity and productivity	Natural confinement, Metals in water, Temperature max, Fish species introductions, Artificial confinement, Metals in soil, Temperature min, Harassment, Bed scour, Pollutants in water, Temperature spatial variation, Hatchery outplants, Embeddedness, Nutrient enrichment, Turbidity, Fish community richness, Fine sediment, Natural flow regime, Water withdrawals, Predation, Obstructions, Regulated flow regime, Salmon carcasses, Benthos community richness, Wood, Within year high flow, Riparian function, Predation, Alkalinity, Within year low flow, Gradient, Icing, Dissolved oxygen, Diel flow pattern, Fish pathogens, Channel Length, Channel width, Channel stability, Habitat Diversity
103	Shortreed *et al.* (2001)	See Shortreed *et al.* (2001) - same model applied to 60 BC Lakes	see Shortreed et al (2001) - same model applied to 60 BC Lakes
104	Dauble *et al.* (2003)	Lineal distance of suitable chinook spawning habitat (historic, i.e., pre-dam, and current) and the Lower and Upper Columbia River and Lower and Upper Snake River	geomorphic categorization was based on three features: geologic composition of the riverbank (100% unconsolidated, 50/50 unconsolidated/bedrock, or 100% bedrock.), longitudinal gradient of water surface, and presence or absence of channel bars or islands (islands or bars present, islands or bars absent, or unknown). Shoreline length was also used in the model.
105a	Baran *et al.* (1995)	Brown trout (all stages) biomass per lineal m of stream (kg /100 m)	weighted usable area, area of cover
105b	Baran *et al.* (1995)	Brown trout (all stages) density per lineal m of stream (# /100 m)	weighted usable area, area of cover
106	Beechie *et al.* (1994)	Changes in coho smolt production since European settlement began in Skagit River basin (number and % change of smolts)	useable area by habitat type, parr density by habitat type, survival to smolt stage by habitat type, potential smolt production by habitat type based on area or length, historical and current areas of different habitat types, impact type (hydromodification due to agricultural and urban use, blocking culverts, forestry activities, dams for hydropower)

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
107	Jager and Rose (2003)	Number of chinook smolts	Numerous biological, flow, habitat, behavioral, and temperature variables.
108a	Downing and Plante (1993)	Annual production of fish populations in lakes	annual mean standing biomass (kg per hectare) and maximum individual body mass (g)
108b	Downing and Plante (1993)	Annual production of fish populations in lakes	annual mean standing biomass (kg per hectare), maximum individual body mass (g), and average annual air temperature (°C)
108c	Downing and Plante (1993)	Annual production of fish populations in lakes	annual mean standing biomass (kg per hectare), maximum individual body mass (g), and total phosphorus (μg/L)
109a	Smith (2000)	Wild adult steelhead catch-per-angler-day for north coast rivers (coastal Region 6) and the Skeena and Nass watersheds (excluding the Babine River and 3 rivers in the Nass watershed)	August freshwater discharge 0 and 3–5 years prior to the year that wild adult steelhead return to their natal river to spawn
109b	Smith (2000)	Wild adult steelhead catch-per-angler-day for the Dean River	August freshwater discharge 0 and 3–5 years prior to the year that wild adult steelhead return to the Dean River to spawn
109c	Smith (2000)	Wild adult steelhead catch-per-angler-day for the Bella Coola watershed	August freshwater discharge 3 and 4 years prior to the year that wild adult steelhead return to their natal rivers to spawn
110a	Bartz *et al.* (2006)	Past, present, and future prespawning tempterature (mean of daily maxima, °C) for chinook; used as input in Shiraz population model (Scheuerell *et al.* (2006))	Past, present, and future % riparian forest cover, mean annual precipitation (cm), and % alluvium
110b	Bartz *et al.* (2006)	Past, present, and future incubation temperature (mean of montly means, °C) for chinook, used as input in Shiraz population model (Scheuerell *et al.* (2006))	Past, present, and future road density (km/km^2), mean elevation (m)
110c	Bartz *et al.* (2006)	Past, present, and future peak flow (largest daily mean, cms) for chinook, used as input in Shiraz population model (Scheuerell *et al.* (2006))	Past, present, and future drainage area (km^2), mean annual precipitation (cm), % impervious cover

Document	Author(s)	Species (Model Output)	Significant Independent Variable(s) in Model
110d	Bartz *et al.* (2006)	Past, present, and future fine sediment (mean fraction < ~6.3 mm in diameter, %) for chinook, used as input in Shiraz population model (Scheuerell *et al.* (2006))	Past, present, and future % total forest cover, drainage area (km^2), % alluvium
111	Scheuerell *et al.* (2006)	Past, present, and future number of chinook smolts and spawners in the Snohomish River subbasin	Past, present, and future prespawning tempterature (mean of daily maxima, °C), incubation temperature (mean of montly means, °C), peak flow (largest daily mean, cms), fine sediment (mean fraction < ~6.3 mm in diameter, %), habitat capacity (potential juvenile capacity (#/subbasin) and potential adult capacity (#/subbasin), survival rates
112	Eaglin and Hubert (1993)	Trout (predominantly brook and brown) standing stock (g/m^2)	# of culverts / km^2, mean bank-full width (m)
113a	Nelitz *et al.* (2006)	Indicator on rainbow trout egg survival	maximum weekly average temperature index (°C)
113b	Nelitz *et al.* (2006)	Indicator of rainbow trout juvenile growth at 4 food rations	maximum weekly average temperature index (°C)
113c	Nelitz *et al.* (2006)	Indicator of rainbow trout resistance to disease mortality	maximum weekly average temperature index (°C)

Table 3. **Comparison of salmon habitat models and DFO habitat performance indicators.**

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
1a	channel stability		
1b			
2			
3		total stream length?	
4		total stream length?	forested area
5	flow		
6	flow	specific high value habitat	
7	channel stability		
8	flow		
9	flow		
10a	flow		
10a	flow		
10a	flow		
11a	flow		
11b	flow		
11c	flow		
12a	flow		
12b	flow		
12c	flow		
12d		specific high value habitat	
12e		specific high value habitat	
13a	flow		
13b	flow		
13c	flow		
13d		specific high value habitat	
13e		specific high value habitat	
14	flow		
15a	flow		
15b	flow		
16	flow	specific high value habitat	
17			
18	flow		
19	flow		
20	substrate quality		
21	substrate quality	specific high value habitat	
22a	channel stability		
22b		specific high value habitat	
22c	channel stability	specific high value habitat	
23a	substrate quality		

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
23b	substrate quality		
23c	substrate quality		
23d	substrate quality		
23e	substrate quality		
24	specfic high value habitat		
25		specific high value habitat	
26	substrate quality	specific high value habitat	
27		specific high value habitat	
28	substrate quality		
29	substrate quality		
30	substrate quality		
31	substrate quality	specific high value habitat	
32	flow, substrate quality, stream chemistry, summer max temperature		
33	flow, substrate quality, stream chemistry, summer max temperature		
34a		specific high value habitat	
34b		specific high value habitat	
34c		specific high value habitat	
34d		specific high value habitat	
34e		specific high value habitat	
35	flow		
36		specific high value habitat	
37	substrate quality	specific high value habitat	
38		specific high value habitat	
39		specific high value habitat	
40		specific high value habitat	
41	flow, water temperature	specific high value habitat	
42a	substrate quality		
42b		specific high value habitat	
43	substrate quality	specific high value habitat	
44	substrate quality, channel stability	specific high value habitat	watershed condition
45	substrate quality, channel stability	specific high value habitat	watershed condition
46		specific high value habitat	
47	flow, stream chemistry, substrate quality, water temperature, channel stability	specific high value habitat	
48a	channel stability, water chemistry		
48b	water chemistry	specific high value habitat	
49	flow, channel stability	specific high value habitat	
50		specific high value habitat	

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
51	water temperature		
52		specific high value habitat	
53		specific high value habitat	
54		specific high value habitat	
55		specific high value habitat	
56		specific high value habitat	
57		specific high value habitat	
58a		specific high value habitat	
58b		specific high value habitat	
59a		specific high value habitat	
59b		specific high value habitat	
59c	stream chemistry		
59d	substrate quality	specific high value habitat	
60			
61a	flow, water temperature		
61b	water temperature, macroinvertebrates		
61c	water temperature, substrate quality	specific high value habitat	land use
61d	water temperature, macroinvertebrates	specific high value habitat	
62	stream chemistry	specific high value habitat	
63a		specific high value habitat	
63b	stream chemistry	specific high value habitat	
64		total stream length?	
65	lake chemistry		
66a		specific high value habitat	
66b		specific high value habitat	
67a	flow, water temperature		
67b			
67c	flow, drainage area		
67d			
67e	water temperature		
67f			
67g	water temperature		
67h			
68	channel stability		
69a	channel stability	specific high value habitat	
69b	substrate quality	specific high value habitat	
69c	substrate quality, water temperature	specific high value habitat	
69d	channel stability	specific high value habitat	
70a			% riparian forest integrity
70b			

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
71	peak discharge events		
72	substrate quality		
73			
74	water temperature	specific high value habitat	
75	substrate quality, water temperature	specific high value habitat	
76			agriculture, urban landuse, road density, forrest cover
77			landuse, road density
78			landuse
79a			
79b			
80	substrate quality		
81		specific high value habitat	road density
82a	water temperature, substrate quality	specific high value habitat	
82b	water temperature, substrate quality	specific high value habitat	
83a			road density
83b			
84			%watershed urban and agricultural development, road density, a "habitat concerns index" that factors in forestry, agriculture, urbanization, recreation, mining, industrial development, linear development, hydro development, cumulative impacts, and special biophysical concerns), and % of land recently logged or burned in last 20-25 years
85	lake chemistry (seasonal average daily photosynthetic rates)		

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
86		watershed area	
87	MADs (used in conjunction with length to estimate stream area)	accessible stream length, stream area	
88		accessible stream length	
89	water temperature (stream and ocean), peak discharge, sea surface salinity		indices of stream features affected by logging activities
90	discharge	accessible stream length	
91	lake chemistry (total seasonal lake carbon production)		
92	mean cross-sectional velocity		
93		length (small channels) and area (large channels, derived from length and width) of spawning habitat within accessible stream length	
94	discharge, water temperature, substrate quality		road length (used and unused), area loggedsurface area
95	lake chemistry (mean total phosphorus)		
96			as per Bradford and Irvine (2000, included above): %watershed urban and agricultural development, road density, a "habitat concerns index" that factors in forestry, agriculture, urbanization, recreation, mining, industrial development, linear development, hydro development, cumulative impacts, and special biophysical concerns), and proportion of land recently logged or burned in last 20-25 years
97	alkalinity, unit runoff (latter not presented)		
98 (Linear Model)	alkalinity, water temperature	accessible stream length	
98 (Area Model)	alkalinity, water temperature, mean annual discharge	accessible and useable stream area (each in a separate model versions)	

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
98 (Process Model)	alkalinity, water temperature, mean annual discharge	accessible and useable stream area (each in a separate model versions)	
99	mean annual discharge, alkalinity, water temperature	accessible stream length, accessible and useable stream area	
100 (Linear Model)	alkalinity, water temperature	accessible stream length	
100 (Area Model)	alkalinity, water temperature, mean annual discharge	accessible and useable stream area (each in a separate model versions)	
100 (Biological Model)	alkalinity, water temperature, mean annual discharge	accessible and useable stream area (each in a separate model versions)	
101	alkalinity (in recommended version of model), water temperature, mean annual discharge	accessible length, useable stream area (in separate model versions)	
102	Metals in water, Temperature max, Metals in soil, Temperature min, Bed scour, Pollutants in water, Temperature spatial variation, Embeddedness, Nutrient enrichment, Turbidity, Fine sediment, Natural flow regime, Salmon carcasses, Within year high flow, Alkalinity, Within year low flow, Dissolved oxygen, Diel flow pattern, Benthos community richness	Channel Length, Channel width	Natural confinement, Artificial confinement, Water withdrawals, Regulated flow regime, Riparian function, Fish pathogens, Hatchery outplants, Icing, Channel stability, Habitat Diversity
103	lake chemistry (total seasonal lake carbon production)		
104	substrate quality	accesible stream length	examined under pre- and post-dam conditions
105a		specific high value habitat	
105b		specific high value habitat	
106		specific high value habitat, accesible stream length	urban and agricultural development (diking, ditching, dredging, and bank protection), forestry, blocking culverts, dam impacts

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	**Highly Productive Habitats**	**Land and Water Use**
107	power function exponent relating velocity to flow, slope between travel time (d/km) and flow (m^3/s), minimum flow needed to upmigrate and spawn (m^3/s), probability of upstream movement at low temperatures, lower threshold for behavioural avaoidance (°C), upper temperature threshold for chinook salmon spawning (°C), upper lethal temperature for chinook salmon (°C), degree days (°C, for hatching to emergence, egg laying to hatching, and to develop into a smolt)	Stream distance below dam used for spawning	
108a			
108b	average annual air temperature (°C) (reflects average annual water temperature)		
108c	total phosphorus (µg/L)		
109a	August freshwater discharge 0 and 3–5 years prior to the year that wild adult steelhead return to their natal river to spawn in northerly snowmelt-driven watersheds (north coast rivers (coastal Region 6) and the Skeena and Nass watershed, excluding the Babine River)		
109b	August freshwater discharge 0 and 3–5 years prior to the year that wild adult steelhead return to the Dean River to spawn		
109c	August freshwater discharge 3 and 4 years prior to the year that wild adult steelhead return to their natal rivers to spawn in the Bella Coola watershed		
110a	past, present, and future mean annual precipitation (cm)		Past, present, and future % riparian forest cover
110b			Past, present, and future road density (km/km^2)

Document	Overlap with DFO Habitat Performance Indicators		
	Habitat State		Habitat Pressure
	Water Quantity and Quality	Highly Productive Habitats	Land and Water Use
110c	Past, present, and future drainage area (km^2) and mean annual precipitation (cm)		Past, present, and future % impervious cover
110d	Past, present, and future drainage area (km^2)		Past, present, and future % total forest cover
111	Past, present, and future prespawning temperature (mean of daily maxima, °C), incubation temperature (mean of montly means, °C), peak flow (largest daily mean, cms), fine sediment (mean fraction < ~6.3 mm in diameter, %)	Past, present, and future habitat capacity (potential juvenile capacity (#/subbasin) and potential adult capacity (#/subbasin))	NOTE: all habitat state indicators are based on past, present, and future land use
112		mean bank-full width (m)	# of culverts / km^2
113a	maximum weekly average temperature index (°C)		
113b	maximum weekly average temperature index (°C)		
113c	maximum weekly average temperature index (°C)		

APPENDIX A: Annotated Bibliography of Selected Habitat Productivity Model Literature

Baran, P.B., M. Delacoste, F. Dauba, J.M. Lascaux, A. Belaud, and S. Lek. 1995. Effects of reduced flow on brown trout (*Salmo trutta* L.) populations downstream dams in French Pyrenees. Regul. Rivers: Res. Manage. 10: 347-361.

Populations of brown trout and their physical habitat characteristics were studied upstream (control) and downstream (treatment) of 16 hydroelectric plants (15 streams). Average velocity, depth, and area of cover were significantly lower below the dams. The total abundance of brown trout (per lineal metre of stream) was lower below the dams in 9 cases for biomass and in 8 cases for densities. Adults were affected to a greater extent by flow reductions than fry; modifications to biomass and density were significantly related to flow below the dams. The differences of adult, juvenile, and fry abundances between the upstream and downstream sites were significantly related to differences in WUA, average depth, average velocity, and area of cover. A multiple linear regression model using WUA and area of cover explained 84% of the difference in biomass per linear metre and 68% of the difference in density.

Baran, P., S. Lek, M. Delacoste, and A. Belaud. 1996. Stochastic models that predict trout population density or biomass on a mesohabitat scale. Hydrobiologia 337: 1-9.

Forty sections on 11 streams in the Pyrenees were used in this study. Compared both neural networks, and multiple regression approaches to modelling brown trout abundance to habitat variables. Habitat variables included width, gradient, mean depth, coefficient of variation of depth, coefficient of variation of bottom velocity, froude number, area of cover, area of shelter, deep water area, elevation, biomass of brown trout, density of brown trout. Biomass of trout is related to 9 variables, while density is related to 8. The neural networks were shown to predict densities and biomass the best.

Bartz, K.K., K. Lagueux, M.D. Scheuerell, T.J. Beechie, A. Haas, and M.H. Ruckelshaus. 2006. Translating restoration scenarios into habitat conditions: an initial step in evaluating recovery strategies for Chinook salmon (*Oncorhynchus tshawytscha*). Can. J. Fish. Aquat. Sci. 63: 1578-1595.

The authors evaluate the effects of alternative land use scenarios on four habitat conditions that are potentially important to chinook salmon survival: 1) stream temperature during the prespawning period (mid-July to mid-October, mean of daily maxima), 2) stream temperature during the egg incubation period (mid-September to mid- February, mean of monthly means), 3) peak stream flow during the egg incubation period (largest daily mean), and 4) fine sediment in the stream bed (mean fraction < ~6.3 mm diameter (%)). This was done under historical, current, and future habitat conditions. A best model was generated for each habitat condition using the following independent variables: road density, % impervious cover, % total forest cover, % riparian forest cover, mean elevation, drainage area, mean channel gradient, mean annual precipitation, and % alluvium. The best model for estimating prespawning temperature had inputs of riparian forest cover, annual precipitation, and % alluvium. The best model for estimating incubation temperature had inputs of road density and elevation. For estimating peak flow during the egg incubation period, the best model had inputs of drainage area, annual precipitation, and impervious cover. The best model for estimating fine sediment had inputs of total forest cover, drainage area, and % alluvium. Estimates of change in habitat quanity, measured by potential juvenile capacity and potential adult capacity, were generated using modified approaches presented in Beechie *et al.* (1994), Lunetta *et al.* (1997), and Beechie *et al.* (2006). Finally, Monte Carlo simulations were used to generate confidence intervals for both habitat quality and quantity estimates. Results from the analysis were used as the habitat inputs to a population model (Shiraz, a life cycle model described by Scheuerell *et al.* (2006)) linking changes in habitat to salmon population status at the subbasin scale.

Beechie, T., E. Beamer, and L. Wasserman. 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. N. Am. J. Fish. Manage. 14: 797-811.

Estimated changes in coho smolt production in the 8,270 km^2 Skagit River basin following European settlement based on changes in summer and winter rearing habitat areas. They assessed changes in smolt production by habitat type (side-channel sloughs, distributary sloughs, small tributaries, large tributaries, ponds, mainstems, and lakes) and by cause of habitat alteration (blocking of culverts, forestry activities, and hydromodification associated with agricultural and urban lands, i.e., diking, ditching, dredging, and bank protection). Smolt production capacity of summer habitats was found to be reduced by 24% from 1.28 million smolts to 0.98 million smolts and the production capacity of winter habitats was found to be reduced by 34% from 1.77 million to 1.17 million smolts. The largest proportion of summer non-mainstem losses occurred in side-channel sloughs, followed by small tributaries and distributary sloughs. The largest loss of winter habitats occurred in side-channel sloughs, followed by distributary sloughs and small tributaries.

Beechie, T.J., C.M. Greene, L. Holsinger, and E.M. Beamer. 2006. Incorporating parameter uncertainty into evaluation of spawning habitat limitations on chinook salmon (*Oncorhynchus tshawytscha*) populations. Can. J. Fish. Aquat. Sci. 63: 1242-1250.

Developed a Monte Carlo procedure in which the number of chinook spawners in six populations in Puget Sound is predicted. Separate equations were used to predict spawner numbers in small and large channels. The length of spawning habitat was used as inputs in both equations; spawning habitat area (derived from length and bankful width) was used in the equation for large channels. The authors concluded that spawning capacity does not limit chinook population sizes in the 6 populations examined.

Bocking, R. and K. English. 1992. Evaluation of the Skeena steelhead habitat model. Report by LGL. Ltd., Sidney, B.C. for Fisheries Branch, B.C. Ministry of Environment, Lands and Parks. Victoria, B.C.

Bocking and English (1992) rolled the different components of the 3 models (linear-based, area-based, and process-based – or biological-based as per the review of Parken (1997)) presented in Tautz *et al.* (1992) into one model (with slight modifications in that they used fry density at capacity in conjunction with fry-smolt and smolt-adult survival instead of smolt density at capacity and smolt-adult survival; they also used a different estimate of smolt-adult survival). They also extended the models in that a minimum escapement and allowable harvest rate are estimated. Key habitat-related model inputs include accessible stream length, mean annual discharge, total stream area (based on width and mean annual discharge), useable stream area, alkalinity, and water temperature. They give 7 points summarizing the model review, four of the more significant points are: the model overestimated fry biomass, smolt yield is very sensitive to mean smolt age, biological parameters (fecundity, egg-fry survival, and smolt-adult survival) were critical in determining escapement, yearling fork length and its effect on fry per unit area and smolt yield most important factor determining model results.

Bocking, R.C. and D. Peacock. 2004. Habitat-based production goals for coho salmon in Fisheries and Oceans Statistical Area 3. DFO Canadian Stock Assessment Secretariat Research Document 2004/129.

Discusses literature that estimates coho smolt production from stream length, stream area, and latitude. Developed two habitat-based (stream length) models to predict maximum smolt abundance and then used survival and fecundity estimates to back calculate the associated number of required spawners for individual streams. The model calculates accessible stream length based on stream gradient, known barriers, and stream order. In each of the two models a relationship between stream length and smolt yield was generated: 1) a log linear predictive regression of smolt yield from stream length for Alaskan and B.C. streams; and 2) recent decadal smolt yield and stream length for 3 northern B.C. coho indicator streams. Model 2 estimates of smolt production were greater than estimates from the first model. Model estimates of smolt production were compared to empirical data in a subset of the watersheds examined – for both models the predicted smolt yield for Zolzap Creek was comparable to maximum smolt yield estimates from Ricker and Hockey stick recruitment models. However, estimates of the number of spawners required to fully seed individual streams were generally highly variable as they depended on survival and fecundity estimates.

Bocking, R.C., C.K. Parken, and D.Y. Atagi. 2005. Nass River steelhead habitat capability production model and preliminary escapement goals. Skeena Fisheries Report SK#109. Prepared for the Ministry of Water, Land and Air Protection, Skeena Region Smithers, BC.

The goal of the model was to estimate steelhead (34 summer populations, 26 winter populations, and two sympatric populations) smolt production capacity and spawning potential in Nass River tributaries using watershed features, physical habitat data, and biological production parameters. Model outputs include the amount of suitable habitat for fry rearing, production estimates for smolts, and the minimum escapement required to fully seed available habitat. Watershed features considered in the model included stream order (model was run on both 3rd order or larger and 4th order or larger streams), mean annual discharge, stream gradient, and barrier presence – these parameters were used to identify steelhead streams and accessible length within them. Physical habitat data included late summer stream width (predicted from mean annual discharge, point width measurements, or aerial photos), useable stream width and area (calculated from mean annual discharge and critical period mean monthly flows), water temperature (to estimate growing season length), and total alkalinity (used to adjust productivity), estimated from conductivity or water yield when data unavailable). Biological production parameters included mean smolt age, female length, fecundity, survival rates, and smolts/km or smolt density at carrying capacity.

Six versions of the model were run using either the amount of useable stream length or stream area for fry and biological production parameters from either the Keogh or Cranberry rivers (models 1 to 4). Model version 5 used stream length, Keogh River biological production parameters, and adjustments for nutrients (alkalinity) and growing season length (mean smolt age). The 6th model was the same as the 5th model, but useable stream area was applied rather than accessible stream length. The latter model was the recommended model, which is also the same model developed by Tautz *et al.* (1992) for Skeena River steelhead. A sensitivity analysis of model 6 revealed that the model was sensitive to alkalinity, mean smolt age, and egg-fry survival estimates.

Bradford, M.J., G.C. Taylor, and J.A. Allan. 1997. Empirical review of coho salmon smolt abundance and the prediction of smolt production at the regional level. Trans. Am. Fish. Soc. 126: 49-64.

Related smolt abundance estimates to habitat features (from maps and discharge records). Habitat features examined included stream length, latitude, valley slope, discharge (mean annual, minimum monthly mean, and maximum monthly mean), and water yield (mean annual discharge/drainage area); they did not consider stream area or the degree and type of land use in the drainage basin as this information was not readily available. They used both simple and multiple regression to search through the above list of habitat variables for predictors of mean smolt abundance. Database included 474 annual smolt abundance estimates from 86 streams in western North America. Concluded that smolt abundance is limited by spatial habitat and that it is possible to predict smolt yield from stream length and latitude at the watershed or regional level (albeit with poor precision for individual streams).

Bradford, M.J. and J.R. Irvine 2000. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. Can. J. Fish. Aquat. Sci. 57: 13-16.

Investigated the major decline in the abundance of a large aggregate coho spawning in the Thompson River watershed. Attributed it to a decline in productivity which is likely caused by changing ocean conditions, overfishing, and freshwater habitat alterations. The authors correlated the decline in adult coho abundance (measured by the annual change in recruitment) with agricultural and urban land use, road density, and a qualitative measure of stream habitat status (which factored in forestry, agriculture, urbanization, recreation, mining, industrial development, linear development, hydro development, cumulative impacts, and special biophysical concerns), and with the proportion of land logged or burned in the last 20-25 years. There was a significant correlation in all instances except with the proportion of land logged or burned in the last 20-25 years.

Creque, S.M., E.S. Rutherford, and T.G. Zorn. 2005. Use of GIS-derived landscape-scale habitat features to explain spatial patterns of fish density in Michigan rivers. N. Am. J. Fish. Manage. 25: 1411-1425.

They used a multiple linear regression analysis to explain spatial patterns in fish density (chinook, steelhead, brown trout, brook trout, and white sucker). Two approaches were taken. The first used GIS-derived landscape-scale habitat independent variables including drainage area, flow (90% exceedance flow yield), and mean July water temperature, the range in July water temperature (max – min), and gradient. The second approach used site-scale variables that are measured in the field as independent variables, including depth, velocity, gradient, bank cover, substrate as sand or finer material (%; Softsub), substrate as gravel, cobble, or boulder (%;

Rocksub). They found that landscape (i.e., GIS-derived) variables accounted for 18-69% of the variation in fish density whereas site-scale variables explained 12-57% of the variation in fish density. At the landscape scale, the 90% exceedance flow yield and mean July water temperature were significant predictors for chinook fry/smolt density whereas depth was the only significant predictor of chinook fry/smolt density at the site-scale.

Dauble, D.D., T.P. Hanrahan, D.R. Geist, and M.J. Parsley. 2003. Impacts of the Columbia River hydroelectric system on main-stem habitats of fall chinook salmon. N. Am. J. Fish. Manage. 23: 641-659.

Used a geomorphic model to identify three river reaches downstream of present migration barriers with high potential for restoration of riverine processes. Used the model to estimate the amount of suitable chinook spawning habitat in the Columbia and Snake Rivers prior to hydroelectric development at a watershed scale and at a channel scale; they compared this to currently available spawning habitat. The geomorphic categorization was based on three features: geologic composition of the riverbank (100% unconsolidated, 50/50 unconsolidated/bedrock, or 100% bedrock.), longitudinal gradient of water surface, and presence or absence of channel bars or islands (islands or bars present, islands or bars absent, or unknown). Shoreline length was also used in the model. All information sources were GIS-based. The model output is the predicted lineal distance of current and historic (pre-dam) chinook spawning habitat. The authors conclude that historic spawning areas for fall chinook occurred mainly within wide alluvial floodplains which were once (pre-dam) common in the rivers examined. This is primarily due to more unconsolidated sediment, more bars and islands, and lower water surface slopes in these locations.

Dent, L., H. Salwasser, and G. Achterman. 2005. Environmental Indicators for the Oregon Plan for Salmon and Watersheds. Prepared for the Oregon Watershed Enhancement Board by the Institute for Natural Resources (Oregon State University).

The Oregon Plan for Salmon and Watersheds is an effort to restore watersheds and recover fish and wildlife populations to productive and sustainable levels while providing substantial environmental, cultural, and economic benefits. The authors use six principles to screen their indicators in an attempt to use only the most scientifically rigorous set of indicators. They include 1) Quantifiable (the indicator can be described numerically and objectively; 2) Relevant (the indicator will be biologically and socially relevant to the questions being asked); 3) Responsive (the indicator will be sensitive to the stressors of concern); 4) Understandable (the indicator can be summarized in a matter that is meaningful to a broad audience and pertinent for decision makers); 5) Reliable (statistical properties will be well understood and have acceptable levels of accuracy, sensitivity, precision, and robustness); and 6) Accessible (data are available or the collection of data is feasible from a cost, time, and skills perspective).

The plan has developed 15 environmental indicators in four classes: Aquatic and Riparian Ecosystems, Terrestrial Ecosystems, Estuarine Ecosystems, and Ecosystem Biodiversity. Of these 15 indicators, 5 have been identified as priority indicators, including: 1) Anadromous fish abundance, distribution, and life histories; 2) Coldwater Index of Biotic Integrity (IBI) for fish and for macroinvertebrates; 3) Water Quality Index (WQI) (length or percent of streams with rating of poor, fair, or good WQI); 4) Area, distribution, and types of riparian and wetland vegetation; and 5) Change in land use and land cover.

Dent *et al.* (2005) present a draft study approach for utilizing a subset of the indicators (fish distribution and abundance, index of biotic integrity, water quality index, and riparian condition). This general approach, along with some of the indicators suggested, could be used in the development of habitat-based salmon production models for British Columbia.

Downing, J.A. and C. Plante. 1993. Production of fish populations in lakes. Can. J. Fish. Aquat. Sci. 50: 110-120.

Downing and Plante collected annual production and standing biomass data for fish populations in lakes from the primary literature (post 1969). They excluded stocked populations and production rates calculated where age classes <3 years were excluded. Estimates were collected for a total of 100 fish populations in 38 lakes around the world. Analyses of relationships between fish population production, population biomass, and body-mass were performed using simple and multiple regression. They found the relationship between the annual production of fish populations (P, kilograms per hectare per year), annual mean standing biomass (B, kilograms per hectare), and maximum individual body mass (W, grams) to be approximately: (Eqn 1) $\log_{10}P = 0.32 + 0.94 \log_{10}B - 0.17 \log_{10}W$ ($R^2 = 0.84$, $n = 100$, $p < 0.0001$). When average annual air temperature (T, °C) is included, production can be described by the multiple regression equation: (Eqn 2) $\log_{10}P = 0.20 + 0.93 \log_{10}B - 0.19 \log_{10}W + 0.02T$ ($R^2 = 0.88$, $n = 100$, $p = 0.0001$). When total phosphorus (TP, µg/L) is included, production can be described by the multiple regression equation: (Eqn 3) $\log_{10}P = -0.25 + 0.90 \log_{10}B - 0.15 \log_{10}W + 0.29 \log_{10}TP$ ($R^2 = 0.81$, $n = 52$, $p < 0.0001$).

Residuals from (Eqn 1) were correlated with several lake characteristics. They included total phosphorus (log), primary production, chlorophyll *a* (log), pH, primary production (log), species richness (log), air temperature, latitude, total dissolved solids (log), total nitrogen (log), conductivity (log), lake area (log), altitude, the morphoedaphic index (log), and mean depth (log). The results suggest that fish production is positively correlated with temperature, lake phosphorus concentration, chlorophyll a concentration, primary production, and with pH; the morphoedaphic index (total dissolved solids in mg/L divided by mean depth in meters) is not a good predictor of the production of fish populations. Downing and Plante apply their results to exploitation of fish populations. They assume that sustainable yield is about 10% of production, and conclude that sustainable yield would be less than 15% of the standing biomass for the majority of fish populations examined. They found exploited populations to be on average about 70% more productive than unexploited populations with the same standing biomass and body-mass.

Downing, J.A., C. Plante, and S. Lalonde. 1990. Fish production correlated with primary productivity, not the morphoedaphic index. Can. J. Fish. Aquat. Sci. 47: 1929-1936.

Collected estimates of production of entire lake fish communities from the literature for lakes over a wide geographic range and trophic status. Also gathered data on biotic and abiotic characteristics of the lakes. Morphometric data included lake area, volume, mean and maximum depth, and watershed area. Lake productivity data collected included phytoplankton productivity, total phosphorus, nitrogen, chlorophyll *a* concentration, and conductivity. Air temperature (surrogate for water temperatures) data were also collected. They then analysed relationships between fish community production and lake characteristics with simple and multiple regression. The objective was to determine which of the above lake characteristics is most closely correlated with fish productivity. Results indicate that fish production is closely correlated with annual phytoplankton production followed by mean total phosphorus concentration and average annual fish standing stock. Found that sustainable yields were frequently as little as 10% of annual fish community production.

Dunham, J.B., B.S. Cade, and J.W. Terrell. 2002. Influences of spatial and temporal variation on fish-habitat relationships defined by regression quantiles. Trans. Am. Fish. Soc. 131: 86-98.

They modelled potentially limiting relationships between cutthroat trout standing crop (#/m) and measures of stream channel morphology using regression quantiles (both linear and non-linear) in northern Nevada and southeast Oregon streams. They found variation in cutthroat density to be inversely related to the width:depth ratio, but not to width or depth alone. Modelled variation from 1993-1997 predicted variation observed in 1998-1999. However, results were highly dependent on the spatial variation in fish density among streams. The non-linear model performed slightly better. They concluded that stream specific characteristics must be considered when interpreting results due to factors such as interspecific competition and habitat connectivity.

Eaglin, G.S. and W.A. Hubert. 1993. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. N. Am. J. Fish. Manage. 13: 844-846.

The authors examined the influence of logging and road construction on substrate quality and standing stocks of trout (predominantly brook and brown) in Wyoming. They found that culvert density in a watershed and the proportion of the watershed that has been logged were positively correlated to both the amount of fine substrate and embeddedness. A multiple regression model showed that trout standing stocks declined as the mean bank-full width increased and the density of culverts increased. They conclude that sediment deposition due to erosion of soil from road surfaces, ditches, and disturbed areas adjacent to roads seems to be an important mechanism by which logging affects stream habitat.

Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2003. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Can. J. Fish. Aquat. Sci. 60: 1266-1280.

They performed multiple regression and correlation analyses to identify associations between reach-scale characteristics, cold water patch availability, and salmonid (chinook and rainbow) abundance in northeastern Oregon. Generated 10 best habitat models for each species, excluding cold water patch availability as an input. Input variables consisted of various combinations of channel wetted width–depth ratio, proportional pool area, channel sinuosity, mean substrate embeddedness, large wood frequency (number/100 m), maximum 7-day mean maximum daily temperature, and subbasin location (riparian canopy density also included for rainbow trout). Following this they added cold water patch frequency and proportional relative cold water patch area to the 10 best habitat models for each species. They found that doubling the cold water patch frequency was associated with 31% and 59% increases in rainbow and chinook abundances, respectively. Doubling of cold water patch area was associated with a change of 10% in rainbow abundance and not change in chinook abundance.

Fausch, K.D., C.L. Hawkes, and M.G. Parsons. 1988. Models that predict standing crop of stream fish from habitat variables: 1950-85. Gen. Tech. Rep. PNW-GTR-213. Portland. OR: U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station. 52 p.

Provides a summary of 99 studies that relate number or biomass of stream fish per unit area or length of stream to habitat variables. The scale of habitat variables include primary drainage basin; primary channel morphology and flow, primary habitat structure, biological, physical, and chemical; combination of above factors; and weighted usable area (WUA).

Feist, B.E., E.A. Steel, G.R. Pess, and R.E. Bilby. 2003. The influence of scale on salmon habitat restoration priorities. Anim. Conserv. 6: 271-282.

Examined the relationship between habitat data (GIS-based) and spring/summer chinook redd densities in the Salmon River basin (Idaho). This was done at two spatial scales: stream reach and watershed using predictive regression models with different combinations of independent variables. Independent variables examined include network distance (reach scale only), channel sinuosity (reach scale only), channel gradient (reach scale only), hillslope less than 1.5%, major lithology, USGS Land Use and Land Cover, GAP Land Use and Land Cover, mean daily mean, maximum and minimum air temperature, cumulative annual precipitation, livestock grazing allotments, mining claims, and water diversions. Models were run over a period of 18 years (1960-1997). The 5 best watershed scale models included percent non-forested riparian wetlands, air temperature, percent sedimentary geology, and percent hillslope less than 1.5%. Of these 5 best models, the highest mean adjusted r^2 was 0.297 and the model did not include air temperature. The 7 best reach scale models included air temperature, a wetlands indicator, glacial deposits, and granitic geology. Of these 7 models, the one with maximum air temperature and glacial deposits as inputs had the highest mean adjusted r^2 of 0.158. They authors conclude that there was a strong correlation between redd density and climate, geology, wetlands, and terrain and that stream reach models poorly predicted redd densities compared to watershed scale models.

Fight, R.D., L.D. Garrett, and D.L. Weyermann (tech. eds.). 1990. SAMM: a prototype southeast Alaska multiresource model. Gen. Tech. Rep. PNW-GTR-255. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 109 p.

A multiresource model with 4 interlinked submodels (timber, hydrology and soils, fisheries, and deer) was built for watersheds in southeast Alaska ranging in size from ~20 to 80 km^2. The submodels are linked in a unidirectional fashion, i.e., there are no feedback loops; they also incorporate management actions that have been applied to the modeled area as well as economic and social characteristics of the area. The fisheries submodel considers fisheries regulations and also has several inputs generated from the timber and hydrology/soils submodels including: logging related parameters (percentage of bank cut, area logged), road parameters (length of road used, length of road constructed), total sediment load, fine sediment concentration in gravel, amount of large organic debris, bedload shift, water temperature (summer mean and maximum, fall mean, and winter degree-days), flow (summer and winter lows), stream velocity, and canopy cover. Available spawning gravel area is also required as an input. It is designed for pink, chum, and coho salmon and models escapement to a particular stream reach, egg deposition, egg survival, rearing success, smolting success, and harvest. The multiresource model as presented is in a prototype stage and was not formally validated, i.e., it had not been tested against observed data. We could not find any current information on this model and its application. A user guide for the model (Weyermann *et al.* 1991) has been included with the digital files.

Greene, C.M., D.W. Jensen, G.R. Pess, E.A. Steel, and E. Beamer. 2005. Effects of environmental conditions during stream, estuary, and ocean residency on chinook salmon return rates in the Skagit River, Washington. Trans. Am. Fish. Soc. 134: 1562-1581.

Predicted 22 years of return rates for Skagit River chinook using a regression model relating return rates with environmental conditions in four different habitats (freshwater, tidal delta, bay, and ocean) and egg production (indicator of density dependence). Environmental parameters considered included flood recurrence interval (frequency at which a flood of a given magnitude will occur) during intragravel development, and sea surface temperature, sea level pressure, sea level, and coastal upwelling during non-freshwater residency (did a principal components analysis of the ocean habitat factors because they are interrelated – generated a habitat factor for each habitat type based on the first factor from the principal components analysis). The best predictors of return rate were the magnitude of floods during incubation, the principal habitat component for bay residency, the principal habitat factor for the third ocean year, and an estimate of egg production. Results suggest that chinook return rates can be predicted with high precision with this method.

Hatfield, T. and J. Bruce. 2000. Predicting salmonid habitat-flow relationships for streams from western North America. N. Am. J. Fish. Manage. 20:1005-1015.

The authors review a large set of instream flow studies from western North America to develop predictions for flow needs for salmonids and to test whether habitat-flow relationships for salmonids are related to watershed characteristics and geographic location. More than 1,500 habitat–flow curves from 127 PHABSIM (physical habitat simulation, the component microhabitat model of the instream flow incremental methodology) were examined. Regression equations were generated that predict PHABSIM habitat optima for four life history stages (fry, juvenile, adult, and spawning) of four salmonid species (brown trout, chinook salmon, rainbow trout, and steelhead trout) and for all salmonid species as a whole. The modified stepwise regression procedure that was used eliminated flow variability (i.e., the coefficient of variation in flow), elevation, watershed area, and distance to the coast as predictors of PHABSIM habitat optima. Mean annual discharge (MAD) was found to be the best predictor of optimum flow for salmonids. Regression equations varied among life stages and species and explained 36 to 82% of the variation in optimum flow; equations took the general form of $\log_e(\text{optimum flow}) = A * \log_e(\text{MAD})$, where $A < 1$. When latitude and longitude were included in the regression, there was minor improvement in predictive power in some cases. The results suggest that optimum flow does not increase as rapidly as MAD and that the proportion of MAD required to protect fish habitat declines with increasing stream size. The general relationship between optimum flow and habitat is an asymptotic one that differs considerably from the fixed flow percentages recommended by Tennant. The authors caution that the results of the study are not intended to be used uncritically, but as a planning tool to (1) allow managers and project proponents to conduct a preliminary assessment of proposed wateruse development projects, (2) optimize research efforts for instream flow studies and experiments, and (3) set experimental boundaries for adaptive management of streamflow.

Hedger, R.D., J.J. Dodson, N.E. Bergeron, and F. Caron. 2004. Quantifying the effectiveness of regional habitat quality index models for predicting densities of juvenile Atlantic salmon (*Salmo salar* L.). Ecol. Freshwat. Fish 13: 266-275.

Used non-linear regression regional Habitat Quality Index (HQI) models to predict juvenile (fry and parr) Atlantic salmon densities in streams in Quebec and compared the model output to results from local HQI models for individual rivers. Independent variables used to estimate HQI's included flow velocity, depth, and a substrate size index. Local models were more effective than regional models in all cases. Densities were found to increase exponentially with increasing HQI values, however, the models left much of the variation in density unexplained.

Holtby, L.B. and J.C. Scrivener. 1989. Observed and simulated effects of climatic variability, clear-cut logging, and fishing on the numbers of chum salmon (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) returning to Carnation Creek, British Columbia. *In* C.D. Levings, L.B. Holtby, and M.A. Henderson [ed.] Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks. Can. Spec. Publ. Fish. Aquat. Sci. 105. pp. 62-81.

Developed a model to predict coho escapements and a model to predict chum escapements in Carnation Creek, B.C.. Each model consists of several sequentially linked regression sub-models which predict survival and fish size at various life stages in various physical habitats to ultimately predict adult escapements. Stream habitat parameters required as input into the models include water temperature, peak discharge, gravel particle size, and habitat quality indices for stream features affected by logging. Sea surface salinity and temperature were also required as model inputs. They concluded that most of the observation variation in escapements for both species was due to climatic variability in the stream and in the ocean. Coho were unaffected by logging (both observed and simulated) whereas chum were negatively affected.

Hughes, R.M., S. Howlin, and P.R. Kaufmann. 2004. A biointegrity index (IBI) for coldwater streams of western Oregon and Washington. Trans. Am. Fish. Soc. 133: 1497-1515.

The authors developed an index of biological integrity (IBI) for fish and amphibian assemblages in coastal Oregon and Washington streams. The model was tested at 101 reference sites. They eventually narrowed the number of IBI metrics down to 8 from 109 potential metrics; there were nine key habitat variables including residual pools > 1 m, % sand and fines, bed stability, log total N, log total P, riparian human disturbance, riparian condition index, catchment road density, and catchment and riparian condition index. Results indicated that low IBI scores are associated with low bed stability, low instream cover, and low riparian cover and structural complexity; low IBI scores were also associated with high percent fine substrate, high road density, and high human disturbances of riparian areas. High IBI score were clustered near national parks and wilderness. They determined that 45% of stream length in the areas examined could be classified as impaired.

Hume, J.M.B., K.S. Shortreed, and K.F. Morton. 1996. Juvenile sockeye rearing capacity of three lakes in the Fraser River system. Can. J. Fish. Aquat. Sci. 53: 719-733.

Sockeye escapements that maximize production in Fraser River lakes were estimated with 3 approaches: 1) effective female spawners and adult returns (Ricker stock-recruit analysis); 2) effective female spawners and fall fry or smolts; and 3) photosynthetic rates (seasonal daily average), a modification of an Alaskan sockeye production model (Koenings and Burkett 1987, not directly applicable to Fraser lakes due to differences in limnology – mainly water clarity and nutrient inputs). The goal of using these models is to determine escapement levels that will maximize subsequent adult returns. Compared results of model 3 with that of models 1 and 2 and with observed maximum juvenile sockeye production estimates from the study lakes. Sockeye escapements that maximize production in Fraser River lakes were best predicted by photosynthetic rates in the lakes and it is possible to make predictions after collecting data for only 1-2 years.

The authors state that "One disadvantage of determining PR is that it is a more difficult measurement to obtain than most limnological variables". They suggest that reliable PR data can be obtained in monthly surveys carried out from spring to fall for 1–2 years.

Inoue, M. and S. Nakano. 2001. Fish abundance and habitat relationships in forest and grassland streams, northern Hokkaido, Japan. Ecol. Res. 16: 233-247.

They used a regression analysis to examine the relationship between habitat variables and densities of masu salmon, rosyface dace, Siberian stone loach, and wrinklehead sculpin in 55 reaches of forest and grassland streams in Japan. Habitat variables included maximum water temperature, gradient, mean wetted width, substrate coarseness, substrate heterogeneity, cascade area, rapid area, riffle area, glide area, pool area, woody debris cover area; potential competitor density was also used as an independent variable. For each species, two stepwise multiple regressions were run, one with all habitat variables and the other with all of the habitat variables in addition to potential competitor density. For masu salmon, mean depth, woody debris cover, and water temperature affected salmon density (densities were also higher in forested reaches compared to grassland reaches).

Jager, H.I. and K.A. Rose. 2003. Designing optimal flow patterns for fall chinook salmon in a Central Valley, California, River. N. Am. J. Fish. Manage. 23: 1-21.

The goal of this study was to understand how seasonal flow patterns in the flow-regulated Tuolumne River (California) could be managed to meet two conservation objectives: 1) attain sufficient recruitment to rebuild a self-sustaining population of a fall and late-fall run of chinook salmon, and 2) maintain phenotypic diversity. The authors used simulated annealing in conjuction with a recruitment model to find flow regimes that maximize either the number of smolt out-migrant "recruits" (MR) or the variation in spawning times among recruits (MV). The recruitment model has a biotic (i.e., life history) and a habitat component to it. Habitat input parameters include a variety of water temperature inputs, a variety of air temperature inputs, stream distance below dam used for spawning, and weighted usable area. Optimal flow regimes for the MR and MV objectives changed as the amount of water available increased on an annual basis, allocating higher flows during the spring and fall seasons. Flow regimes that optimized the MR and MV objectives were also different. There were less recruits produced by MV flow regimes (and they had parents that spawned later and over a wider range of dates) than recruits produced by MR flow regimes. The results of modelling have not been verified by empirical studies.

Jowett, I.G. 1992. Models of the abundance of large brown trout in New Zealand rivers. N. Am. J. Fish. Manage. 12: 417-432.

Hydrological, catchment, physical, water quality, and benthic invertebrate biomass variables were used to explain abundance of large (>200 mm) brown trout. Weighted usable area (WUA) and invertebrate biomass explained 64.4% of the variation in trout abundance. Winter temperature, and instream cover were also important factors. Lakes, land development, site elevation, and river gradient were of lesser importance.

Knowler, D.J., B.W. MacGregor, M.J. Bradford, and R.M. Peterman. 2003. Valuing freshwater salmon habitat on the west coast of Canada. J. Environ. Manage. 69: 261-273.

Used the Habitat Concerns Index (HCI) presented in Bradford and Irvine (2000, included in this review, see entry in Annotated Bibliography for summary) as a measure of habitat quality for 16 streams in the South Thompson River drainage. Coho recruitment was modeled with a Beverton-Holt stock-recruitment function that was modified to include a habitat quality factor. The habitat quality factor and the maximum number of smolts that can be produced by a stream were derived from the HCI. To do this, they ran repeated simulation trials while comparing the projections of population abundance with an observed empirical relationship between rates of change in recruitment and habitat quality. The modified Beverton-Holt function was then scaled up for the entire Strait of Georgia fishery. A bioeconomic model was used to place value on the coho fishery and they estimated the value of changing the quality of fish habitat on an areal (drainage basin) and stream length basis.

Lestelle, L.C., L.E. Mobrand, and W.E. McConnaha. 2004. Information structure of Ecosystem Diagnosis and Treatment (EDT) and habitat rating rules for chinook salmon, coho salmon and steelhead trout. Prepared by Mobrand Biometrics, Inc. 29 p. + App. Available on the internet at: http://www.mobrand.com/MBI/library.html.

The Ecosystem Diagnosis and Treatment (EDT) model was developed to diagnose the current environmental constraints in a system and allow managers to determine the outcomes of different habitat restoration strategies. To date, model development has been completed for chinook, coho, chum, and steelhead (it is under development for bull trout, cutthroat, and interior rainbow trout; it is also being considered for sturgeon). This paper describes the habitat rating rules for chinook, coho, and steelhead. EDT rates both the quality and quantity of stream habitat by assuming that biological capacity and productivity are functions of the environment (it is assumed that habitat-based estimates of both of these parameters create a Beverton-Holt production function). Both parameters are calculated for each life stage at the reach scale; all estimates are then integrated for an overall estimate of capacity and productivity. Note that capacity refers to the size of the environment available and productivity refers the density independent survival rate.

Basic steps in model use are briefly described in the following text. The stream is partitioned into 8 Stream Unit Types (see below). Within each stream unit the habitat quality is described with 35 Environmental Quality Attributes (see below). Next the quantity and quality of habitat is ranked with respect to the focal species using a set of biological rules relating the Environmental Quality Attributes to survival of one or more life stages (depending on the management question). An index number is assigned to the required Environmental Quality Attributes based on empirical information or scientific consultation. There are 17 Habitat Attributes which are then formed from various combinations of the Environmental Quality Attributes. The quantity of habitat is rated by summing the amount of stream unit types in a reach and weighting them according to their potential value to a particular life stage. Productivity (or density independent survival) is then estimated for all reaches by applying the Environmental Attributes to Survival Factors and multiplying the survival factors together.

This paper does not describe model results. All documents in the Mobrand electronic library (http://www.mobrand.com/MBI/library.html) have been included with the electronic literature provided with the literature review. These documents do not contain model results, but provide more background and direction on model application. Included are some general EDT information sheets, subbasin planning documents, user manuals, documentation of mathematical algorithms used in EDT, bull trout species habitat rules, and guidelines for rating Environmental Attributes.

Environmental Quality Attributes			
Natural confinement	Metals in water	Temperature max	Fish species introductions
Artificial confinement	Metals in soil	Temperature min	Harassment
Bed scour	Pollutants in water	Temperature spatial variation	Hatchery outplants
Embeddedness	Nutrient enrichment	Turbidity	Fish community richness
Fine sediment	Natural flow regime	Water withdrawals	Predation
Obstructions	Regulated flow regime	Salmon carcasses	Benthos community richness
Wood	Within year high flow	Riparian function	Predation
Alkalinity	Within year low flow	Gradient	Icing
Dissolved oxygen	Diel flow pattern	Fish pathogens	

EDT Stream Unit Types
Backwater pools
Beaver ponds
Large cobble/boulder riffles
Primary pools
Pool tailouts
Glides
Off-channel areas
Small cobble riffles

General Geographic Descriptors
Subbasin name
Stream name
Reach name
6HUC
Channel length (for the reach)
Channel width (by month for the reach)

EDT Habitat Attributes			
Channel stability	Sediment load	Food	Competition
Habitat diversity	Temperature	Pathogens	Water withdrawals
Key habitat	Flow	Predation	
Obstructions	Oxygen	Harassment	
Chemicals	Salinity	Predation	

Mathur, D., W.H. Bason, E.J. Purdy, Jr., C.A. Silver. 1985. A critique of the Instream Flow Incremental Methodology. Can. J. Fish. Aquat. Sci. 42: 825-831.

The authors reviewed published literature where the Instream Flow Incremental Methodology (IFIM) was used to predict the standing crop of fish, and they provide a critique of some of the assumptions underlying the IFIM. A reanalysis of published data showed that several assumptions are often violated in the application of the IFIM. They state that the fundamental assumption of a positive linear relationship between weighted usable area (WUA) and biomass of fish has not been documented or validated, and conclude that this precludes the prediction of changes in fish populations. They also found that the assumption of independent selection of habitat variables by fish was violated – significant interaction among habitat variables can affect the streamflow recommendations. The authors identify a problem in the application of Physical Habitat Simulation (PHABSIM): they caution that one WUA unit should not be interpreted as being equal to another in biological production or habitat value unless shown to be an exact replica. This is due to the fact that different combinations of physical variables could give rise to the same amount of WUA, without any of the physical variables being correlated to the biomass of fish. Finally, they note that the utilization, suitability, or preference curves should not be treated as probability functions; a rating of 1.0 is not equivalent to probability of 1.0.

McHugh, P., P. Budy, and H. Schaller. 2004. A model-based assessment of the potential response of Snake River spring-summer chinook salmon to habitat improvements. Trans. Am. Fish. Soc. 133: 622-638.

The authors modelled egg to smolt survival rates of chinook as a function of 5 habitat variables in Idaho and Oregon. The habitat variables were % fines in spawning gravel, incubation temperature, riffle-run embeddedness, summer parr rearing temperature, and pool embeddedness. They validated their model by applying it to three independent sites with known survival rates – they found that their model had reasonable accuracy in predicting egg-smolt survival for individual stocks and across stocks.

Nelitz, M.A., E.A. MacIsaac, and R.M. Peterman. 2006. A science-based approach for identifying temperature-sensitive streams for rainbow trout. In press in: N. Am. J. Fish. Manage. (accepted 21 Feb. 2006).

The objective of this study was to help develop methods to designate temperature-sensitive streams in B.C. The focal species was rainbow trout, and using previously published models, they generated relationships between an indicator of egg survival, an indicator of juvenile growth, and an indicator of disease mortality with a maximum weekly average temperature (MWAT) index. They found that particular increases in stream temperatures resulted in different effects on juvenile growth rate compared to egg survival rate and resistance to mortality from diseases. A separate regression analysis using data from 104 streams was carried out to evaluate the chance that cumulative forestry activities will increase stream temperatures. Results showed high probabilities that increasing road density and density of road crossings are associated with increases in temperature (e.g., 60% chance that MWAT will increase by 1 to 3°C for road densities of 2 to 4 km of road per km^2 of watershed area, respectively).

Opperman, J.J., K.A. Lohse, C. Brooks, N.M. Kelly, and A.M. Merenlender. 2005. Influence of land use on fine sediment in salmonid spawning gravels within the Russian River Basin, California. Can. J. Fish. Aquat. Sci. 62: 2740-2751.

The authors built a model to calculate an embeddedness index from land use or land cover at multiple scales. Independent land use / land cover variables included agriculture, urban, herbaceous, shrub, forest, road density, volcanic, Franciscan, sedimentary, low relief, and high relief. Agricultural and urban land uses and road density were positively related to embeddedness. Forest cover was negatively related. The entire watershed scale provided best prediction of embeddedness. Land use within the riparian corridor did not relate to embeddedness. It was also found that the models predicted embeddedness better in the largest (r^2 = 0.73) than in the smallest watersheds (r^2 = 0.46).

Parken, C.K. 1997. An overview of the algorithms and parameters used in the Skeena steelhead carrying capacity model. Skeena Fisheries Report SK#109. Prepared for the Fisheries Branch, Ministry of Environment, Lands and Parks, Smithers, BC.

The Skeena steelhead carrying capacity model was originally developed by Tautz *et al.* (1992) and presented in a slightly modified form (biological component parameters, components of separate models rolled into one model) in Bocking and English (1992). This paper provides an overview of the model structures and required parameters as presented in both Tautz *et al.* (1992) and Bocking and English (1992). There are 3 models (linear, area (two versions), and biological based) with habitat components that area used to estimate the number of adult summer steelhead produced at Skeena River tributaries are at carrying capacity. The linear based model has inputs of accessible stream length and adult capacity/km in the Keogh River. The area based model has inputs of total area of stream available to steelhead, smolt density at capacity (Keogh River), and smolt-adult survival (Keogh River) (the other version of this model differs in that it uses total useable stream area available to steelhead). The biological based model has inputs of total useable stream area available to steelhead, smolt density at capacity adjusted to better suit Skeena tributaries (based on higher alkalinity), and smolt-adult survival (Keogh River). In all models smolt density was estimated using alkalinity, water temperature (for growing season length), and the required rearing area to produce 1 smolt. In the area and biological based models mean annual discharge (dependent on watershed area) was used to estimate the average width and the percentage of useable width which in turn were used to estimate stream area and useable stream area, respectively.

Parken, C.K., J.R. Irvine, R.E. Bailey, and I.V. Williams. 2002. Habitat-based methods to estimate spawner capacity for chinook salmon in the Fraser River watershed. DFO Canadian Stock Assessment Secretariat Research Document 2002/114.

Developed a habitat-based model to estimate chinook spawner capacity in the Fraser River watershed. They first categorized spawning systems based on their biophysical similarity and within each category they developed spawner density-habitat relationships. Using predictive relationships for the numbers of spawners, they estimated spawner capacities (both considering and ignoring habitat quality) for spawning systems within each biophysical category. Model inputs included annual escapement, spawner counts, stream length, stream area (estimated from length and wetted width during late summer low flow which were calculated from MAD), and gradient. Model outputs included the number of spawners a system would contain based on maximum observed densities as well as spawner carrying capacities. The authors concluded that the habitat capacity models worked well overall, but additional work is required before the models will consistently give realistic estimates of chinook spawner capacity in high gradient and confined-channel systems. Significant spawner-density gradient relationships were generated for several spawning system categories, however there was high uncertainty in some spawning capacity estimates.

Parken, C.K., R.E. McNicol, and J.R. Irvine. 2006. Habitat-based methods to estimate escapement goals for data limited chinook salmon stocks in British Columbia. PSARC Draft Paper S2004-05.

Used a meta-analysis of 25 chinook stocks ranging from California to central Alaska to relate productive capacity to freshwater watershed area. Model outputs were the number of spawners required to produce the maximum sustained yield and replacement. In addition to watershed area, spawner escapements of known accuracy and reliability are also required as model inputs. They also developed a multi-stock model using meta-analysis that estimates stock-recruitment reference points using only watershed area data.

Paulsen, C.M. and T.R. Fisher. 2001. Statistical relationship between parr-to-smolt survival of Snake River spring-summer chinook salmon and indices of land use. Trans. Am. Fish. Soc. 130: 347-358.

Simple regression models were used to relate chinook parr-smolt overwinter survival to a land use index and road density in the Snake River drainage (Idaho and Oregon). Independent variables for the land use index model included 5 land use categories (based on land use, land ownership, elevation, and vegetation pattern), fish length, month of tagging, and the Palmer drought severity index. A null model with no land use was also run which included only fish length, month of tagging, and the Palmer drought severity index as independent variables. The road density model had road density, fish length, month of tagging, and the Palmer drought severity index as independent variables. The land-use and road density models explained the variation in overwinter survival well (r^2 0.64, 0.54 respectively). The results suggest that road building and associated land-use activities may adversely affect juvenile chinook overwinter survival.

Pess, G.R., D.R. Montgomery, E.A. Steel, R.E. Bilby, B.E. Feist, and H.M. Greenberg. 2002. Landscape characteristics, land use, and coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, Wash., U.S.A. Can. J. Fish. Aquat. Sci. 59:613-623.

The author used linear regression to examine the relationship between coho abundance (adult returns in the form of density) and landscape characteristics and land use patterns in the Snohomish River watershed (Washington). Independent landscape/land use variables included urban, rural, agriculture, forest, roads, wetland, water, unstable slopes, advanced outwash, recessional outwash, till, peat, alluvium, bedrock, and stream gradient. Individual variables were related to coho returns at the reach and watershed scales. Adult density was significantly correlated with wetland occurrence, local geology, stream gradient, and land use. Abundance was also higher in forest-dominated areas (1.5-3.5 times) than rural, urban, and agricultural areas. The approach taken in this paper can be used to identify and prioritize freshwater areas for protection and restoration.

Platts, W.S. and R.L. Nelson. 1989. Stream canopy and its relationship to salmonid biomass in the intermountain west. N. Am. J. Fish. Manage. 9: 446-457.

Investigated whether riparian habitat components (canopy density, light intensity, average potential daily thermal input, unobstructed sun-arc) were correlated with salmonid biomass (per unit area or volume). The study was carried out in grazed and non-grazed (rested) portions of streams in of Idaho, Nevada, and Utah. Differences in biomass between these habitats and between basins (Great Basin, Rocky Mountains) were also tested. No significant correlations were detected between salmonid biomass per unit area and the environmental variables. In the Great Basin area, all four parameters were significantly correlated with salmonid biomass per unit volume. There were no significant correlations in the Rocky Mountain area. Thermal input was the best predictor of biomass per unit volume in the Great Basin ($r^2 = 0.92$).

Ptolemy, R.A. 1982. Salmonid biomass assessment and potential carrying capacity of Louis Creek near Barriere, British Columbia. Prepared by the British Columbia Fish and Wildlife Branch, Ministry of Environment for M.D. Sheng and G. Logan, Fisheries and Oceans, Pacific Region.

Based on a habitat assessment, potential coho juvenile biomass at complete fry saturation was predicted using an exponential curve relating biomass to mean cross-sectional velocity within hydraulic units or reaches. Predictions were compared to observed estimates of the mid-August (1981) standing crop of juvenile coho. It was concluded that there is an order of magnitude difference between the existing and potential summer standing crop of juvenile coho in Louis Creek.

Ptolemy, R.A. 1993. Maximum salmonid densities in fluvial habitats in British Columbia. *In* L. Berg and P.W. Delaney (eds.), Proceedings of the Coho Workshop, Nanaimo, BC, May 26-28, 1992. pp 223-250.

Re1ationships between fish density and size with nutrient indicators in streams of British Columbia were examined. Maximum density of eight salmonid specieds was estimated using a non-linear function with mean weight. Fish abundance in glacial streams was negatively related to fixed non-filterable residue. A multiple regression of fish density (fish per 100 m2; FPU) on mean size (grams) by age group, a nutrient index, and suspended sediment explained 86% of the variance in maximum density. The models can be used to predict maximum densities of fluvial salmonids based on water chemistry provding site specific data area available on stream chemistry.

Ptolemy, R.A. 2005. Biomass benchmarks for coastal cutthroat trout (*Onchorychus clarki clarki*): Can ecoregions be used as a place-based standard for abundance? *In* Proceedings of the Coastal Cutthroat Trout Symposium: Biology, Status, Management, and Conservation. September 29 - October 1, 2005; Fort Worden State Park. Sponsored by the U.S. Fish and Wildlife Service, Pacific States Marine Fisheries Commission, Oregon, Humboldt, Alaska, and North Pacific International Chapters of the American Fisheries Society.

Developed a method to assess the maximum stream capacity for coastal cutthroat trout at the mesohabitat scale using data extracted from the literature. Streams with data were classified according to EcoProvince, EcoRegion, and EcoSection. Hydrometric and water quality (summer baseflows) data were compiled for the streams. There is an underlying assumption that water chemistry varies systematically between EcoRegions due to differences in climate, rainfall, runoff, vegetation, and geology. Landscape-based patterns of coastal cutthroat biomass were examined (1-way ANOVA) throughout B.C. and water quality (alkalinity) and unit runoff (not presented) were correlated with biomass in a regression model. Biomass was highly correlated with alkalinity (alkalinity explained 84% of the variation, $p<0.0001$). Alkalinity was highly correlated with annual unit runoff (-0.94). The alkalinity model was validated with an independent dataset.

Rosenfeld, J., M. Porter, and E. Parkinson. 2000. Habitat factors affecting the abundance and distribution of juvenile cutthroat (*Oncorhynchus clarki*) and coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 57: 766-774.

They regressed total cutthroat, small cutthroat, large cutthroat, and juvenile coho density on a number of habitat variables including: bankfull channel width, dominant substrate class, percent pool, b-axis of the largest particle moved by flowing water, percent valley flat, reach gradient, canopy cover, and conductivity. For coho, only bankful width and reach gradient were significantly related to density with regression coefficients of -0.51 and -0.64, respectively. The r^2 for the bankful width regression was 0.27.

Scheuerell, M.D., R. Hilborn, M.H. Ruckelshaus, K.K. Bartz, K. Lagueux, A. Haas, K. Rawson. 2006. The SHIRAZ model: a tool for incorporating anthropogenic effects and fish–habitat relationships in conservation planning. Can. J. Fish Aquat. Sci. 63: 1596-1607.

The Shiraz model is a multistage Beverton-Holt model that describes the production of salmon from one life stage to the next under historical, current, and future land use related habitat conditions. It uses user-defined relationships among habitat attributes, fish survival, and carrying capacity to evaluate population performance. The example presented in the paper is for chinook salmon in the Snohomish River basin (Puget Sound, Washington). The habitat quality and quantity input parameters were generated by Bartz *et al.* (2006). Habitat quality parameters include 1) stream temperature during the prespawning period (mid-July to mid-October, mean of daily maxima), 2) stream temperature during the egg incubation period (mid-September to mid- February, mean of monthly means), 3) peak streamflow during the egg incubation period (largest daily mean), and 4) fine sediment in the stream bed (mean fraction < ~6.3 mm diameter (%)). Habitat quantity was measured as potential juvenile capacity and potential adult capacity. The model also considers hatchery operations and harvest management, allowing the authors to show how proposed actions to improve physical habitat translate into projected improvements in chinook abundance, productivity, spatial structure, and life-history diversity. The authors also describe how to adapt the model to other management applications.

Sharma, R. and R. Hilborn. 2001. Empirical relationships between watershed characteristics and coho salmon (*Oncorhynchus kisutch*) smolt abundance in 14 western Washington streams. Can. J. Fish. Aquat. Sci. 58:1453-1463.

Used a linear regression analysis to examine the relationships between habitat variables (large woody debris, road densities in the watershed, gradient of streams, valley slope adjacent to the stream, drainage area, and pool, pond, and lake areas) and smolt density. Data came from 11 streams in Washington. The density of pools (r^2 = 0.85) and ponds (r^2 = 0.68) were good predictors of smolt density. Lower valley slopes, lower road densities, and lower stream gradients were also correlated with higher smolt densities. A multiple regression using pool and pond densities explained 92% of the residual error in smolt densities.

Shirvell, C.S. 1989. Habitat models and their predictive capability to infer habitat effects on stock size. *In* C.D. Levings, L.B. Holtby, and M.A. Henderson (eds.), Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks. Can. Spec. Publ. Fish. Aquat. Sci. 105: 173-179.

Six models relating fish populations to habitat variables were reviewed to assess how well the they performed. Overall no variable within the models was capable of correlating with fish abundance across all models. The most useful variable was water depth, which was frequently correlated with fish abundance, often significantly. However, the models did not show consistent relationships between fish populations and habitat among geographic areas. Although the models could explain high proportions of the variants in fish numbers or biomass (50-95%), when applied to two other data sets their predictive ability to decreased to unacceptable levels (7-30%).

Shortreed, K.S., J.M.B. Hume, and J.G. Stockner. 2000. Using Photosynthetic Rates to Estimate the Juvenile Sockeye Salmon Rearing Capacity of British Columbia Lakes. *In* E.E. Knudsen, C.R. Steward, D.D. MacDonald, J.E. Williams, and D.W. Reiser (eds.), Sustainable Fisheries Management: Pacific Salmon. pp. 505-521.

Refined a sockeye photosynthetic rate based rearing capacity model described in Hume *et al.* (1996), which is based on a correlation between photosynthetic rate (PRunits, i.e., daily photosynthetic rates) and sockeye smolt biomass. The model developed in Hume *et al.* (1996) was originally developed in Alaska by Koenings and Burkett (1987) and used euphotic volume rather than photosynthetic rates. The model discussed in this paper uses photosynthetic rate (metric tons C/lake) to predict maximum sockeye smolt numbers and biomass in lakes as well as the required optimum adult escapement to the lakes. Data limitations with respect to known estimate of maximum juvenile biomass prevent independent development of a rearing capacity model specifically for British Columbia. Predictions can be tested in few lakes in B.C., however they correspond well with observed optimum escapements where known (Quesnel and Shuswap lakes). Predictions can be made after 2-3 years of photosynthetic rate data collection (even after only 1 year but annual variability can be large). Photosynthetic rate data currently exist for 57% of the area of B.C.'s sockeye nursery lakes. Predictions were made in lakes with no photosynthetic rate data by inferring rates from nearby lakes or regions (the largest gaps in photosynthetic rate data are for lakes in the Queen Charlotte Islands and lakes north of the Nass River watershed).

Shortreed, K.S., K.F. Morton, K. Malange, and J.M.B. Hume. 2001. Factors limiting juvenile sockeye production and enhancement potential for selected B.C. nursery lakes. DFO Canadian Stock Assessment Secretariat Research Document 2001/098.

Summarize current knowledge of freshwater factors limiting sockeye production in 60 B.C. lakes. No model is developed but they do apply the photosynthetic rate model of Shortreed *et al.* (2000) to predict optimum escapements (where appropriate data is available) to fully seed a lake's rearing capacity and compare the predictions to recent escapements and identify opportunities for restoration and enhancement of sockeye stocks.

Smith, B.D. 2000. Trends in wild adult steelhead (*Oncorhynchus mykiss*) abundance for snowmelt-driven watersheds of British Columbia in relation to freshwater discharge. Can. J. Fish. Aquat. Sci. 57: 285-297.

Exploratory analyses examined correlations between the mean annual standardised catch-per-angler-day (CpAD) for steelhead (i.e., an index of steelhead abundance) and annual freshwater discharge anomalies in 10 regions or watersheds. The analyses clearly separated rainfall-driven regions from snowmelt-driven watershed. Models relating CpAD to August discharge in years prior to return were then constructed for three snowmelt-driven areas – the north coast, the Dean River, and the Bella Coola watershed. The models accounted for 62, 58, and 40% of the total variation in CpAD for these three areas, respectively. Within this, 28, 14, and 29% of the total variance was attributed to annual variability in August freshwater discharge 3–5 years prior to the years that steelhead return to their natal river to spawn. Smith suggests potential mechanisms by which interannual variation in freshwater discharge can modulate adult steelhead abundance, including 1) reduced juvenile mortality due to lower flow velocities during the warm summer months and 2) the creation of more juvenile habitat in low-velocity refuges. Another interpretation is that interannual variability in adult steelhead abundance is driven by variability in ocean climate, which is an index of freshwater discharge. Smith suggests that the results support an interpretation that survival to adulthood for steelhead may be influenced by freshwater conditions more so in northern snowmelt-driven rivers than in rainfall-driven rivers because steelhead from those rivers spend more years in freshwater as juveniles.

Stoneman, C.L. and M.L. Jones. 2000. The influence of habitat features on the biomass and distribution of three species of southern Ontario stream salmonids. Trans. Am. Fish. Soc. 129: 639-657.

Used a discriminant function model and a regression tree model to predict habitat use and productive capacity (biomass density) of brook trout, brown trout, and rainbow trout in southern Ontario streams. A total of 57 habitat variables collected at 118 study sites were used including those describing morphology and substrate, water quality, instream physical habitat types, and bank vegetation. Water temperature was the most important habitat variable in distinguishing sites with low, medium, and high total trout biomass density (percent pools, substrate, and cover were also important). Where trout biomass was dominated by either rainbow, brook, or brown trout, a species-level discriminant analysis distinguished sites based on differences in water temperature, percent pools, substrate size, average competitor biomass, and cover.

Tautz, A.F., B.R. Ward, and R.A. Ptolemy. 1992. Steelhead trout productivity and stream carrying capacity for rivers of the Skeena drainage. PSARC Working Paper S92-6 (Draft).

Three models to estimate the summer steelhead carrying capacity of Skeena River tributaries are presented. They include a linear-based, areal-based (two versions: total area and useable area), and process-based (referred to as biological-based in the review by Parken (1997)). The linear based model has inputs of accessible stream length and adult capacity/km in the Keogh River. The area based model has inputs of total area of stream available to steelhead, smolt density at capacity (Keogh River), and smolt-adult survival (Keogh River) (the other version of this model differs in that it uses total useable stream area available to steelhead). The process based model has inputs of total useable stream area available to steelhead, smolt density at capacity adjusted to better suit Skeena tributaries (based on higher alkalinity), and smolt-adult survival (Keogh River). In all models smolt density was estimated using alkalinity, water temperature (for growing season length), and the required rearing area to produce 1 smolt. In the area and biological based models mean annual discharge (dependent on watershed area) was used to estimate the average width and the percentage of useable width which in turn were used to estimate stream area and useable stream area, respectively. Note that Bocking and English (1992) estimated the number of adult spawners at capacity using a different algorithm for the biological component of the area and biological based models: they used fry density at capacity in conjunction with fry-smolt survival and a different estimate of smolt-adult survival.

Thompson, W.L. and D.C. Lee. 2000. Modelling relationships between landscape-level attributes and snorkel counts of chinook salmon and steelhead parr in Idaho. Can. J. Fish. Aquat. Sci. 57: 1834-1842.

Used existing data sets to model and snorkel count categories of spring-summer chinook and steelhead parr in Idaho based on landscape-level attributes (including precipitation, temperature, slope, lithology, road density, and forest management cluster). Chinook count categories were negatively related to geometric mean road density and positively related to mean annual precipitation. Steelhead count categories were negatively related to percent unconsolidated lithology. The model predicts that where road densities are > 1 km/km^2 and/or < 700 mm mean annual precipitation, there would be low counts of chinook parr. Similarly for steelhead, low counts were predicted to be observed where there is >30% unconsolidated