The Lake Nipissing Bayesian Walleye Model[1]

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Executive Summary

This report is a direct response to the Lake Nipissing management plan timeline for a review after 5 years and further builds upon the recommendations of the third-party Quantitative Fisheries Centre report. Using the Fall Walley Index Netting time series (starting in 1998) a Bayesian state-space model has been developed to assist with future management discussions. Besides the structural differences between the current Risk Assessment Model for Joint Adaptive Management and Bayesian model the most important change was not to incorporate the harvest data, from either the angling or commercial fisheries, in the present model version. This change was made to address the concern that the cost and feasibility of maintaining the collection of fisheries-dependent information (i.e., winter and open water angler creel surveys, and commercial catch monitoring) may not be sustainable on an annual basis into the future. The results from the Bayesian model have shown that the current management system should allow the Lake Nipissing Walleye population to reach its desired biomass recovery target in the near future. The simulated effects of a variety of alternate recreational angling rules were compared and there appear to be several options that can greatly decrease the risk to the resource while maintaining or increasing harvest into the near future. The model requires the annual data collected from the Fall Walley Index Netting program on Lake Nipissing (at least until the Walleye population has reached the recovery target of $1.3B_{MSY}$).

Résumé

Ce rapport est une réponse directe à l’échéancier du plan de gestion des pêches du lac Nipissing, qui prévoit un examen au bout de cinq ans. Il s’appuie sur les recommandations du rapport de l’organisme tiers Quantitative Fisheries Center. À partir des séries issues du décompte automnal de prises de dorés jaunes au filet (en place depuis 1998), un modèle d’espaces d’états bayésien a été mis au point pour alimenter les discussions futures en matière de gestion. Outre les différences structurelles entre le modèle actuel d’évaluation des risques applicable à la gestion adaptative conjointe et le modèle bayésien, le principal changement était de ne pas intégrer de données sur la récolte, qu’il s’agisse de pêche à la ligne ou de pêches commerciales, à la version actuelle du modèle. Ce changement a été apporté en réponse à la préoccupation selon laquelle le coût et la faisabilité du maintien de la collecte de données tributaires des pêches (c.-à-d. des enquêtes par interrogation des pêcheurs en eaux libres et d’hiver et la surveillance des prises commerciales) pourraient à l’avenir ne pas être viables selon un cycle annuel. Les résultats extraits du modèle bayésien ont montré que le système de gestion actuel devrait permettre à la population de dorés jaunes du lac Nipissing d’atteindre sa cible de rétablissement de la biomasse souhaitée dans un avenir proche. Les effets simulés de diverses autres règles pouvant être appliquées à la pêche récréative ont été comparés, et il semble qu’il y ait plusieurs options pouvant réduire grandement le risque pesant sur la ressource tout en maintenant ou augmentant la récolte dans un avenir proche. Le modèle nécessite les données annuelles collectées dans le cadre du programme de décompte automnal de prises de dorés jaunes au filet dans le lac Nipissing (au moins jusqu’à ce que la population de dorés jaunes ait atteint sa cible de rétablissement, à savoir une biomasse correspondant au rendement maximal durable de 1,3).

Lake Nipissing Walleye – Bayesian Model and Harvest Control Rules

1 – Introduction

Sustainable fisheries management is an adaptive process that relies on sound science, innovative management approaches, effective enforcement, meaningful partnerships, and robust public participation. Sustainable fisheries play an important role in Ontario's economy by providing opportunities for recreational, commercial, and subsistence fishing. Lake Nipissing Walleye (*Sander vitreus* (Mitchill, 1818)) support harvest-oriented fisheries that are of exceptional recreational, subsistence, and commercial importance in northeastern Ontario with complex management and distinct challenges. As a highly exploited fishery subject to multiple forms of fishing mortality, several attempts have been made to develop stock-recruitment relationships for this species to inform management policies (Zhao and Lester 2013, Rowe et al. 2013). Under the current management plan, biologists and resource managers already track changes in population numbers, size, growth, and mortality (OMNRF 2014). The current Walleye management system on Lake Nipissing uses a limit reference point method to manage harvest alongside population biomass estimates (Rowe et al. 2013). There is a need to implement evidence-based management, where scientific evidence from monitoring and research is used to inform more robust and transparent management decisions. Monitoring, evaluation, and reporting are critical stages of evidence-based management, which focus on assessing environmental state and pressures, evaluating management effectiveness, publicly reporting findings, demonstrating public accountability, and delivering the evidence-base to inform adaptive management.

The angling and commercial fisheries on Lake Nipissing are both defined as open access. Open access is the condition where access to the fishery (for the purpose of harvesting fish) is unrestricted (i.e., the right to catch fish is free and open to all). The angling fishery has limited regulation of effort (season timing and duration) and is managed using length- and creel-based restrictions while the commercial fishery has direct control of effort (through season, gear restrictions, and harvest termination – closing the fisheries and cancellation of fishing permits – once the quantity of Walleye specified in the annual Nipissing First Nation Fisheries Law is reached). Subsistence fishing is defined under the Nipissing First Nation Fisheries Law as "an NFN member fishing with one panel of net, or if subsistence fishing with more than one panel of net, the member is registered with the NFN Natural Resources Department. This may also include other fishing activity including but not limited to angling or spear fishing" (Nipissing First Nation 2019).

Annual estimates of the number and weight of Walleye harvested are derived from creel surveys (performed by Ontario Ministry of Natural Resources and Forestry (OMNRF) staff during both the winter and open water angling seasons) and harvest monitoring (with mandatory daily catch reporting by permitted fishers and catch sampling by Nipissing First Nation (NFN) Natural Resources Department staff) of the commercial fishery (fisheries-dependent data). The extent of the subsistence fishery and the amount harvested is unknown. Annual Fall Walleye Index Netting (FWIN) have been cooperatively performed annually since 1998 by OMNRF and NFN to provide fisheries-independent data on various life history parameters (e.g., length, weight, sex determination, maturity, and tissues collected for age interpretation) and biomass of Walleye ≥350mm total length. The current management model – Lake Nipissing Walleye **R**isk **A**ssessment **M**odel for **J**oint **A**daptive **M**anagement (i.e., the RAMJAM model) –

uses the data from both the fisheries-dependent and fisheries-independent sources to set annual safe harvest ceilings (Rowe et al. 2013).

In the 2014 Lake Nipissing management plan the OMNRF committed to review the RAMJAM model after 5 years (OMNRF 2014). Moreover, an external third-party review conducted by the Quantitative Fisheries Center (QFC) suggested that the current RAMJAM model was unnecessarily complex, relied upon questionable (and sometimes difficult to assess) assumptions and may not be implementable as detailed in the RAMJAM report (Jones et al. 2016). The panel believed the most pressing task was to create an age-structured stock assessment model using FWIN data.

This report is a direct response to the Lake Nipissing management plan timeline for a review after 5 years and further builds upon the recommendations of the third-party QFC report. Using the FWIN time series (starting in 1998) a Bayesian state-space model has been developed to assist with future management discussions. Besides the structural differences between the RAMJAM and Bayesian models the most important change was not to incorporate the harvest data, from either the angling or commercial fisheries, in the present model version. This change was made to address the concern that the cost and feasibility of maintaining the collection of fisheries-dependent information (i.e., winter and open water angler creel surveys, and commercial catch monitoring) may not be sustainable on an annual basis into the future. The results from the Bayesian model have been used to:

- modify the current harvest control rule,
- evaluate the effectiveness of the current management efforts (i.e., the 460mm minimum size limit with 2 fish daily creel limit for the winter and open water angling fisheries, and the measures stipulated in the Nipissing First Nation Fisheries Laws),
- simulate the effects of a suite of 11 possible angling regulations, and
- propose future monitoring needs to assess the status of the Lake Nipissing Walleye population

2 – Model Description

2.1 – Model objectives

The model has four main objectives:

(i) to estimate Walleye population structure and demographic parameters from the Fall Walleye Index Netting (FWIN) surveys on Lake Nipissing,
(ii) to assess the importance of stock size versus environmental drivers on Walleye recruitment,
(iii) to simulate population dynamics and its response to fisheries regulation scenarios, and
(iv) to estimate parameter uncertainty and account for it when making population projections.

2.2 – Model overview

This section of the report provides and overview of the model structure. More detailed descriptions of its variables, parameters, and their relationships are provided in Sections 2.3 and 2.4.

The Bayesian state-space model is an age- and size-structured model of Lake Nipissing Walleye population dynamics. It is also data-driven, as the processes and state variables reflect the structure and availability of data from the FWIN monitoring protocol (Morgan 2002). FWIN surveys have been carried out on Lake Nipissing annually since 1998. The main annual fisheries assessment (FWIN) occurs during the fall, usually in October. The catch from the FWIN provides information on fish age, size, sex, and maturity state, which help to infer the true state of the population at that time. An important annual event is spawning, which for Walleye typically occurs during the spring (Figure 1). Reproduction is dependent on the size (length) and number of potential spawners, and because these two variables are only assessed during the preceding fall, annual mortality and growth are assumed to be concentrated between Spawning and Catch events (Figure 1). From the total number of produced eggs, only a fraction will survive to become Age-0 recruits the next fall. The survivorship from eggs and recruits is determined by an annually variable recruitment carrying capacity which encapsulates all density-dependence in the model (Andersen et al. 2016). Although spawning data were not assessed on an annual basis, auxiliary data from the Wasi Falls spawning site sampled during a subset of years could be used to infer on reproductive traits of Walleye, such as gonad production and absolute fecundity as a function of fish length.

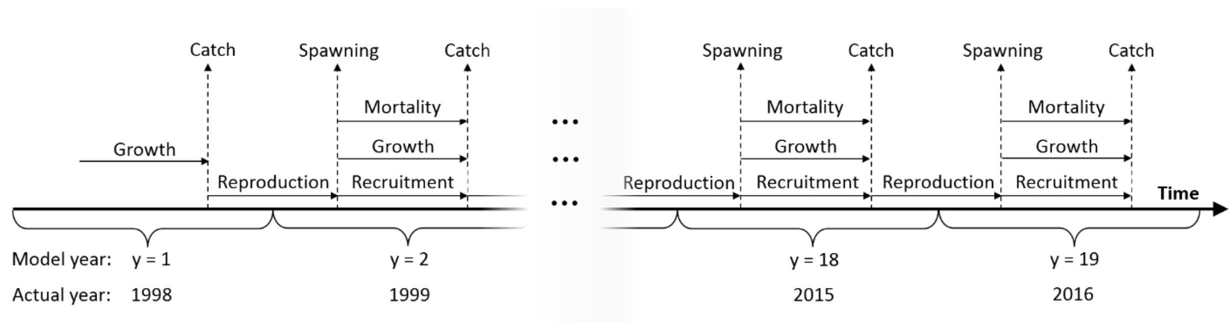


Figure 1. Schedule of the main events and population processes in the model. Each year y starts on January 1st and ends on December 31st. "Catch" represents the occurrence of a FWIN survey, typically in the Fall, and "Spawning" represents spawning events that typically occur in the Spring. "Reproduction" represents the production of eggs by adults whose size and abundance were assessed in the previous Fall (during a Catch event). "Recruitment" represents the survivorship from egg (Spawning) to the next FWIN event (Catch). For the first year (1998), only "Growth" was included as a process because growth parameters were assumed to be constant, whereas mortality and recruitment varied annually. Estimating mortality and recruitment for 1998 would require an independent estimate of initial abundance in 1997, which was not possible (the FWIN program on Lake Nipissing was started in 1998).

The model represents the catch from the FWIN surveys explicitly as a stochastic phenomenon resulting from underlying (latent) population states (Newman et al. 2014). This is formally represented in Figure 2. The connection between population state and the observed data (i.e., the transition from $\mathbf{N}$ to $\mathbf{C}$ in Figure 2) is given by an **observation** sub-model, which specifies how gillnet catchability, selectivity, sampling effort, and observation error translate abundances and size distributions into expected catches. Changes between states, which make up population dynamics, are also stochastic and are determined in-part by a **process** sub-model (i.e., the transition from $\mathbf{N}_y$ to $\mathbf{N}_{y+1}$). This means that the quantities of interest – abundance, biomass, age and size structure, mortality, and recruitment – are explicitly represented as unobserved variables in an age-structured population model. They are estimated only indirectly through their connection with the observed variables. The model also includes auxiliary variables (represented by $\mathbf{V}_{proc}$ and $\mathbf{V}_{obs}$ in Figure 2), which comprise variables such as observed maturity states or captured length-at-each-mesh-size. Even though these variables were recorded as part of the annual catches, they were assumed to be constant, and as such, the lack of temporal dynamics is what distinguishes them from other variables. They do not affect any other variable in the model but are affected by process or observation parameters, and therefore are important to make inferences on these parameter values.

One advantage of this multi-level representation is that it can impose more realistic constraints on the population states, for instance by forcing the expected abundance of a cohort to only decrease with time. Additionally, this formulation allows the propagation of uncertainty around all population state variables and parameters, as well as accounting for their correlation structure. This is important if the model is to be used for predicting the variability in population dynamics arising from parameter uncertainty, which in turn can be used to estimate probabilities of any given state being above or below certain threshold – the probability of achieving a stated objective (e.g., the probability that adult biomass will be above a hypothetical management target in a given year).

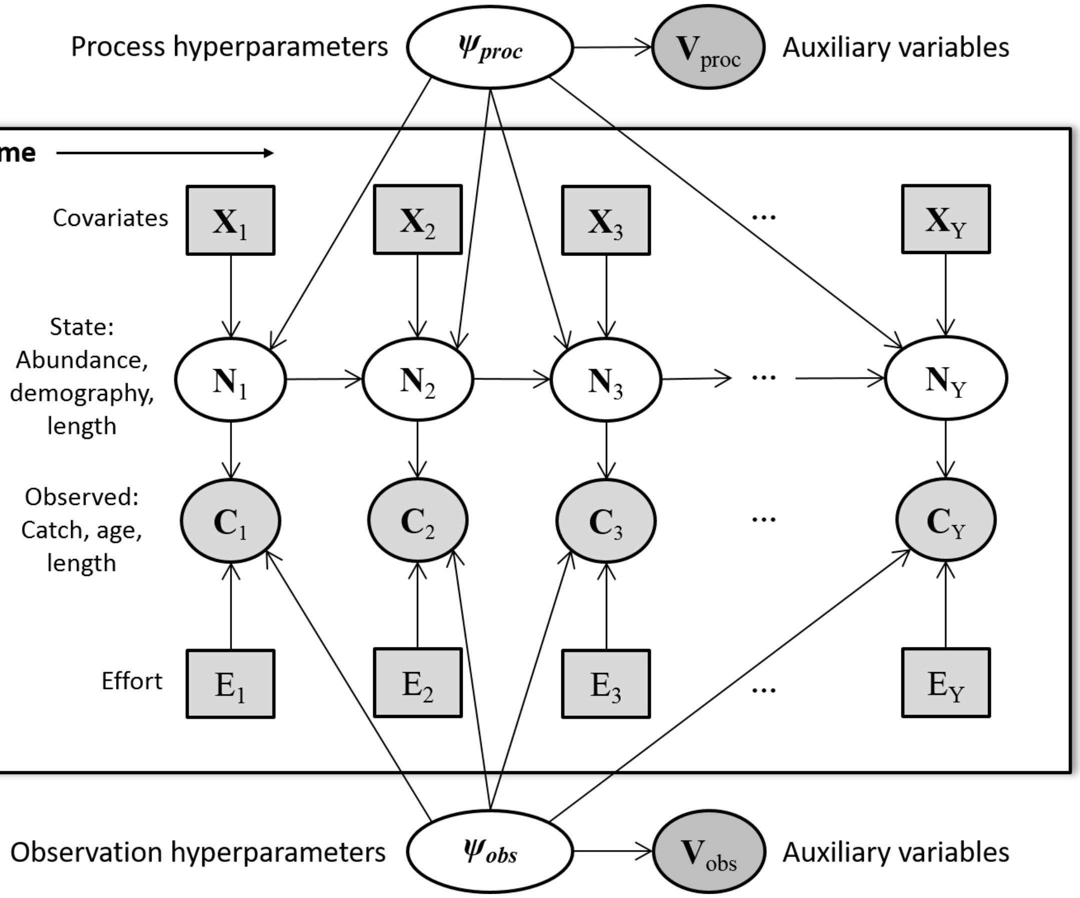


Figure 2. Bayesian network for the Walleye population state-space model, showing how variables and parameters are related through conditional probabilities. The large rectangle comprehends time-varying (dynamical) variables. Subscripts in each variable represent sampling year (y = 1, 2, 3, …, Y). Ellipses represent random variables (or parameters); squares represent factors assumed to be fixed at a constant value. Gray filling represents directly observed (sampled) data, whereas white filling represents unobserved (latent) variables whose values are estimated. Arrows represent relationships, i.e., the distribution of the random variable the arrow is pointing at is conditional on the values of the variable the arrow is pointing from. $\mathbf{X}_y$ is the set of environmental covariates observed in year 'y'; in the current model version, only the annual growing degree-days above 5ºC (GDD5) was used. $\mathbf{N}_y$ is the set of population states in year 'y' that include: (i) abundance per age class, (ii) mean size (total length) per age class, (iii) mortality rate (year^{-1}) per age class, and (iv) carrying capacity of Age-0 recruits. $\mathbf{C}_y$ is the set of variables observed in the FWIN catch that year, including: (i) number of fish caught per age class, and (ii) lengths of all fish caught. E_y is sampling effort (number of nets) used that year. ψ_{proc} is the set of hyperparameters determining population processes in the model, i.e., the transition between population state variables. ψ_{obs} is the set of hyperparameters determining observation (catch), i.e., the transition from population states to observed variables in the catch. The hyperparameters also influence observed variables that are important to infer on population processes ($\mathbf{V}_{proc}$) or observation ($\mathbf{V}_{obs}$), but whose temporal structure was ignored for simplicity. They are referred to as auxiliary variables. $\mathbf{V}_{proc}$ is the set of auxiliary variables representing the reproductive state of the population, including (i) the maturity state (mature female versus other) of all fish caught, and (iv) the gonad-somatic index (GSI) of females caught during Spring at Wasi Falls on a subset of years. $\mathbf{V}_{obs}$ is the set of fish total length and gillnet mesh size variables, including only individuals containing information for both and used to inform on gillnet selectivity.

The process and observation sub-models are formulated as equations whose shape and magnitude are determined by the so-called hyperparameters (ψ_{proc} and ψ_{obs}, Figure 2), which are random variables whose values are not conditional on any other variable. For instance, in the process sub-model, the number of

Age-0 Walleye recruits surviving from spawning to the time of a FWIN survey is constrained by a carrying capacity (i.e., the maximum of the stock-recruitment relationship for a given year, $Rmax$). The expected value of this carrying capacity (μ_{Rmax}) is modelled in a logarithmic scale and is assumed to follow a linear relationship with the annual growing degree-days above 5°C (GDD5). The expected value for the carrying capacity and the realized carrying capacity represent two hierarchical levels of a population state (member of $\mathbf{N}$), GDD5 is an environmental covariate (member of $\mathbf{X}$), whereas the intercept and slope of the linear relationship with GDD5 are process hyperparameters (members of ψ_{proc}). In the observation sub-model, one example is the function relating fish length to the encounter-contact rate with the gillnet, which is assumed to follow a power law $\propto length^{\beta}$. The distribution of fish lengths is another population state, then a member of $\mathbf{N}$, whereas the encounter rate exponent β – which determines how rapidly encounter rate with the FWIN nets increases with length – is an observation hyperparameter (member of ψ_{obs}). Together, they help determining the chances of gillnets catching any specific group of fish lengths in a given year, represented by the vector $\mathbf{l}_y$, which is a member of $\mathbf{C}$ (Table 1).

In summary, to get to the observed variables from the FWIN catch in a given year, there is a chain of conditional probabilities from the most basic parameters and variables through a series of intermediate latent variables (e.g., carrying capacity of recruits, population length distribution). This also serves to point out that Figure 2, by aggregating several population states or observed variables into a single major category, is just a higher-level and low-resolution simplification. The details of all process and observation variables and functions will be described in the following sections. The full list of process and observation variables and hyperparameters, which helps to outline their hierarchical structure, is presented in Table 1.

Table 1. State variables, covariates, and hyperparameters in the model

Symbol	Description
State variables	
$\mathbf{N}_y$	Set of population state variables in year y
$\mathbf{n}_y$	Vector of population abundances (number of fish per age class) in year y
$n_{a,y}$	Abundance (number of fish) of age class a in year y
$\mathbf{z}_y$	Vector of mortality rates (year^{-1}) per age class in year y
$z_{a,y}$	Mortality rate (year^{-1}) of age class a in year y
z_{2-}	Mortality rate (year^{-1}) of 2-year old or younger fish, i.e., for $a \ \leq 2$
$z_{3+,y}$	Mortality rate (year^{-1}) of 3-year old or older fish, i.e., for $a \geq 3]$ in year y
$s_{a,y}$	Survival probability from age a to age a+1, from year y to year y+1
$F_{a,y}$	Absolute fecundity of a mature female fish aged a in year y
$\rho_{a,y}$	Probability of fish aged a in year y being a mature female
$O_{a,y}$	Mean fecundity of fish aged a in year y
$R_{a,y}$	Realized number of age-0 recruits produced per fish aged a in year y
$Rmax_y$	Maximum total number (carrying capacity) of Age-0 recruits in year y

μ_{Rmax_y}	Expected (mean) value of $log_{10}(Rmax_y)$
$\boldsymbol{\lambda}_y$	Vector of mean total length (mm) per age class in year *y*
$\lambda_{0,y}$	Mean total length (mm) of age-0 recruits in year *y*
$\mu_{\lambda_{0,y}}$	Expected (mean) value of $\lambda_{0,y}$
$\lambda_{a,y}$	Mean total length (mm) of fish aged a in year *y*
$\mathbf{C}_y$	Set of FWIN catch variables in year *y*
$\mathbf{c}_y$	Vector of catches (number of fish caught per age class) in year *y*
$c_{a,y}$	Number of fish aged a caught in year *y*
$\mathbf{l}_y$	Set of vectors of total lengths (mm) of fish caught in year *y*
$\mathbf{l}_{a,y}$	Vector of total lengths (mm) of fish aged a caught in year *y*
$l_{a,y,i}$	Total length of individual fish i aged a and caught in year *y*
$\mathbf{V}$	Set of auxiliary variables
$\mathbf{V}_{proc}$	Set of auxiliary process variables
$\boldsymbol{\phi}$	Vector of maturity states
$\phi_{a,y,i}$	Maturity state of fish i aged a and caught in year *y* ($\phi_{a,y,i}$=1 if mature female, 0 otherwise)
$\mathbf{g}$	Vector of gonad-somatic indices from Wasi Falls spawning sample
g_i	Gonad somatic index of individual i from Wasi Falls spawning sample
$\mathbf{V}_{obs}$	Set of auxiliary observation variables
$\mathbf{l}_{mesh}$	Vector of total lengths from mesh-specific samples
$l_{mesh,i}$	Total length (mm) of individual fish i from mesh-specific samples
$\mathbf{m}_{mesh}$	Vector of mesh sizes from mesh-specific samples
$m_{mesh,i}$	Mesh size (mm) of gillnet panel where individual fish i was caught
Covariates	
$\mathbf{X}_y$	Set of environmental covariates
$GDD5_y$	Growing degree-days above 5°C of year *y*
E_y	Sampling effort (number of nets) in year *y*
Process hyperparameters ($\boldsymbol{\psi}_{proc}$)	
A_{Rmax}	Intercept of maximum recruitment-GDD5 relationship
B_{Rmax}	Slope of maximum recruitment-GDD5 relationship
σ_{Rmax}	Standard deviation of maximum recruitment-GDD5 relationship
A_{λ_0}	Intercept of recruit mean length-GDD5 relationship
B_{λ_0}	Slope of recruit mean length-GDD5 relationship
σ_{λ_0}	Standard deviation of recruit mean length-GDD5 relationship
ρmax	Maximum probability of being a mature female
θ	Steepness of the maturation curve
$\lambda_{50\%}$	Mean size at 50% probability of maturation (mm)
g	Mean gonad somatic index
σ_g	Standard deviation of gonad somatic index
λ_∞	Asymptotic body size (mm)
k	von Bertalanffy growth coefficient (year^{-1})
z_{2-}	Mortality rate of age-0 to age-2 fish (year^{-1})
$\sigma_{z_{3+}}$	Standard deviation around annual mortality rate of Age 3+ fish
$z_{3+,1}$	Initial mortality rate of age 3 and older fish (year^{-1})

ϵ	Egg size (g)
ω	Coefficient of weight-length relationship
b	Exponent of weight-length relationship
$\mathbf{n}_1$	Vector of initial age distribution of abundances ($\log_{10}$ scale)
$n_{a,1}$	Initial abundance of age a fish ($\log_{10}$ scale)
$\boldsymbol{\lambda}_0$	Vector of initial age distribution of mean lengths (mm)
$\lambda_{a,0}$	Initial mean length of age a fish (mm)
Observation hyperparameters ($\boldsymbol{\psi_{obs}}$)	
δ	Dispersion factor for the number of fish caught
σ_l	Dispersion factor for individual length distribution
μ_r	Position factor for retention rate
σ_r	Dispersion factor for retention rate
α	Coefficient determining individual probability of catch
β	Exponent relating length to probability of catch

2.3 – Process sub-model

The process sub-model contains a mix of deterministic and stochastic relationships between variables (Figure 3). The deterministic processes mostly comprehend the transition of population abundance and size distribution from one year to another, for given mortality and growth parameters. The stochastic processes are constrained to: (i) recruitment, determining the number and length of Age-0 fish during the fall, (ii) adult mortality, which varies annually, and (iii) reproductive traits, such as maturity and gonad production (both used as auxiliary variables).

2.3.1 – *Deterministic processes*

The basic information comprising the population state in year y is given by the vectors of abundance $\mathbf{n}_y$, mortality $\mathbf{z}_y$, and mean length $\boldsymbol{\lambda}_y$, represented in Figure 2 as the set $\mathbf{N}_y$:

$$\mathbf{N}_y = \{\mathbf{n}_y, \mathbf{z}_y, \boldsymbol{\lambda}_y\} \tag{1}$$

The abundance vector is a column vector $\mathbf{n}_y = [n_{0,y}, n_{1,y}, n_{2,y}, \ldots, n_{12+,y}]^{\mathrm{T}}$ (where T means the transpose operation), whose elements $n_{a,y}$ give the abundance of fish of age *a* in year *y*. The last age class 12+ include all fish 12 years old or older and was chosen as a compromise between the range of ages necessary to properly inform demographic processes and the availability of fish in the catch. Similarly, the mortality vector $\mathbf{z}_y = [z_{0,y}, z_{1,y}, z_{2,y}, \ldots, z_{12+,y}]^{\mathrm{T}}$ and the mean length vector $\boldsymbol{\lambda}_y = [\lambda_{0,y}, \lambda_{1,y}, \lambda_{2,y}, \ldots, \lambda_{12+,y}]^{\mathrm{T}}$ contain age- and year- specific mortality rates (year^{-1}) and mean total lengths (mm). Here the use of the Greek letter λ to represent unobserved (latent) mean lengths, in contrast to observed lengths, which are represented by l (Section 2.4).

Mortality rates, when integrated over the course of a year, give the probabilities of survival:

$$s_{a,y} = e^{-z_{a,y}} \tag{2}$$

which determine the change in abundance within a cohort from one year to the next:

$$n_{a+1,y+1} = s_{a,y} n_{a,y} \tag{3}$$

The total number of Age-0 recruits in year y+1 is equal to the sum of recruits ($R_{a,y+1}$) produced by each fish that had age a in the previous fall multiplied by their abundance ($n_{a,y}$):

$$n_{0,y+1} = \sum_a R_{a,y+1} n_{a,y} \tag{4}$$

The transition between abundances in year y to year y+1 can be represented in a more compact way using matrix multiplication:

$$\mathbf{n}_{y+1} = \mathbf{M}_y \mathbf{n}_y \tag{5}$$

where $\mathbf{n}_y$ is the abundance vector as defined above, and $\mathbf{M}_y$ is a population transition matrix containing survivorships and recruitment terms:

$$\mathbf{M}_y = \begin{bmatrix} R_{0,y+1} & R_{1,y+1} & R_{2,y+1} & R_{3,y+1} & \cdots & R_{11,y+1} & R_{12+,y+1} \\ s_{0,y} & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & s_{1,y} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & s_{2,y} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & s_{11,y} & s_{12+,y} \end{bmatrix} \tag{6}$$

The recruitment term $R_{a,y+1}$ in turn depends on: (i) the mean number of eggs (or mean fecundity) produced by each fish that were aged a in the previous Fall ($O_{a,y}$) (i.e., the transition marked as "Reproduction" in Figure 1), and (ii) an implicit mortality that occurs between spawning in spring and the time of population assessment in the following Fall ("Recruitment" in Figure 1). This egg to age-0/juvenile mortality is assumed as the only source of density dependence in the model, and is represented by a Beverton-Holt stock-recruitment relationship (Andersen et al. 2016):

$$R_{a,y+1} = \frac{Rmax_{y+1} O_{a,y}}{Rmax_{y+1} + \sum_a \left(n_{a,y} O_{a,y}\right)} \tag{7}$$

where $Rmax_{y+1}$ is the maximum total number, or carrying capacity, of Age-0 Walleye recruits surviving to the fall in year y+1. By assuming that the potential number of spawners is equal to the number of fish in the previous fall, Equation (7) also includes implicitly the effects of adult mortality between fall and spring (when $O_{a,y}$ eggs are produced by age a). This effect should be negligible though when compared to the mortality of young fish from spring to fall.

This stock-recruitment relationship incorporates the effects of both stock size and structure, represented by $n_{a,y} O_{a,y}$, and environmental drivers, represented by $Rmax_{y+1}$. The subscript $'y+1'$ in $Rmax$ indicates that the carrying capacity can vary from year to year, depending on the conditions of the lake that determine early survivorship, which include temperature, availability of habitat and prey, predation pressure, diseases, among many other factors. The survivorship of eggs in that year can be calculated as $S_0 = n_{0,y+1}/\sum_a \left(n_{a,y} O_{a,y}\right)$, and gives a measure of the relative strength of stock versus environmental influences: the lower the survivorship, the less influential the stock size will be in determining recruitment.

Because the stock-recruitment relationship is itself annually variable, any other function relating a single value of a year's egg production to egg survival could provide an equally good fit to available data. One alternative is the Ricker model, which has been widely used in fisheries research typically for incorporating the possibility of negative effects of stock size on recruitment (which could result from e.g. cannibalism, Hilborn and Walters 1992). Walleye is a cannibal species and the Ricker model has been previously suggested in the literature to explain Walleye recruitment dynamics, for instance in Escanaba Lake, Wisconsin (Hansen et al. 1998). Nonetheless, we opted for a Beverton-Holt (BH) relationship (Equation 7) for two reasons: (i) preliminary analyses of Age-0 versus mature stock biomass from the FWIN did not indicate the existence of a negative relationship for Lake Nipissing Walleye, and (ii) the BH model is much more easily interpretable, its single parameter being a carrying capacity of recruits. The position of a single point along the BH curve is informative on the relative influence of stock size versus environmental factors driving recruitment in a given year, depending on how close to the asymptote the point is. In contrast, it is not so clear what a Ricker relationship for a single year would represent. In addition, our approach is flexible enough to incorporate cannibalistic effects on recruitment, which could be done in the future by using the biomass of suitably sized Walleye (that could potentially prey upon pre-recruits), and even other important predatory species such as Yellow Perch (*Perca flavescens* (Mitchill, 1814)), explicitly as a covariate affecting recruitment carrying capacity. This would represent a more mechanistic approach than aggregating all stock size effects (egg production and predation) into a single curve such as the Ricker model to fit multiple years of recruitment.

The mean fecundity $O_{a,y}$, used to represent the reproductive potential of a stock, is the product of the absolute fecundity of a typical female of age a in year y ($F_{a,y}$) and the probability that the fish is a mature female ($\rho_{a,y}$):

$$O_{a,y} = \rho_{a,y} F_{a,y} \tag{8}$$

The absolute fecundity (number of eggs per mature female) is a function of mean body length $\lambda_{a,y}$, a gonad-somatic index g, and egg size ϵ (g):

$$F_{a,y} = \frac{\omega\left(\lambda_{a,y}\right)^b g}{\epsilon} \tag{9}$$

where ω and b are parameters determining the relationship between total length (mm) and somatic weight (g).

The probability of being a mature female is also assumed to be a function of length, according to a logistic relationship:

$$\rho_{a,y} = \frac{\rho max}{1 + e^{-\theta\left(\lambda_{a,y} - \lambda_{50\%}\right)}} \tag{10}$$

where $\lambda_{50\%}$is the length at 50% probability of maturity, θ is a coefficient determining how sharply maturity increases with size, and ρmax is the maximum proportion of mature females in the population (which accounts for the presence of males).

Finally, the mean length of a cohort is assumed to change in discrete annual increments according to a von-Bertalanffy growth curve:

$$\lambda_{a+1,y+1} = \lambda_{a,y} + (\lambda_\infty - \lambda_{a,y})(1 - e^{-k}) \tag{11}$$

where λ_∞ is the asymptotic mean length (mm) and k is the growth rate parameter (year^{-1}).

2.3.2 – *Stochastic processes*

Process stochasticity is assumed to occur mainly during early life (first year), determining the distribution of recruitment carrying capacities ($Rmax_{y+1}$) and the mean size of recruits ($\lambda_{0,y+1}$). For older fish, only mortality rates are assumed to vary stochastically from year to year.

$Rmax_{y+1}$ and $\lambda_{0,y+1}$ are each characterized by a probability density function for each year. In principle, the probabilities should be conditional on many environmental factors expected to affect recruitment. Here we assume that most these factors are correlated with the cumulative growing degree-days above 5°C (GDD5), so for simplicity this was used as the sole environmental covariate explaining the distribution of $Rmax_{y+1}$ and $\lambda_{0,y+1}$. Given that variation in recruitment and the usual effects of temperature are both exponential in nature, $Rmax_{y+1}$ was assumed to follow a lognormal distribution, i.e.:

$$log(Rmax_{y+1}) = \sim\mathcal{N}\left(\mu_{Rmax_{y+1}}, \sigma_{Rmax}\right) \tag{12}$$

The lognormal parameter $\mu_{Rmax_{y+1}}$ is the expected value of $log(Rmax_{y+1})$ and is assumed to be linearly related to GDD5:

$$\mu_{Rmax_{y+1}} \; = \; A_{Rmax} + B_{Rmax} GDD5_{y+1} \tag{13}$$

where A_{Rmax} and B_{Rmax} are the intercept and slope of the relationship. The dispersion parameter σ_{Rmax} gives a measure of variability of $log(Rmax_{y+1})$ around the expectation and is assumed to be constant.

Similarly, recruit mean length is assumed to follow a normal distribution:

$$\lambda_{0,y+1} \sim \mathcal{N}\left(\mu_{\lambda_{0,y+1}}, \sigma_{\lambda_0}\right) \tag{14}$$

whose expected value is also a linear function of GDD5:

$$\mu_{\lambda_{0,y+1}} \; = \; A_{\lambda_0} + B_{\lambda_0} GDD5_{y+1} \tag{15}$$

With the objective of simplifying the estimation of the model parameters, the mortality values were aggregated into two categories: (i) for all fish younger than 3 years, $z_{0,y} = z_{1,y} = z_{2,y}$, and mortality is hereby represented simply as z_{2-}; (ii) for all fish 3 years old and older, $z_{3,y} = z_{4,y} = \cdots = z_{12+,y}$, and mortality is hereby represented as $z_{3+,y}$. The mortality of young fish $z_{2-}$is assumed to be constant (notice the lack of year subscript), whereas $z_{3+,y}$can vary annually and stochastically. Although adult mortalities can be influenced by environmental factors, they are also expected to respond strongly to fishing pressure. As harvest data have not yet been incorporated for estimation of the present model version, the annual variation in $z_{3+,y}$was not explicitly modelled as a function of covariates, but followed a random walk process, so that the realized mortality in one year becomes the expected value of a normal distribution in the next year, i.e.:

$$z_{3+,y+1} \sim \mathcal{N}\left(z_{3+,y}, \sigma_{z_{3+}}\right) \tag{16}$$

where the dispersion parameter $\sigma_{z_{3+}}$ determines how variable mortality is from year to year. This allows for adult mortality to vary stochastically while preserving potential temporal autocorrelation that could exist within its implicit environmental, biological, and anthropogenic drivers.

The process sub-model also includes the auxiliary variables $\boldsymbol{\phi}$ and $\mathbf{g}$, members of $\mathbf{V}_{proc}$. They represent, respectively, the vector with observed individual maturity states and the vector with observed gonad-somatic indices. They are both random variables, implying their values are determined by probability distributions, conditional on process hyperparameters (which is the reason why they were included in this section, although their stochasticity is not technically qualified as "process stochasticity", Newman et al. 2014). The maturity state of an individual i can assume the value 1 if i is a mature female and 0 otherwise, following a Bernoulli distribution:

$$\phi_i \sim Bernoulli(\rho_i) \tag{17}$$

where ρ_i is the probability that i is a mature female (as opposed to males or immature females), which depends on its observed length l_i according to Equation (10) (replacing mean latent length λ by individual length l) and on the hyperparameters ρmax, θ, and $\lambda_{50\%}$.

The gonad-somatic index is assumed to follow a normal distribution:

$$\mathrm{g}_i \sim \mathcal{N}\left(g, \sigma_g\right) \tag{18}$$

where the mean and standard deviation g and σ_g are both hyperparameters.

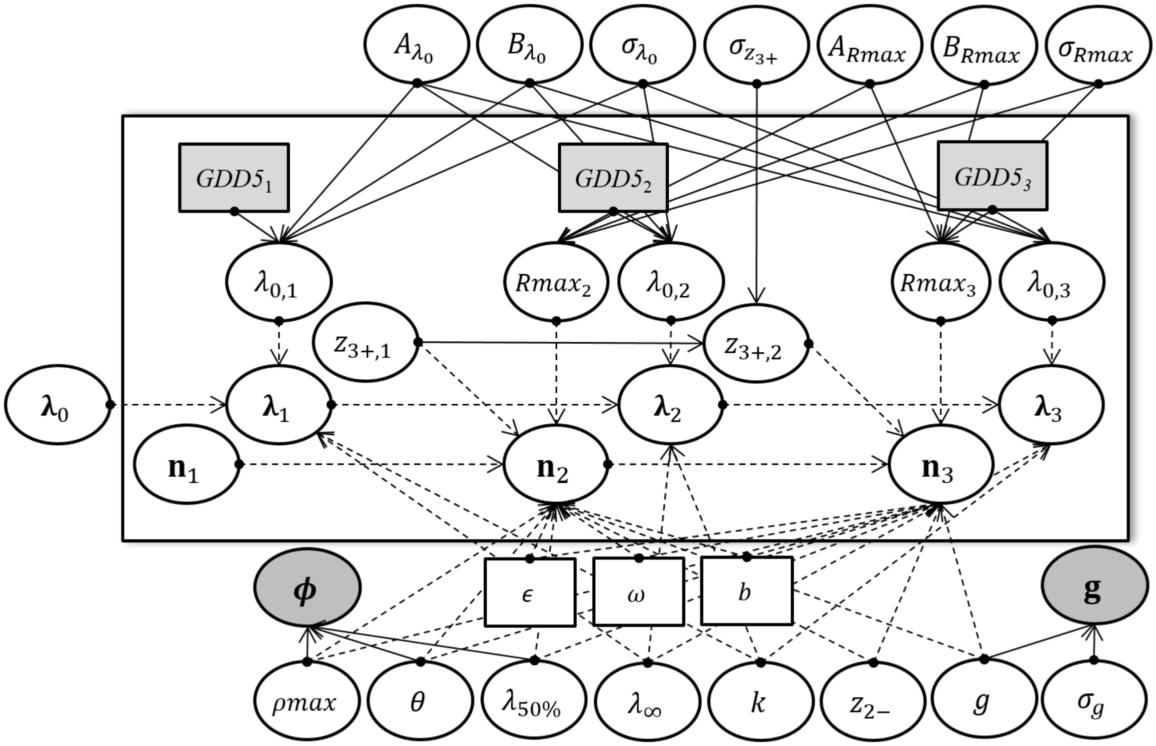


Figure 3. Bayesian network for the process sub-model, exemplifying a three-year period (assuming hypothetically that the third year is the last year). Annually variable population states and covariate (growing degree-days, GDD5) are contained within the major rectangle, and their subscripts indicate the year. The other variables are either (i) hyperparameters (white filled ellipses represent random variables and rectangles represent fixed parameters, i.e., estimated separately or imposed as constants in the model) or (ii) observed auxiliary variables (sampled gonad-somatic indices at the spawning site, $\mathbf{g}$; and maturity states from the FWIN catches, $\boldsymbol{\phi}$). Dashed arrows represent deterministic relationships, continuous arrows represent stochastic relationships (each arrow starts with a black dot, to facilitate identifying the conditioning variable they are pointing from versus the conditioned variable they are pointing to). Symbols marked in bold represent vectors. Initial lengths ($\boldsymbol{\lambda}_0$) were based on year 0, whereas initial abundances ($\mathbf{n}_1$) and adult mortality ($z_{3+,1}$) were based on year 1 as both varied annually and required the existence of catch data to not be confounded. For a full list of symbols and definitions, see Table 1.

2.4 – Observation sub-model

All relationships between variables and parameters in the observation sub-model are stochastic (Figure 4). The FWIN catch $\mathbf{C}_y$ is defined by the distribution of Walleye ages and sizes found in the FWIN nets in year's y survey, i.e.:

$$\mathbf{C}_y = \{\mathbf{c}_y, \mathbf{l}_y\} \tag{19}$$

where $\mathbf{c}_y = [c_{0,y}, c_{1,y}, c_{2,y}, \ldots, c_{12+,y}]^{\mathrm{T}}$ is the vector with the number of fish caught per age class in year y, $\mathbf{l}_y = \{\mathbf{l}_{1,y}, \mathbf{l}_{2,y}, \ldots, \mathbf{l}_{12+,y},\}$ is the set of length vectors for each age, where $\mathbf{l}_{a,y} = [l_{a,y,1}, l_{a,y,2}, l_{a,y,3}, \ldots, l_{a,y,c_{a,y}}]$ is the vector with individual fish lengths $l_{y,a,i}$.

The number of fish caught $c_{a,y}$ depends stochastically on the available fish (i.e., population size $n_{a,y}$), their mean size ($\lambda_{a,y}$), their interaction with the FWIN net and sampling effort E. Firstly, the "average" fish is characterized by its potential catch rate (γ, net^{-1}). The catch rate depends in part on the retention rate of fish that encountered-contacted the net ($r(\lambda)$), which varies as a function of fish length and the distribution of mesh sizes in the net (Millar and Holst 1997). It also depends on the encounter-contact rate with the net ($\xi(\lambda)$), which is assumed here to be a power function of size, i.e., $\xi(\lambda) \propto \lambda^{\beta}$ (Rudstam et al. 1984), where β is an exponent defining how steeply encounter and/or contact increases with increasing fish size. The total expected catch rate will be given by:

$$\gamma(\lambda) = \alpha E \lambda^{\beta} r(\lambda) \tag{20}$$

where α is a coefficient of proportionality. The mean probability that any randomly chosen fish will not be caught is given by the negative exponential of the expected catch rate, i.e., $e^{-\gamma(\lambda)}$, whose complement gives the mean individual probability of catch P_c:

$$P_c(\lambda) = 1 - e^{-\alpha E \lambda^{\beta} r(\lambda)} \tag{21}$$

This probability determines (i) the relative distribution of sizes and (ii) the expected number of fish of age *a* caught in year *y*, given by $n_{a,y} P_c(\lambda_{a,y})$. The actual number of fish caught follows a negative binomial distribution:

$$c_{a,y} \sim NB\left(\frac{1}{\delta}, \frac{1}{\delta n_{a,y} P(\lambda_{a,y}) + 1}\right) \tag{22}$$

This parametrization ensures that the mean value of the distribution is equal to $n_{a,y} P_c(\lambda_{a,y})$, with variance controlled by the dispersion parameter δ. The use of a negative binomial distribution allows for catch to be more aggregated (i.e., few large versus many small catches) than expected by pure chance. This implicitly means that probabilities of catch can be heterogeneous across fishes of the same size. The degree of heterogeneity is determined by δ, and in the special case $\delta \to 0$ the probabilities become homogeneous and the distribution of $c_{a,y}$ converges to a Poisson distribution.

The retention rate is a function of both fish size and mesh size, following a unimodal function of their ratio according to the principle of geometric similarity (Millar and Holst 1997). Preliminary analysis using standard methods for selectivity estimation (Walker et al. 2013) with the FWIN Walleye catches indicated that a lognormal type of function had the best fit for Walleye FWIN catch-by-mesh on Lake Nipissing:

$$r(\lambda) = \sum_{j=1}^{8} \left[\frac{m_j}{25 \lambda \sigma_r} e^{\mu_r - \frac{\sigma_r^2}{2} - \frac{\left(ln(\lambda) - \mu_r - ln(m_j/25)\right)^2}{2\sigma_r^2}} \right] \tag{23}$$

where m_j is the size of mesh *j* (mm, stretched). The FWIN net is composed by a series of 8 mesh sizes varying from 25 to 152mm. The parameters μ_r and σ_r are the location and dispersion parameters, determining (i) the fish length relative to mesh size at which retention is maximal and (ii) how spread the curve is around that value. The function for each mesh size is identical to that proposed by Millar and Holst (1997), except for the inclusion of σ_r in the first denominator (outside the exponential). This inclusion does not affect the shape of the curve, only its overall height, and serves as a constraint on the area under the curve that is necessary for estimation purposes. The retention values resulting from

Equation (23) are in an arbitrary scale and serve as relative indicators only. The adjustment towards the appropriate scale is achieved by its multiplication with the coefficient α in Equation (21).

Having defined the number of fish caught ($c_{a,y}$), the distribution of individual lengths in the catch ($\mathbf{l}_{a,y}$) will also depend on the probability of catch defined by Equation (21), but this time applied to individual lengths, i.e., $P_c(l)$. Firstly, we define the distribution of individual lengths within each age class and year in the population ($L_{a,y,i}$ with $i = \{1,2,3, \dots , n_{a,y}\}$). It is modelled as a lognormal distribution around the mean length $\lambda_{a,y}$, i.e.:

$$ln(L_{a,y}) \sim \mathcal{N}\left(ln(\lambda_{a,y}) - \sigma_l^2/2\,, \sigma_l\right) \tag{24}$$

Here the normal parameter μ is being adjusted through the expression $ln(\lambda_{a,y}) - \sigma_l^2/2$ to ensure that the mean of the lognormal distribution is equal to $\lambda_{a,y}$. The dispersion parameter σ_l is assumed to be constant. The probability that a fish i from $\mathbf{l}_y$ will be of a given length l is then proportional the product of the lognormal distribution of lengths in the population and their probability of catch:

$$P(l_{a,y,i} = l) \propto P_c(l)\frac{1}{l\sigma_l}e^{\frac{-\left(ln(l) - ln(\lambda_{a,y}) + \sigma_l^2/2\right)^2}{2\sigma_l^2}} \tag{25}$$

Actual probabilities can be obtained by normalizing Equation (25) so that it integrates to 1. However, this is not necessary for numerical simulation and estimation purposes (see "Estimation" section)

It must be noted that although each age and year combination is characterized by a lognormal distribution of lengths in the population ($L_{a,y}$, Equation 24), only the mean of that distribution ($\lambda_{a,y}$) is assumed to affect the population processes in the process sub-model. The variation around the mean, defined by σ_l, is constant on a log scale and only affects relative likelihoods of sizes within a catch (as part of the observation sub-model), and calculations of response variables that depend on size thresholds (e.g., abundances or biomasses of fish larger than 350mm). Ideally, population process should be based on individual sizes and integrated over their distribution (which should be applicable to any function in Section 3 that uses $\lambda_{a,y}$ as an input). However, the numerical integration is time consuming and became prohibitive during the estimation procedure, and for this reason all population processes were simplified and based on the mean length and not the entire size distribution. For the same reason the catch probabilities in Equation (21) are based on $\lambda_{a,y}$ and not on the entire lognormal distribution of $L_{a,y}$.

The auxiliary variables $\mathbf{l}_{\text{mesh}}$ and $\mathbf{m}_{\text{mesh}}$ comprise the set of all Walleye individuals with recorded information on both length and mesh size within the FWIN catches. They are important for estimating the hyperparameters determining the shape of the retention function. For this purpose, we assumed that the relative probability of catching a fish with length $l_{\text{mesh},i}$ in a mesh of size $m_{\text{mesh},i}$ is proportional to its retention rate function, which, modified from Equation (23) for a given mesh, becomes:

$$P(l_{mesh,i}|m_{mesh,i}) \propto \frac{m_{mesh,i}}{25 l_{mesh,i}\sigma_r}e^{\mu_r - \frac{\sigma_r^2}{2} - \frac{\left(ln(l_{mesh,i}) - \mu_r - ln(m_{mesh,i}/25)\right)^2}{2\sigma_r^2}} \tag{26}$$

The right side of Equation (26) does not integrate to 1, so it is not strictly a probability distribution. However, as the estimation relied on a numerical sampling method, the only requirement is for the sampled function to be proportional to the true probability function.

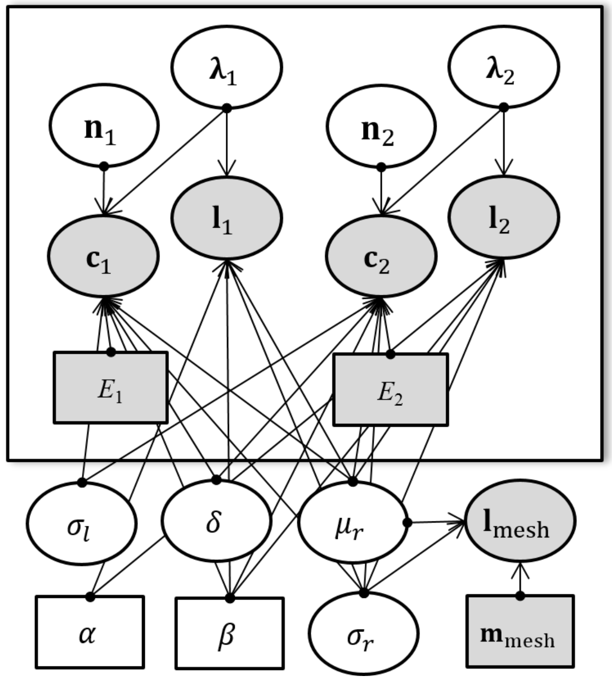


Figure 4. Bayesian graph for the observation sub-model, exemplifying a two-year period. Annually variable population states and covariate (sampling effort E, number of nets) are contained within the major rectangle, and their subscripts 1 or 2 indicate the year. The other variables are either (i) hyperparameters (white filled ellipses represent random variables and rectangles represent fixed parameters, i.e., estimated separately or imposed as constants in the model) or (ii) observed auxiliary variables. Arrows represent stochastic relationships between variables (each arrow starts with a black dot, to facilitate identifying the conditioning variable they are pointing from versus the conditioned variable they are pointing to). Symbols marked in bold represent vectors. For a full list of symbols and definitions, see Table 1.

2.5 – Estimation

The structure of conditional relationships described in the previous two sections and illustrated in Figures 3 and 4 permits the simulation of any latent or observed variable if the distributions of hyperparameters and the values of covariates are known (i.e., "forward" model simulations). From these distributions, a random value can be drawn for A_{Rmax}, B_{Rmax}, σ_{Rmax}, $\sigma_{z_{3+}}$, and so on, cascading forward through all intermediate variables until a value for the final observable variables such as $c_{a,y}$ and $l_{a,y,i}$ can be determined from their own conditional distributions. However, none of those distributions are known beforehand and therefore must be estimated from empirical data. The data sources used for estimation are summarized in Table 2.

The estimation proceeds backwards with respect to the chain of conditional probabilities illustrated in Figures 2 to 4 (Parent and Rivot 2012), i.e., by assessing the relative probabilities (or likelihoods) of observations from the empirical data (e.g., observed $c_{a,y}$, $l_{a,y,i}$, and so on) for given (initially assigned) values of the conditioning parameters (or latent variables, e.g., $n_{a,y}$, $Rmax_y$, $\lambda_{a,y}$, and so on) and of those parameters given other conditioning parameters and covariates (e.g., A_{Rmax}, B_{Rmax}, $GDD5_y$, and so on). The objective is to find a function which defines the distribution of parameter values given the observed data, the so-called posterior distribution. It was estimated using slice sampling, which is a Markov chain Monte Carlo (MCMC) algorithm for sampling posterior distributions (Neal 2003). All analyses were carried out in MATLAB 2018b.

The prior distributions for most parameters were non-informative and uniform, represented by a constant, in some cases with a lower or upper boundary to constraint them within biologically feasible intervals. For simplicity and without loss of generality, that constant was set to 1. These priors are so-called “improper” (Stauffer 2007) as they do not strictly qualify as probability distributions (i.e., they do not integrate to 1 within their domain), but are still appropriate for estimation given that the only important requirement is that their magnitude must be proportional to the actual probabilities (Neal 2003). The prior for each initial population abundance was defined as 1 for $log(n_{a,1}) > 0$, which assumes abundances are equally probable on a log scale, but they must always include more than one individual (as $log(0) = 1$). For initial mean latent lengths $\lambda_{a,0}$ the same is valid but on a linear scale, i.e., $\lambda_{a,0} > 0$ (i.e., only positive lengths allowed). Similarly, the priors of $z_{3+,1}$, σ_{Rmax}, σ_{λ_0}, θ, g, z_{2-}, $\sigma_{z_{3+}}$, δ, σ_l, and σ_r were all set to 1 with the constraint that their values must be positive. For ρmax, which is a measure of probability or proportion, the prior was constrained within the interval [0,1]. The parameters relating GDD5 to maximum recruitment and mean length of recruits (A_{Rmax}, B_{Rmax}, A_{λ_0}, B_{λ_0}) can in theory assume any value from $-\infty$ to ∞, so their priors were unconstrained.

Normal distributions truncated at zero were used as informative priors for $\lambda_{50\%}$, g, λ_∞, k, and μ_r. For length at 50% maturity: $\lambda_{50\%}(\lambda_{50\%} > 0) \sim \mathcal{N}(450{,}50)$, the μ (450mm) and σ (50mm) parameter values were estimated as the mean and standard deviation of female maturation length from a compilation of 70 lakes in Ontario and Quebec (Bozek et al. 2011). For the gonad-somatic index: $g(g > 0) \sim \mathcal{N}(0.17{,}0.06)$, based on estimated mean and standard deviation of relative fecundity (~52000eggs•kg^{-1}) from Bozek et al. (2011) and an egg size of 0.28mg from Shuter et al. (2005). For the von Bertalanffy growth parameters: $\lambda_\infty(\lambda_\infty > 0) \sim \mathcal{N}(625{,}90)$, and $k(k > 0) \sim \mathcal{N}(0.2{,}0.07)$, the parameter values were based on global estimates from a nonlinear mixed effects model fitted to Walleye lakes in the Broad-Scale Monitoring data (Table 2). In this case, lake was used as a random factor and the estimates of sigma σ (90mm for λ_∞ and 0.07year^{-1} for k) $i$ncluded both random (lake) and residual variation. For the gillnet retention position parameter: $\mu_r(\mu_r > 0) \sim \mathcal{N}(5{,}2)$, the mean parameter (5) was based on fitting Equation (26) to a compilation of Walleye catch-by-mesh data using a standard selectivity estimation method (Walker et al. 2013). The method also indicated that the lognormal selectivity curve performed better (lower AIC) than alternative curves, i.e., the normal, inverse-gaussian, and gamma. These priors represent the distribution of life history and size selectivity variables for Walleye across a broad range of lakes in Ontario, so they are informative for estimation of parameters form Lake Nipissing without being too constraining.

Not all parameters listed in Table 1 are stochastic. They were modelled as constants due to problems of identifiability (i.e., their effects are confounded by other parameters due to the lack of sufficiently specific data) or slow convergence during preliminary MCMC runs, which normally happens when parameters multiply one another in a model. The parameters determining somatic weight-length relationship, ω and b, were estimated separately using the Wasi Falls spawning sample, whereas the egg size value ϵ = 2.8mg was based on Shuter et al. (2005), which is also close to the average from Wasi Falls (2.63mg). Together, with the gonad-somatic index, they have multiplicative and potentially confounding effects on the fecundity of a fish of a given size (Equation 9).

The other constants were related to gillnet catchability, α and β. The first determines the overall scale of catchability, and the second how catchability changes with body size. These are not directly estimable for Lake Nipissing due to the lack of mark-recapture data associated with the FWIN. Their values were based on independent estimates from other lakes in Ontario and Quebec making up the gillnet calibration database (Giacomini et al. unpublished manuscript). The catchability coefficient (q) estimated for the FWIN was 1.04ha•net^{-1}, based on marked fish larger than 350mm, whose average size across lakes was 475mm. This coefficient is a measure of effort and area specific probability of catch, i.e., $q = P_c/(E/A)$, where P_c is the probability of catch defined by Equation (21). Based on $q = 1.04$ for a fish measuring 475mm, a relative effort (nets•ha^{-1}) defined by the average from the calibration studies ($E/A = 0.0335$), and the Lake Nipissing surface area ($A = 83048$ha), the above expression for catchability and Equation (21) can be used to determine α:

$$\alpha = \frac{-ln(1 - 1.04 * 0.0335)}{0.0335 * 83048 * 475^{\beta} * r(475, \mu_r = 5, \sigma_r = 0.23)} \tag{37}$$

where $r(475, \mu_r = 5, \sigma_r = 0.23)$ is the retention rate function (Equation 23) evaluated at 475mm with location and dispersion parameters μ_r and $\sigma_r$estimated from a Walleye catch-by-mesh compilation using a standard selectivity curve fitting method (Bell 2018, Table 2). To apply Equation (37), the value of β must be determined before hand. Eight values were used, each in a separate estimation run, uniformly spaced from 0 to 3.5 (Table 3). This interval was chosen based on theoretical expectations. The lower limit ($\beta = 0$) represents a commonly assumed (although criticized, *see* Hamley 1975) scenario in which total gillnet selectivity is entirely due to retention selectivity. Higher values of β will depend on more specific assumptions about encounter and contact rates with the gillnet. For instance, if we assume that average swimming speed scales with length to the power of 0.5 (i.e., speed $\propto l^{0.5}$, Ware 1978, Rudstam et al. 1984), and that swimming speed is the only size-based component affecting encounter-contact, then $\beta = 0.5$. Alternatively, it could be argued that encounter rates with the net is analogous to encounter rates with prey (i.e., there is a reaction distance component and the fish is attracted to the net once it perceives it). Reaction distance is expected to be proportional to length ($\propto l^1$), which in two-dimensional environments would imply encounter rate scaling as $l^{0.5}l^1 = l^{1.5}$ and in three-dimensional environments as $l^{0.5}(l^1)^2 = l^{2.5}$, resulting in $\beta = 1.5$ and $\beta = 2.5$, respectively. If one adds the effect of mesh size on contact rate, it can further increase β. A proportional scaling between contact and mesh size has been suggested in the literature (Anderson 1998), and because mesh size tends to be roughly proportional to the length of the fish being caught, it would add another l^1 component to the overall scaling. The resulting relationship with body size in the aforementioned three-dimensional scenario would be $l^{0.5}(l^1)^2 l^1 = l^{3.5}$, defining our upper limit $\beta = 3.5$. Several combinations of these assumptions can lead to different intermediate values. For most results presented here we focus on a mid-range value $\beta = 2$, which can result from encounter rate being proportional to length and contact rate proportional to mesh size, consistent with estimates from Anderson (1998) for Walleye.

For each value of β initial MCMC chains were run generating 500000 iterations and retaining a sample of 50000 after a thinning of 10 (Stauffer 2007). To check for convergence, seven independent chains were run for β=2 using different initial values. In each of the seven new chains, and for each parameter independently, the initial value was set to the minimum or maximum observed the preliminary chain, with equal chance. Given that many parameters were strongly correlated, this procedure was enough to ensure that the initial values were far outside that sample's distribution, and all seven chains showed convergence after visual inspection of their traces and histograms. It was supported by the Gelman-Rubin statistic (Gelman and Rubin 1992), which was <1.1 for all parameters (the maximum was 1.01), indicating good convergence. These preliminary chains were then used to adjust the width parameter of the slice sampling algorithm to improve mixing and speed up the estimation process in order to generate additional samples. The new chains contained two million values for each parameter. After a burn in of 500000 and a thinning of 150, a final sample of 10000 iterations was retained. After visual inspection of the trace plots (Appendix 1, showing results for $\beta = 2$), the quality of mixing was deemed acceptable. We also generated posterior-predictive distributions and compared their 95% prediction intervals to the observed data.

Table 2. Data sources used for estimation.

Dataset	**Description**
Nipissing FWIN	Fall Walleye Index Netting surveys carried out on Lake Nipissing from 1998 to 2016. Provided the main source of data regarding annual variation in observable catch variables ($\mathbf{C}_y$), with a total of 10883 Walleye caught, and sampling effort E_y. It also provided the auxiliary maturity data $\boldsymbol{\phi}$.
Wasi Falls	A sample of 111 female Walleye caught at the spawning site in Wasi Falls during the Spring of years 2002-2003, 2011-2017, shared by Tom Johnston (OMNRF). Provided the auxiliary data $\mathbf{g}$ used to estimate the gonad-somatic index g, as well as the somatic weight versus length data used to independently estimate the parameters ω and b.
Mesh-specific catch	The prior for the retention position parameter μ_r was based on a compilation of Walleye caught by FWIN surveys with mesh-specific records in Ontario (Bell 2018). The auxiliary data $\mathbf{l}_{mesh}$ and $\mathbf{m}_{mesh}$ used to calculate retention likelihoods were a subset of the Nipissing FWIN data, comprising catches from 1998 and 1999.
Broad-Scale monitoring	Cycle 1 of the Ontario Broad-Scale Monitoring program (Sandstrom 2013), used to inform on the priors for growth parameters (λ_∞ and k), and comprising near 54000 Walleye caught in 475 lakes.
Walleye life-history	Compilation of Walleye life-history traits from 70 lakes in Ontario and Quebec, shared by Nigel Lester (OMNRF) and used for the analyses in Bozek et al. (2011). Provided information for the priors of reproductive traits $\lambda_{50\%}$ and g (the later based on relative fecundities).

GDD5	Annual growing-degree days above 5° for Nipissing in the period 1998-2016, extracted from the Historical Climate Analysis Tool (Cross et al. 2012) database.

2.6 – Results

The effect of changing the gillnet encounter-contact exponent β is felt most prominently on the estimates of mortality (Figure 5), which in turn affected the age distributions. Higher β values are associated with higher mortalities (both z_{2-} and z_{3+}) and larger number of small and young fish. Such strong relationship is the reason why this parameter could not be estimated together with mortalities, due to issues with parameter identifiability, given the absence of additional and independent data to assess size-dependent catchability (e.g., mark-recapture data).

The following results assume an exponent $\beta = 2$. The estimated means and 95% credible intervals for all hyperparameters and initial state variables are presented in Table 3.

Figures 6-7 compare predicted with observed catch statistics, i.e., the number of fish caught per age per year ($c_{a,y}$) and the length distributions of the catch ($\mathbf{l}_{a,y}$) for many cohorts over the years. They show a good agreement between model predictions and observations. The length distributions were underestimated for some age-year combinations and overestimated for some others (Figure 7). This is expected given that the only growth parameter allowed to vary annually was the recruit mean size λ_(0,y). Of relevance is the overestimation of growth for some of the later cohorts (2010-2013), which combined with the relatively strong recruitment in those years (an indication of density-dependent growth) can lead to inflated estimates of biomass in the last years of the time series (2014-2016). Although the major trends in biomass are not expected to be affected, the absolute values for the last three years are probably an overestimation and must be interpreted with caution.

The estimated reproductive traits and functions are shown in Figure 8. The mean estimated gonad-somatic index ($g = 0.168$, Figure 8A) corresponds to a relative fecundity of 51370 eggs•kg^{-1}. The mean fecundity (O) shows a sharp initial increase with body size to due the combined increase in probability of maturation (ρ, Figure 8B) and the allometric increase in the absolute fecundity (F) of a mature female (Figure 8C), later being dominated by the allometric component as ρ levels off at its maximum (ρmax).

Figure 9 presents the annual variation in the main population state variables. Around 2008 the adult mortality was at its highest and recruitment levels at their lowest (Figure 9A, B). This led to a sharp later decline in biomass of fish available for the fisheries (≥350mm, Figure 9E). The following years had an increase in recruitment and a decrease in adult mortality, leading to increases in abundances (Figure 9D) and later in the biomass of fish ≥350mm. The mean length in the population (Figure 9F) mostly tracked fluctuations in recruitment levels, showing an inverse relationship (i.e., more young fish means smaller mean sizes). The trend in the mean length of recruits, despite the wide fluctuations, showed little or no association with the other state variables (Figure 9C). Even though the mean size and the maximum number of recruits had both a mean positive relationship with GDD5 (Figure 10), the relationship was weak and its 95% credible interval included zero as a plausible slope.

Finally, the estimated stock-recruitment relationships showed a broader vertical as opposed to horizontal variation (Figure 11). This indicates that environmental factors affecting the carrying capacity of recruits were dominant when compared to variation in the reproductive potential of the adult stock. The lack of a stock influence is further highlighted by the distance of estimated recruitment levels to the ascending part of the curves (Figure 11A) and by a lack of correlation between point estimates of surviving recruits and the total number of eggs (which is a direct index of stock size) (Figure 11B).

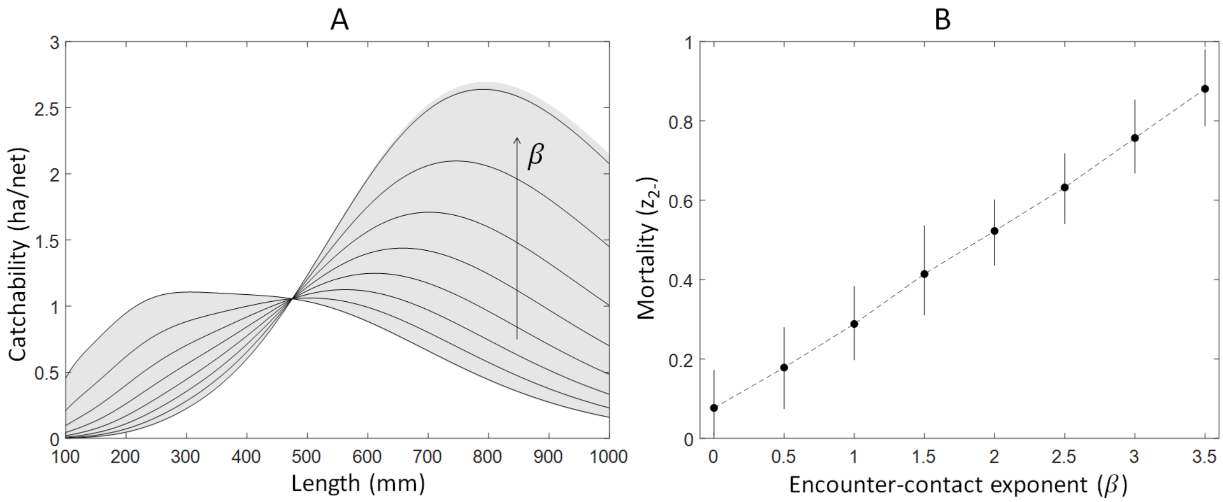


Figure 5. Effect of the encounter-contact exponent (β) on catchability curves (A) and mortalities (B). In (A), solid lines are mean curves from Bayesian samples, and the gray area is their combined 95% credible interval. All curves cross at the same coordinate (475mm,1.04ha•net^{-1}), which is the mean length and catchability from the calibration lake dataset with a relative effort of 0.0335nets•ha^{-1}. In (B), the mean and 95% credible intervals of Age 0 to 2 mortality rate (z_{2-}, year^{-1}) shows a linear relationship with β.

Table 3. Estimated values of process ($\boldsymbol{\psi_{proc}}$) and observation ($\boldsymbol{\psi_{obs}}$) hyperparameters. The values represent the mean from Bayesian samples, with 95% credible intervals within brackets. Parameters with single values were assumed as constants in the model.

Symbol	Description	Values*
Process ($\boldsymbol{\psi_{proc}}$)		
A_{Rmax}	Intercept of maximum recruitment-GDD5 relationship	4.357 (2.16,6.868)
B_{Rmax}	Slope of maximum recruitment-GDD5 relationship	8.52x10^{-4} (-4.9x10^{-4},2x10^{-3})
σ_{Rmax}	Standard deviation of maximum recruitment-GDD5 relationship	0.318 (0.21,0.481)
A_{λ_0}	Intercept of recruit mean length-GDD5 relationship	121.729 (35.04,205.546)
B_{λ_0}	Slope of recruit mean length-GDD5 relationship	0.033 (-0.012,0.079)
σ_{λ_0}	Standard deviation of recruit mean length-GDD5 relationship	11.909 (8.341,17.466)
ρmax	Maximum probability of being a mature female	0.937 (0.888,0.982)
θ	Steepness of the maturation curve	0.038 (0.035,0.041)
$\lambda_{50\%}$	Mean size at 50% probability of maturation (mm)	446.193 (440.328,451.875)
g	Mean gonad somatic index	0.168 (0.163,0.173)
σ_g	Standard deviation of gonad somatic index	0.027 (0.024,0.031)
λ_∞	Asymptotic body size (mm)	547.952 (538.964,557.95)

k	von Bertalanffy growth coefficient (year^{-1})	0.242 (0.232,0.252)
z_{2-}	Mortality rate of age-0 to age-2 fish (year^{-1})	0.523 (0.436,0.601)
$\sigma_{z_{3+}}$	Standard deviation around annual mortality rate of Age 3+ fish	0.07 (0.004,0.22)
$z_{3+,1}$	Initial mortality rate of age 3 and older fish (year^{-1})	0.667 (0.457,0.835)
ϵ	Egg size (g)	$2.8\text{x}10^{-3}$
ω	Coefficient of weight-length relationship	$4.243\text{x}10^{-6}$
b	Exponent of weight-length relationship	3.116
$\mathbf{n}_1$	Vector of initial age distribution of abundances ($\log_{10}$ scale)	
$n_{0,1}$	Initial abundance of age 0 fish ($\log_{10}$ scale)	6.12 (5.938,6.281)
$n_{1,1}$	Initial abundance of age 1 fish ($\log_{10}$ scale)	5.557 (5.39,5.722)
$n_{2,1}$	Initial abundance of age 2 fish ($\log_{10}$ scale)	5.55 (5.379,5.734)
$n_{3,1}$	Initial abundance of age 3 fish ($\log_{10}$ scale)	5.251 (5.049,5.474)
$n_{4,1}$	Initial abundance of age 4 fish ($\log_{10}$ scale)	5.215 (5.002,5.458)
$n_{5,1}$	Initial abundance of age 5 fish ($\log_{10}$ scale)	4.699 (4.471,4.935)
$n_{6,1}$	Initial abundance of age 6 fish ($\log_{10}$ scale)	3.922 (3.587,4.255)
$n_{7,1}$	Initial abundance of age 7 fish ($\log_{10}$ scale)	4.351 (4.102,4.604)
$n_{8,1}$	Initial abundance of age 8 fish ($\log_{10}$ scale)	3.687 (3.302,4.075)
$n_{9,1}$	Initial abundance of age 9 fish ($\log_{10}$ scale)	2.951 (2.069,3.618)
$n_{10,1}$	Initial abundance of age 10 fish ($\log_{10}$ scale)	2.541 (1.208,3.383)
$n_{11,1}$	Initial abundance of age 11 fish ($\log_{10}$ scale)	1.625 (0.083,3.223)
$n_{12+,1}$	Initial abundance of age 12+ fish ($\log_{10}$ scale)	2.866 (1.848,3.542)
$\boldsymbol{\lambda}_0$	Vector of initial age distribution of mean lengths (mm)	
$\lambda_{0,0}$	Initial mean length of age 0 fish (mm)	153.292 (148.716,157.743)
$\lambda_{1,0}$	Initial mean length of age 1 fish (mm)	232.687 (228.272,236.961)
$\lambda_{2,0}$	Initial mean length of age 2 fish (mm)	292.455 (286.731,298.259)
$\lambda_{3,0}$	Initial mean length of age 3 fish (mm)	348.315 (341.831,355.038)
$\lambda_{4,0}$	Initial mean length of age 4 fish (mm)	389.551 (378.175,401.058)
$\lambda_{5,0}$	Initial mean length of age 5 fish (mm)	409.363 (380.137,439.742)
$\lambda_{6,0}$	Initial mean length of age 6 fish (mm)	446.063 (425.624,467.714)
$\lambda_{7,0}$	Initial mean length of age 7 fish (mm)	464.825 (419.928,511.408)
$\lambda_{8,0}$	Initial mean length of age 8 fish (mm)	466.479 (329.788,618.764)
$\lambda_{9,0}$	Initial mean length of age 9 fish (mm)	751.382 (602.218,917.597)
$\lambda_{10,0}$	Initial mean length of age 10 fish (mm)	547.434 (396.552,722.016)
$\lambda_{11,0}$	Initial mean length of age 11 fish (mm)	751.874 (596.323,934.755)
Observation ($\boldsymbol{\psi_{obs}}$)		
δ	Dispersion factor for the number of fish caught	0.211 (0.152,0.286)
σ_l	Dispersion factor for individual length distribution	0.095 (0.094,0.096)
μ_r	Position factor for retention rate	4.746 (4.731,4.761)
σ_r	Dispersion factor for retention rate	0.299 (0.292,0.306)
α	Coefficient determining individual probability of catch	$6.016\text{x}10^{-11}$
β	Exponent relating length to probability of catch	[0,0.5,1,1.5,2,2.5,3,3.5]*

*Eight values of β were used as constants in separate model estimation runs. The estimations for all other parameters in this table are based on $\beta = 2$.

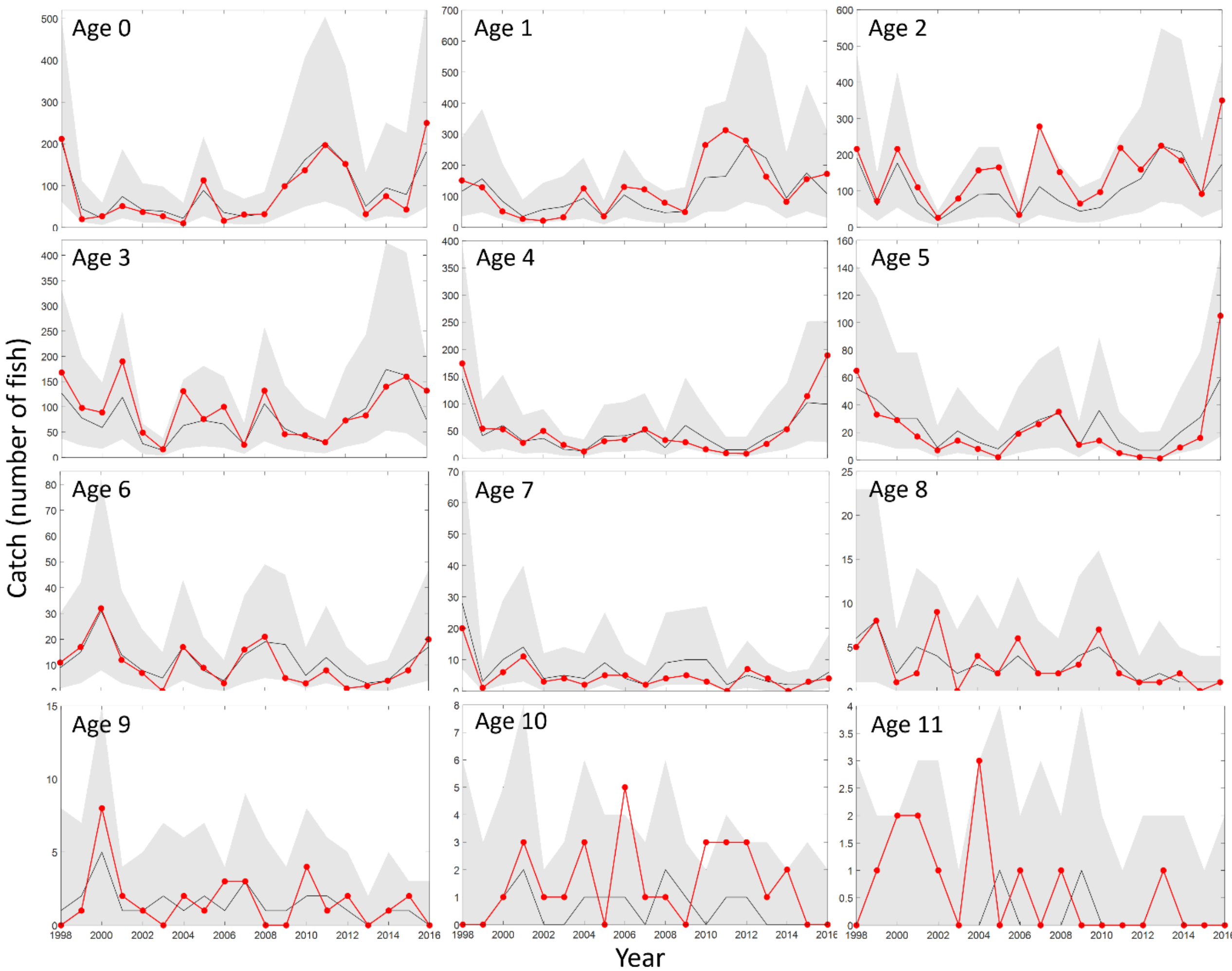


Figure 6. Predicted versus observed catches across years for ages 0 to 11. Red dotted lines represent observations; thin black lines and gray areas represent predictions (median and 95% credible intervals, respectively).

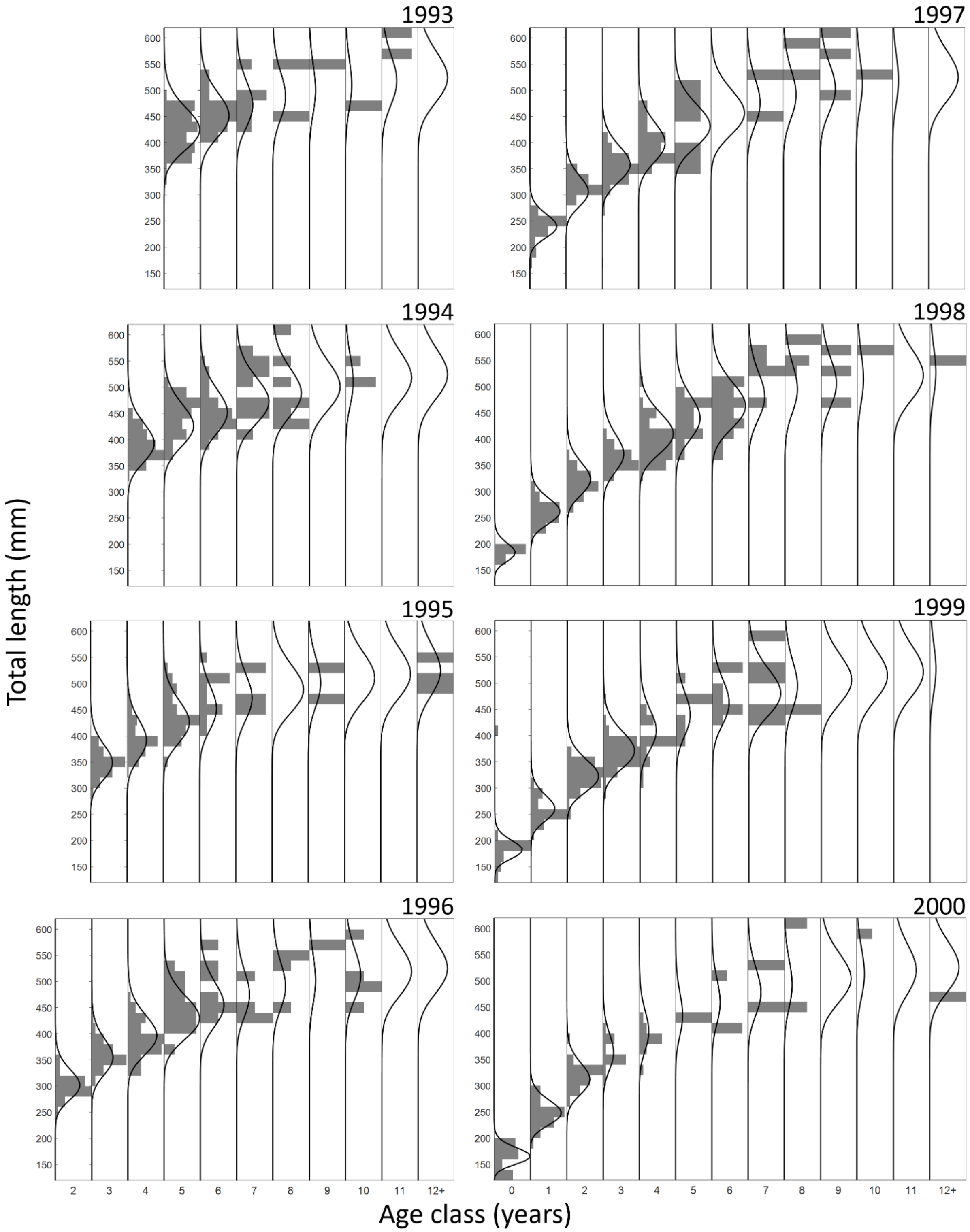


Figure 7. Length-at-age distributions for cohorts born from 1993 to 2016 (birth year at the top of each graph; figure continues in the next two pages). Histograms (gray bars) are empirical probability density distributions of observed catch, and black curves represent the mean predicted size distributions (after adjusting for catch probabilities).

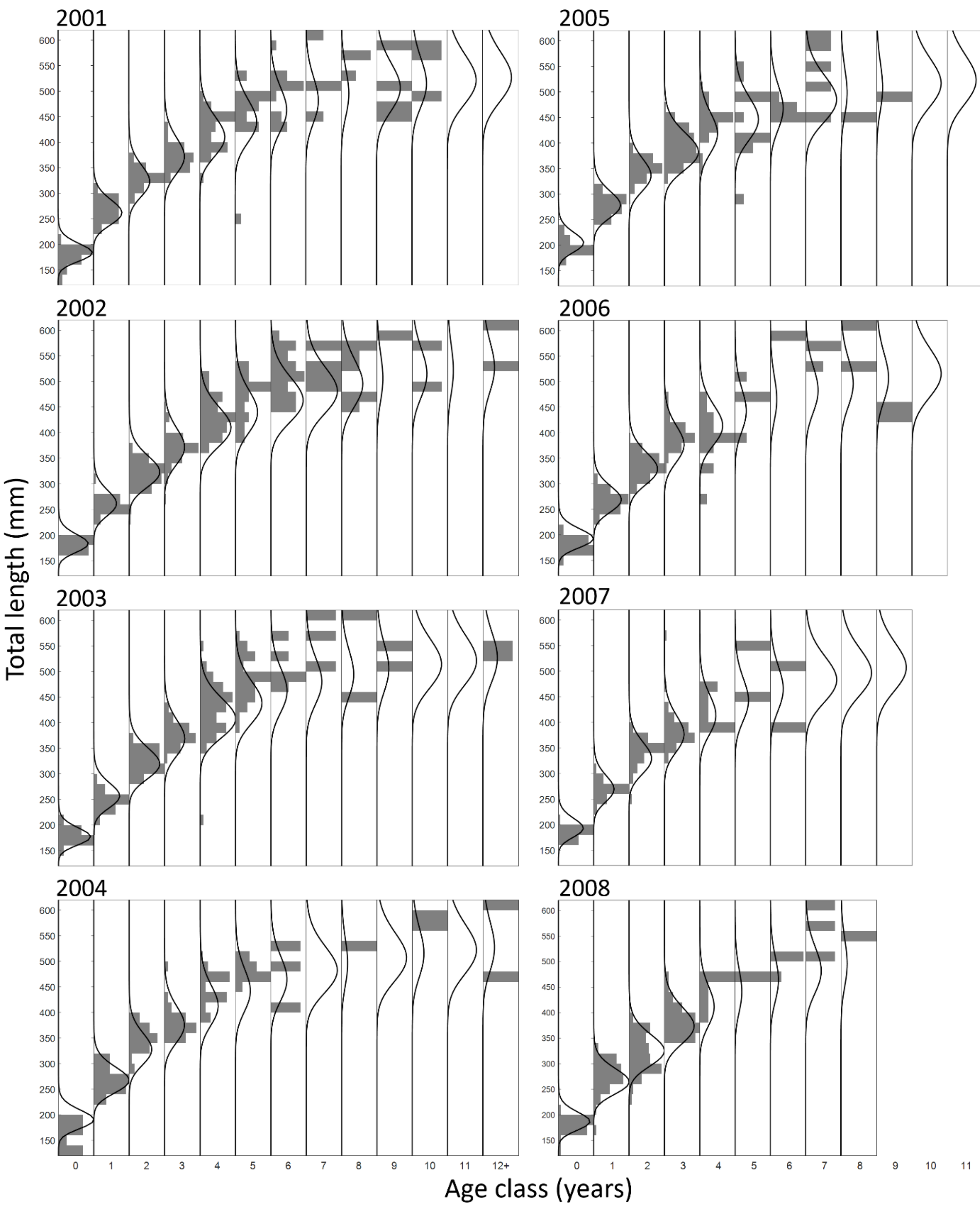


Figure 7. Continued.

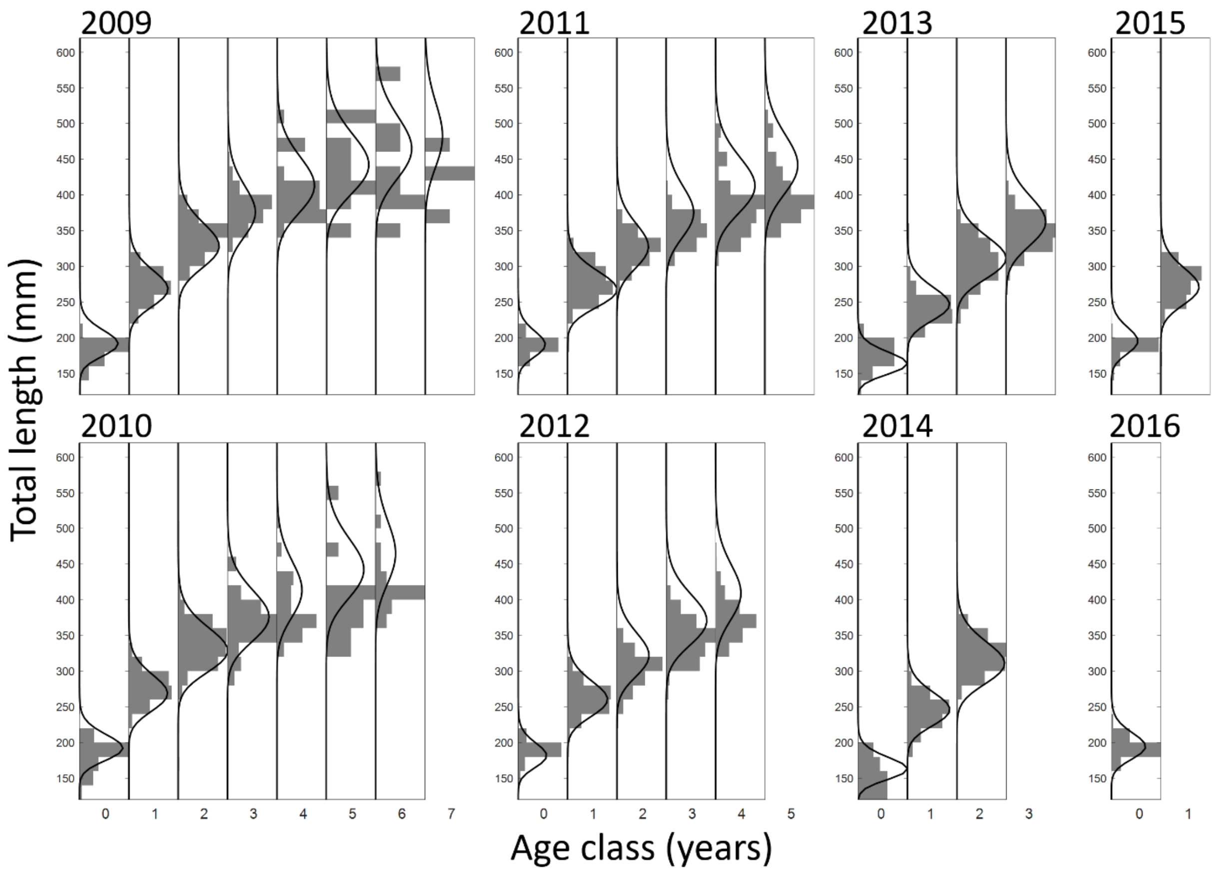


Figure 7. Continued.

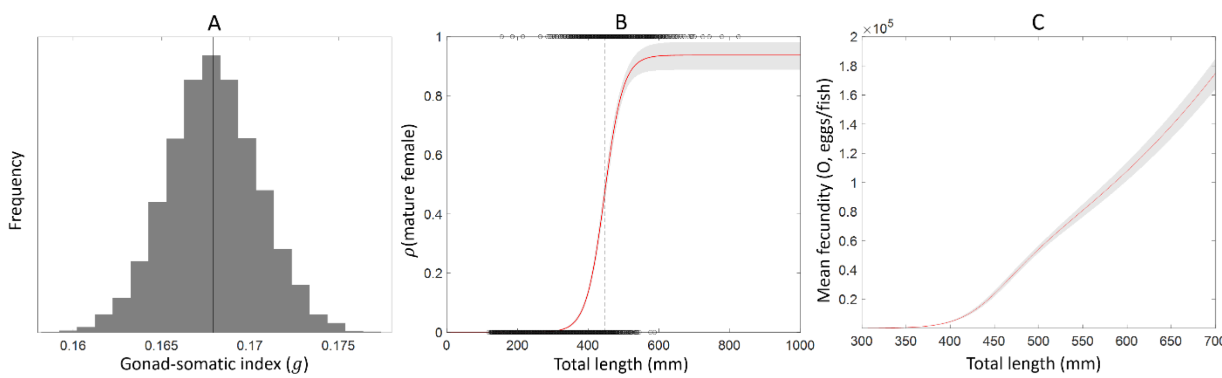


Figure 8. Reproductive parameters. (A) distribution of gonad-somatic index from the Bayesian samples, with the mean (0.168) marked by the vertical line. (B) the probability of being a mature female in the Walleye population as a function of length (red line and gray band are mean the mean curve and 95% credible interval, black dots are observed data). (C) mean fecundity per fish as a function of length (red line and gray band are mean the mean curve and 95% credible interval).

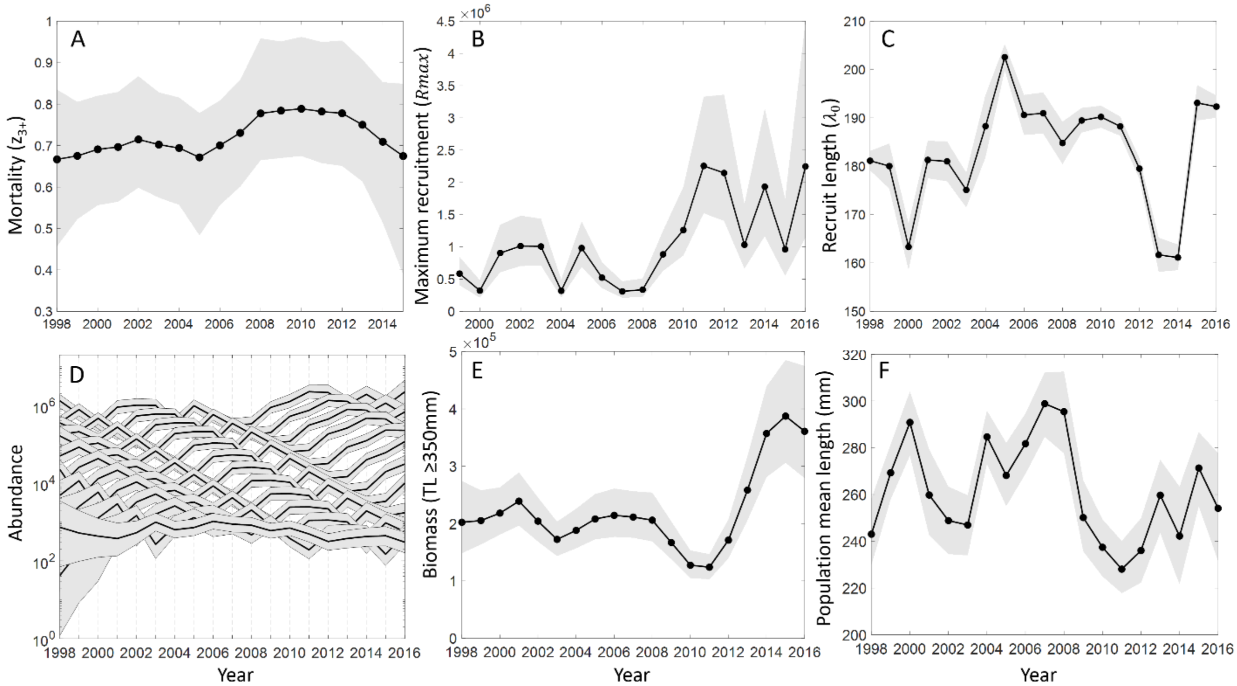


Figure 9. Annual variation in adult mortality (A), maximum recruitment (B), mean length of recruits (C), age-specific abundances (D, ages vary from 0 in the background to 12+ in the foreground)), biomass of fish larger or equal to 350mm (E), and the mean length of fish in the population (F).

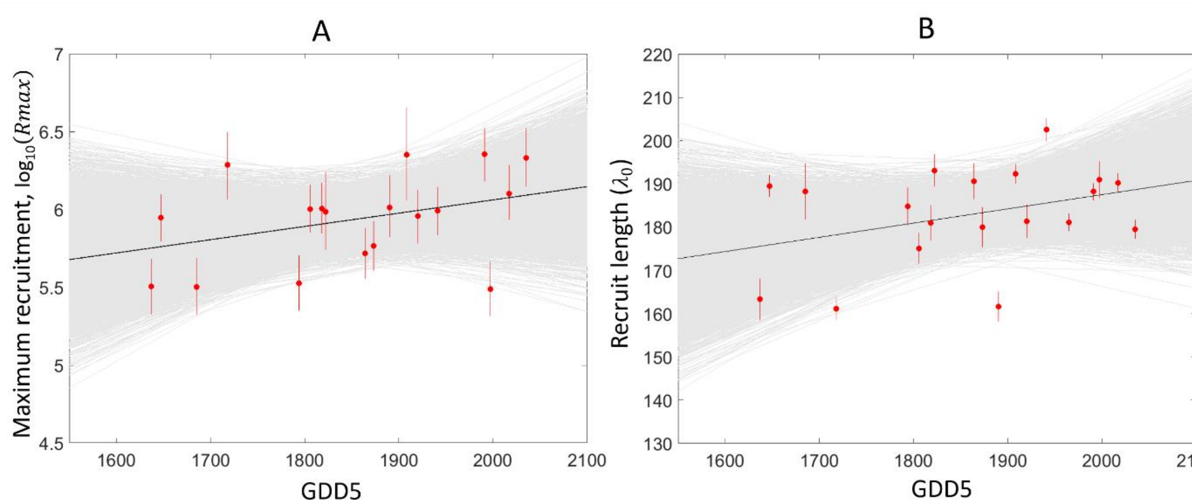


Figure 10. Estimated relationship between Growing-Degree Days (GDD5) and maximum recruitment (A, in a log-scale) and mean length of recruits (B). The black line represents the regression with mean parameter values, and gray lines are regressions from individual Bayesian samples. Red dots and whiskers are the mean and 95% credible interval for each year.

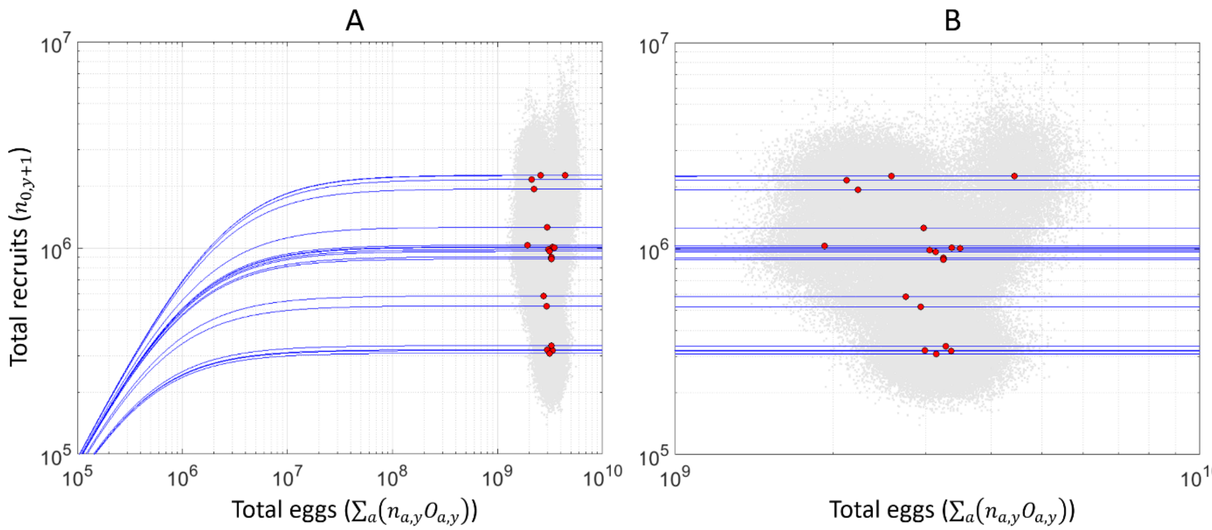


Figure 11. Stock-recruitment relationships. Each curve represents the geometric mean for a year, which goes from 1999 to 2016, based on the estimates of maximum recruitment. Red dots are the geometric means of the total number of eggs produced by adults in a given year (x-axis) and total number of surviving recruits the next year (y-axis). Gray dots are individual estimates from the Bayesian samples. In (A), the x-axis is expanded to show the position of point estimates with respect to the ascending part of the curves; in (B) the x-axis range is restricted to the region containing the point estimates and to show more clearly the relationship between total number of eggs (an index of stock size) and surviving recruits.

3 – Harvest Control Rules

The Lake Nipissing Walleye fisheries are currently managed using a harvest strategy initially implemented in 2013 (Rowe et al. 2013). The harvest control rule (i.e., a set of well-defined management actions that describe how the harvest is to be managed based on the state of a specified indicator(s) of stock status) elements of the strategy are based on the concept of maximum sustainable yield (MSY), with a precautionary target biomass which is 30% larger (target reference point of $1.3B_{MSY}$ = 406458kg) than that which produces MSY (B_{MSY} = 312660kg) with a prescribed target harvest rate of 90% MSY (i.e., 90% of 76746kg or 69071kg). Allowable harvests (for the recreational and commercial fisheries) when the biomass falls below 50% B_{MSY} (limit reference point of 78165kg) are set to zero. Between these endpoints a responsive harvest control rule adjusts exploitation with measured changes in biomass (Figure 12). Below 50% B_{MSY} some limited harvest occurs from subsistence and ceremonial purposes as well as mortality associated with incidental angling catch-and-release. All reference points were derived from the surplus-production model of Zhao and Lester (2013).

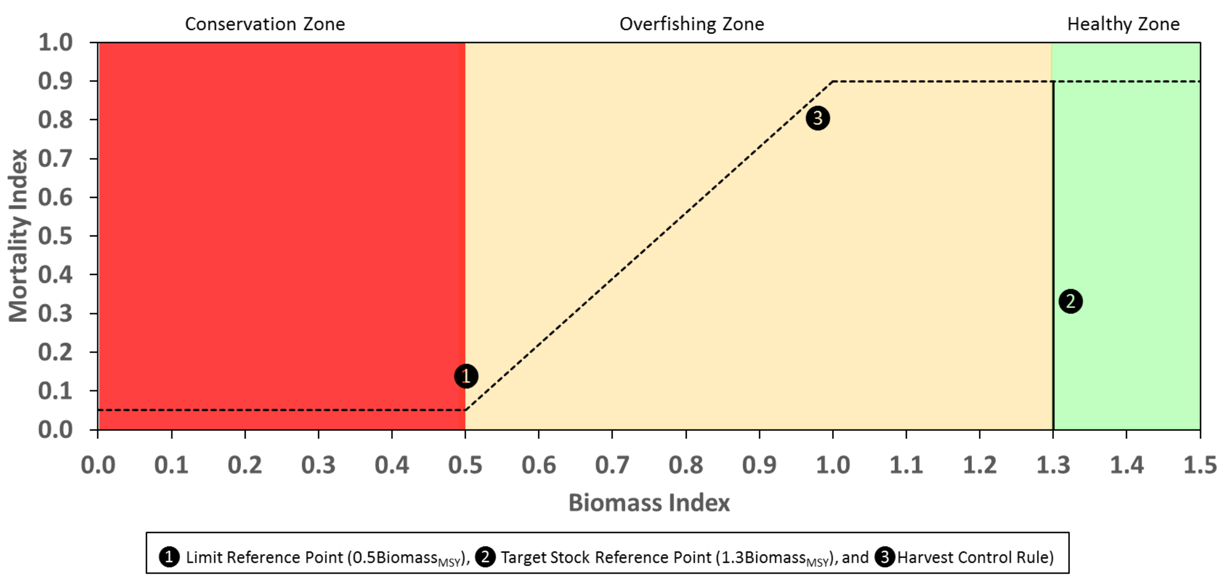


Figure 12. Schematic diagram showing the general harvest control model for managing Walleye on Lake Nipissing, including reference points (1 and 2) and conceptual harvest removal rates (dashed line, 3). Adapted from the Lake Nipissing Walleye **R**isk **A**ssessment **M**odel for **J**oint **A**daptive **M**anagement ('RAMJAM' – *in* Rowe et al. 2013, page 2). Note: The Biomass index (x-axis) = FWIN Biomass Estimate•Biomass-at-MSY^{-1} and Mortality Index (y-axis) = FWIN Z_{350}•$Z_{350\text{-at-MSY}}^{-1}$.

However, there is a hidden consequence with applying this harvest control rule. In order to maintain the constant harvest rate of 90% MSY when the population is above the B_{MSY}, the fishing mortality rate (F) will have to decline (example using F_{MSY} in Table 4) from F_{MSY} = 0.25 at B_{MSY} to F=0.19 at the management target ($1.3B_{MSY}$). It is unlikely given the open access to the recreational and commercial fisheries that management efforts will be able to reduce fishing mortality when there are more Walleye in Lake Nipissing.

Table 4. Estimates of instantaneous and annual mortality rates required to maintain a constant harvest of maximum sustainable yield when biomass levels are $\geq B_{MSY}$. B_{MSY} and F_{MSY} from Zhao and Lester (2013) and described in Rowe et al. (2013).

Biomass (B_{MSY} = 312660kg)	Instantaneous Mortality Rates			Annual Mortality Rates	
	Z=M+F (Total)	M (Natural)	F (Fishing)	A (Annual)	*u* (Exploitation)
B_{MSY}	Z_{MSY} = 0.49	0.24[1]	F_{MSY} = 0.25	39%	20%
1.1B_{MSY}	0.47		0.23	37%	18%
1.2B_{MSY}	0.45		0.21	36%	17%
1.3B_{MSY} (Target)	0.43		0.19	35%	16%
1.4B_{MSY}	0.42		0.18	34%	15%
1.5B_{MSY}	0.41		0.17	33%	14%

1. Natural mortality estimated from Lester et al. 2014.

The Bayesian state-space model estimates a stock-recruitment relationship with broader variation in the number of recruits (Age-0) compared to the variation in the total number of eggs produced by the adult stock (Section 2, Model description, Figure 11). This indicates that environmental factors affecting the carrying capacity of recruits were dominant when compared to variation in the reproductive potential of the adult stock given the amount of contrast in the data presently available. This appears to make the Walleye in Lake Nipissing very resilient (i.e., the capacity of a population to respond to a perturbation or disturbance by resisting damage and recovering quickly) to fishing mortality. Based on these results a revised harvest control rule is being proposed for Lake Nipissing Walleye (Figure 13).

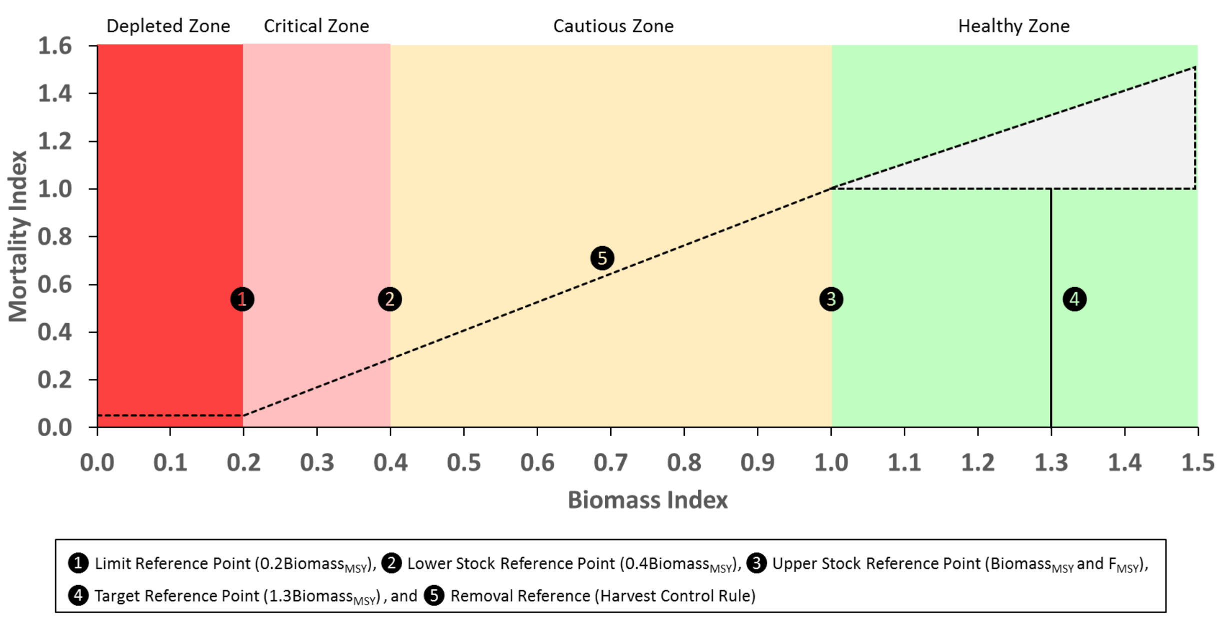


Figure 13. Schematic diagram showing the proposed harvest control model for managing Walleye on Lake Nipissing, including reference points (1 to 4) and conceptual harvest removal rates (dashed line, 5).
Note: The Biomass index (x-axis) = FWIN Biomass Estimate•Biomass-at-MSY^{-1} and Mortality Index (y-axis) = FWIN Z_{350}•$Z_{350\text{-at-MSY}}^{-1}$.

Under the proposed harvest control rules, the Lake Nipissing Walleye biomass (as measured in the FWIN surveys) declined to low levels in 2009 with high levels of fishing mortality (the critical zone) (Figure 14). This condition (defined as overfished with unsustainable fishing mortality) continued to 2013. With the change in angling regulations beginning in the open water period of 2014 and the implementation of the first memorandum of understanding between OMNRF and NFN in 2016, the biomass began to rapidly increase and fishing mortality declined significantly (the cautious zone) from 2015 to the present.

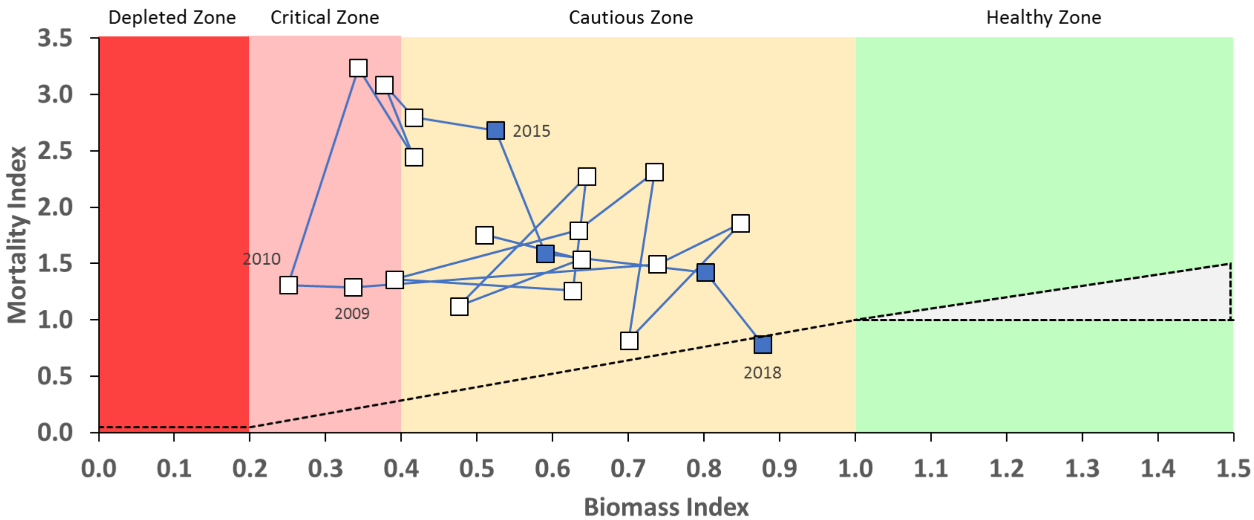


Figure 14. Proposed harvest control rules and Walleye stock status trajectory based on the 1998 to 2018 FWIN fisheries-independent data (boxes joined by blue line). The 2015 to 2018 data points (filled blue boxes) are the years when further restrictions were applied to both the angling and commercial fisheries. Note: The Biomass index (x-axis) = FWIN Biomass Estimate•Biomass-at-MSY^{-1} and Mortality Index (y-axis) = FWIN Z_{350}•$Z_{350\text{-at-MSY}}^{-1}$.

3.1 – Operational harvest control rules

The proposed harvest control rule requires that there is an identified, pre-agreed course of management action as a function of identified stock status (and possibly) other economic or environmental conditions. This report recommends an empirical harvest control rule, where the indicators come from direct measures of stock status – biomass (kg) and mortality (both for Walleye ≥350mm total length). However, the results from the Bayesian model suggest that biomass is the most important indicator to inform management decisions.

To apply the proposed harvest control rule it is necessary to determine the biomass index (index netting estimate, B_{obs} divided by B_{MSY}); where B_{obs} is the area-weighted (for the shallow, 2-5m and deep 5-15m depth strata in the annual FWIN survey corrected for catchability) biomass (kg) of Walleye ≥350mm total length, and B_{MSY} is 312660kg;

- If $B_{obs}/B_{MSY} \leq 0.2$ (Depleted Zone, point ❶ on Figure 13) recreational angling is catch-and-release only and there is no commercial fishery. There will be some fishing mortality associated with incidental harvest from sustenance fishing and release mortality from anglers [7% hooking mortality by number in the winter (Twardek et al. 2018) and ~2% in the open water period (Reeves and Bruesewitz 2007)].

- If $B_{obs}/B_{MSY} > 0.2$ but ≤ 0.4 (Critical Zone, point ❷ on Figure 13) recreational angling is catch-and-release only and there is a limited commercial fishery (total annual harvest from all fisheries <10000 kg).

- If $B_{obs}/B_{MSY} > 0.4$ but <1.0 (Cautious Zone, point ❸ on Figure 13) the angling rule is a 460mm minimum size limit (creel limit of 2 fish•day^{-1}) and there is a limited commercial fishery (<20000 kg).

Note: this is the angling rule and safe harvest ceiling established for the NFN commercial fishery which resulted in the rapid recovery seen in Figure 3.

- If $B_{obs}/B_{MSY} \geq 1.0$ (Healthy Zone. point ❹ on Figure 13) then the fisheries will be managed at $\geq F_{MSY}$ (i.e., the grey triangle are on Figure 2 where $F_{MSY} = 0.25$ *in* Rowe et al. 2013, page 5; total annual harvests from all fisheries ≥75000kg). Possible choice of angling rule depends on the future recruitment levels and declared commercial harvest target.

4 – Recreational Angling Simulations and Performance Indicators

The Bayesian state-space model was used to make projections of Walleye population dynamics in the lake under different fisheries regulation and recruitment scenarios. Each fisheries regulation scenario, described in Section 4.1, was characterized by a distribution of fishing mortality values that were estimated separately from creel surveys, which have been carried out in the lake for over 30 years (Section 4.2). The variability of projected population outcomes within each scenario, which were used to generated indicators such as the probability of reaching a biomass target, emerge from the predictive Bayesian distribution that results from the estimated MCMC samples described in Section 2.

4.1 – Recreational angling rules

In preparation for this report Ontario Ministry of Natural Resources and Forestry staff were canvassed for their opinions of possible recreational angling regulations that could be applied to a recovered Lake Nipissing Walleye population (because under the current 460mm minimum size limit, 2 fish creel limit – and other commercial harvest control measures - the Walleye population is nearing the management recovery target of $1.3B_{MSY}$ or 406458 kg). A series of 11 possible angling regulations were chosen for simulation (Table 5) ranked from least restrictive (no size limit with a 2 fish creel limit) to most restrictive (450-to-500mm fishable slot size limit with a 2 fish creel limit).

Table 5. Candidate list of recreational angling regulations for Lake Nipissing Walleye[1].

←More restrictive angling regulations←	No size limit with 2 fish creel limit
	Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm
	2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm
	400-to-600mm protected slot size limit with 2 fish creel limit
	Current FMZ 11 regulation – 430-to-600mm protected slot size limit with 4 fish creel limit and 1 fish >600m
	400mm minimum size limit with 2 fish creel limit
	Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit
	400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
	450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit
	400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit
	450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit

1. All size limits refer to total length which is a measure from the tip of the mouth with the jaws closed **to** the tip of the tail, with the tail fin lobes compressed to give the maximum possible length.

4.2 – Methods

To project population dynamics into future years for a given fisheries scenario, future mortality values based on expected changes in angling pressure resulting from a prescribed fishing regulation were estimated. Adult mortality levels of age 2 and older (z_{2+}) were determined based on the estimates from the three last years of data (2016-2018): $z = [0.6359_{2016}, 0.5950_{2017}, 0.4344_{2018}]$. These years are the first 3-year memorandum-of-understanding agreement between OMNRF and NFN. Angling mortality ($F_{ang}, year^{-1}$) was modelled as 40% of fishing mortality, which is the average proportion of the annual harvest by angling from 1995 to 2018 (Appendix 2; $\text{average}_{1995\text{-}2018}$ = 40%, $\text{minimum}_{1995\text{-}2018}$ = 11%, $\text{maximum}_{1995\text{-}2018}$ = 84%, 95% confidence interval = 8%), i.e.,

$$F_{ang} = 0.4(z - 0.24) \qquad (1)$$

where 0.24 is the assumed natural mortality, which was estimated using the Walleye life history model of Lester et al. (2014) and is similar to estimates presented in Morgan (2013). To calculate the new angling mortality level resulting from a change in size and creel limits, the expected ratio between the amount of harvest under new (H_{NEW}) and the current (H_{OLD}) regulation was estimated using the creel data. The new angling mortality was calculated as the original angling mortality multiplied by a function of the ratio $\frac{H_{NEW}}{H_{OLD}}$.

First, consider the function $f\left(\frac{H_{NEW}}{H_{OLD}}\right)$ as the ratio itself, i.e., $f\left(\frac{H_{NEW}}{H_{OLD}}\right) = \frac{H_{NEW}}{H_{OLD}}$; for instance, if H_{NEW} is twice as high as H_{OLD}, the new angling mortality would be $2F_{ang}$. Although it makes intuitive sense, it leads to unrealistically high mortality estimates when derived from the creel data using the method outlined below. Therefore, a nonlinear function had to be used to keep estimated mortalities within realistic bounds.

To estimate the harvest ratio $\frac{H_{NEW}}{H_{OLD}}$, the creel data from the 1980's was used, during which time there was no size limit and a relatively large creel limit of 6 fish•angler^{-1}•trip^{-1}. This allows for the simulation of situations that could apply to any new regulation. The procedure was as follow:

(i) For each fishing trip 3 hours or longer, a body length value was attributed to each harvested Walleye. Length values were drawn with replacement (bootstrap) from all available Walleye measurements from the 1980's winter and open water creel surveys.

(ii) The size regulations were then applied to each fishing trip. For the current regulation (460 minimum size, 2 fish creel limit), all fish smaller than 460mm were firstly excluded from the catch. If the remaining harvest exceeded the creel limit of 2 fish•angler^{-1}, the excess was excluded. In general, the size restriction was already enough to limit the harvest below 2fish•angler^{-1}, so the creel limit had no or little effect for the simulated harvest under the current regulation. For the new regulation, a similar procedure was used: first the size limit was applied, then any harvest exceeding the creel limit was excluded from the trip. Creel limits were applied to larger fish first, then to the remaining, smaller fish. As an example, take the FMZ 11 Base Regulation (430-to-600mm protected slot size limit, 4 fish creel limit with only 1 of the 4 fish >600mm). If a trip simulation with two anglers had originally harvested 9 fish >600, 10 fish between 430 and 600, and 5 fish <430, then the new harvest for that trip would be 7 (only 2 allowed fish >600, and all fish <430).

(iii) H_{OLD} and H_{NEW} were then calculated by summing the simulated harvest across fishing trips. The procedure was repeated for each Bayesian sample from the model providing a total of 10000 bootstrap draws, which added some variability to mortality estimates.

The new adult mortalities were then calculated, for each Bayesian sample, as:

$$z_{2+}(\text{new}) = z - F_{ang} + F_{ang} f\left(\frac{H_{NEW}}{H_{OLD}}\right) \qquad (2)$$

The function $f\left(\frac{H_{NEW}}{H_{OLD}}\right)$ was chosen to meet the following criteria:

(i) It is monotonically increasing, i.e., larger harvest ratios result in larger function values;

(ii) A maximum total mortality $z_{2+}(\text{new}) = 1$ is reached when the harvest ratio is equal to the maximum possible. The maximum ratio is around 8.5, which is the sum of all harvested Walleye during the 1980's without any fishing restriction (i.e., original data), divided by the mean simulated total harvest under current fishing regulation (i.e. mean H_{OLD}). For the year with highest mortality within the period 2016-2018 (z = 0.636, in 2016), the function value leading to a new total mortality of 1•year^{-1} is around 2.53. This is done by setting $z_{2+}(\text{new}) = 1, z = 0.636$, and solving Equations (1) and (2) for $f\left(\frac{H_{NEW}}{H_{OLD}}\right)$. The maximum mortality was set to 1•year^{-1} because it is close to the maximum Bayesian 99% percentile estimated for the 1998-2015 time series. This value is also close to the maximum z_{350} from the whole period 1967-2018, based on independent age distribution estimates (Morgan 2012).

(iii) The function crosses the (1,1) coordinate, which means a harvest ratio of 1 (no expected change in total harvest by changing regulation) will result in no change in total mortality.

A simple function that satisfies all three criteria is a power function of the type $f(x) = x^b$, and the exponent b can be calculated by imposing the coordinate (8.5,2.53) as specified by criteria (ii). It resulted in:

$$f\left(\frac{H_{NEW}}{H_{OLD}}\right) = \left(\frac{H_{NEW}}{H_{OLD}}\right)^{0.4337} \qquad (3)$$

The function is plotted in Figure 15. This function works as “buffer”: whenever harvest ratios are larger than 1, the final estimates of mortality are lower than the expected if a simple linear conversion was used, and vice-versa. The function is purely phenomenological though, a mathematical adjustment to keep mortality estimates within reasonable bounds. The mechanisms behind this curve are unknown and can be numerous. For instance, anglers might want to fish harder under more restrictive regulations (such as the current 460mm minimum limit), and this is not incorporated in the process of simulating the regulation from the 1980’s data. Indeed, the average time spent fishing (duration of fishing trip per angler) was longer during 2015-2018 (5.3 hours) than during the 1980’s (4.9 hours), considering trips longer than 3 hours. This difference is still small to account for the strong curvature of the resulting function in Equation (3), so other factors must be at play.

Finally, to simulate dynamics for years 2016-2018, the same values of mortality z as in the “Current – 460mm minimum size limit” regulation were used. Randomly drawing from the three available values (one for each year of z) was applied for future years z_{2+}(new).

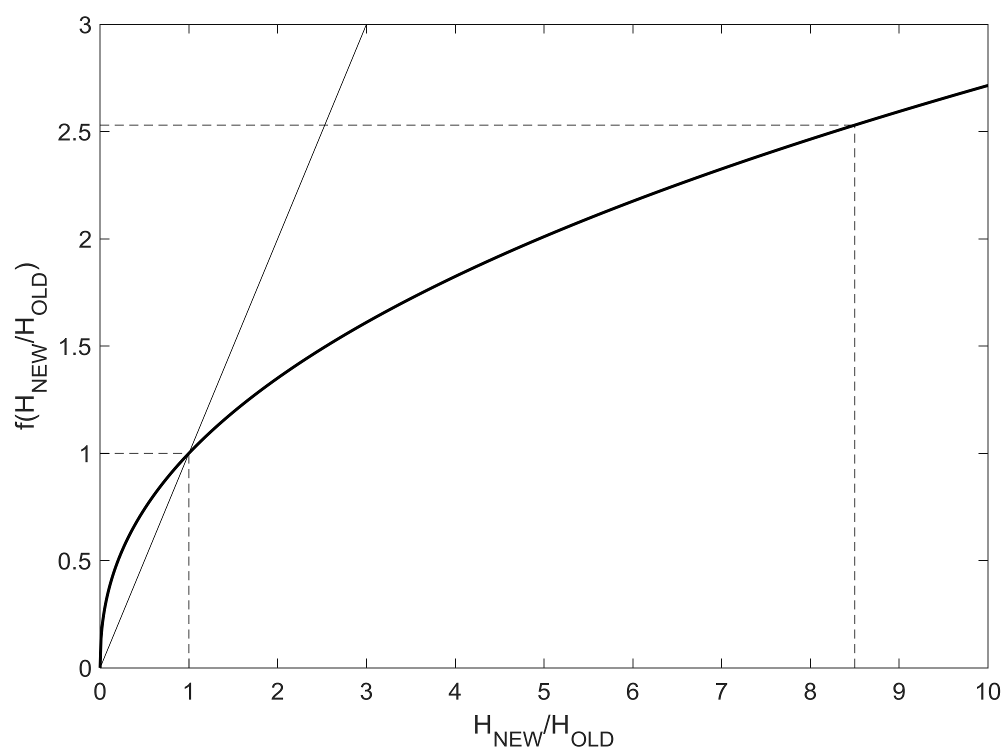


Figure 15. Function used to convert harvest ratios simulated from the creel data (x-axis) into a multiplier of angling mortalities, which in turn are used to calculate new total mortalities according to Equation (2). The function is plotted as the thick curve. The dashed lines mark the coordinates (1,1) and (8.5,2.53) as specified by criteria (ii) and (iii) above; and the thin diagonal line is the 1:1 line.

Results from the Bayesian model suggests that Lake Nipissing Walleye have displayed two recruitment patterns (Figure 16). A period of low recruitment was experienced from 1999 to 2009 and a period of high recruitment from 2010 to 2016. The future recruitment pattern could be either low or high, so each recreational angling regulation was simulated for both low and high recruitment scenarios (1 million Age-0 recruits was used as the reference point separating the low and high recruitment patterns). Within a simulation of a given scenario, the maximum recruitment value (R_{max}) used for any given year was randomly drawn from the Bayesian estimates of years characterizing the recruitment regime (1999-2009 for a low recruitment scenario, 2010-2016 for a high recruitment scenario).

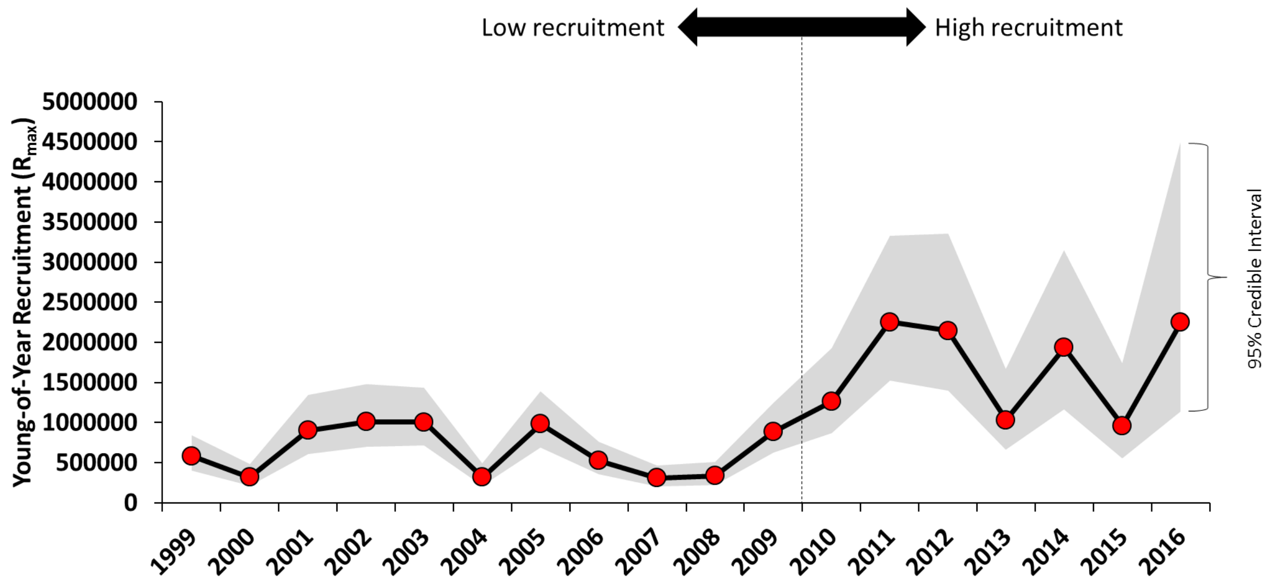


Figure 16. Young-of-year (Age-0) recruitment from Bayesian model (estimate and 95% credible interval) from 1999 to 2016.

4.3 – Performance indicators

The results from the Bayesian model simulations produce several biological performance indicators, and provide the primary information for assessment of Walleye status and risk associated with a proposed recreational angling regulation (under either low or high recruitment). The biological performance indicators used are:

i. Biomass (kg) of Walleye ≥350mm total length
ii. Probability that biomass will be above the management target ($1.3B_{MSY}$)
iii. Abundance of Walleye ≥2 years old (number)
iv. Percent of sexually mature adults (≥5 years old)
v. Adult mortality for Walleye ≥2 years old
vi. Two measures of size structure associated with the angling fishery – quality stock density (QSD) and preferred stock density (PSD) (Neumann and Allen 2007). QSD and

PSD are numerical descriptions of length frequency data and are calculated as:

$$QSD = \frac{Number\ of\ fish \geq minimum\ quality\ length}{Number\ of\ fish \geq minimum\ stock\ length}\ X\ 100, \text{ and}$$

$$PSD = \frac{Number\ of\ fish \geq minimum\ preferred\ length}{Number\ of\ fish \geq minimum\ stock\ length}\ X\ 100;$$ where minimum stock length is defined as 305mm (12 inches), minimum quality length is 381mm (15 inches), and minimum preferred length is 457mm (18 inches). Values of QSD and PSD range from 1 to 100. These lengths were chosen based on the frequency distribution of the harvested Walleye from the winter and open water creel survey measurements 1981 to 1998 (before any length size limits were imposed on the fishery). The minimum stock size is the 10% length quantile, the preferred stock size is the average length (50% percentile), and the quality stock size is the 90% length quantile of angler harvested Walleye in Lake Nipissing.

For each indicator a series of criteria were established to evaluate the level of risk (i.e., low, moderate, high or excessive) that could be associated with a proposed recreational angling regulation 5 years after implementation (i.e., 5 years after the Walleye population had reached or exceeded the management target of $1.3B_{MSY}$) (Table 6).

Table 6. Biological indicators and risk criteria.

Biomass indicator – Kilograms of Walleye ≥350mm total length

Risk	Criteria	Description
Low	$\geq B_{MSY}$	Biomass ≥ Upper reference point[1]
Moderate	$\geq 0.4B_{MSY}$ and $<B_{MSY}$	Lower reference point ≤ Biomass < Upper reference point
High	$>0.2B_{MSY}$ and $<0.4B_{MSY}$	Limit reference point ≤ Biomass < Lower reference point
Excessive	$\leq 0.2B_{MSY}$	Biomass < Limit reference point of harvest control rule

1. Reference points defined in harvest control rule where B_{MSY} = 312660 kg.

Management target indicator – Probability that biomass will be above management target of $1.3B_{MSY}$

Risk	Criteria	Description
Low	>66%	High probability that biomass is above management target
Moderate	40% to 65%	Reasonable probability that biomass is above management target
High	<40%	Low probability that biomass is above management target

Abundance indicator – Number of Walleye ≥2 years old in the population scaled to range in abundance[1]

Risk	Criteria	Description
Low	≥75%	Very high abundance
Moderate	≥50% and <75%	Above average abundance
High	≥10% and <50%$_Y$	Below average abundance
Excessive	<10%	Very low abundance

1. The 450-to-500mm fishable (harvest) slot size limit – 2 fish creel limit (high recruitment) scenario had the maximum abundance (N_{max} =1285275 Walleye ≥2 years old) while the current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm had the minimum abundance (N_{min} = 488484 Walleye ≥2 years old). Abundance indicator: $N_{criteria} = 1-(N_{max}-N_{sim})\bullet(N_{max}-N_{min})^{-1}$.

Adult (i.e., spawning stock) indicator – % of age structure ≥5 years old[1]

Risk	Criteria	Description
Low	≥8%	High proportion of adult spawners in the population
Moderate	5% to 8%	Acceptable proportion of adult spawners in the population
High	<5%	Low proportion of adult spawners in the population

1. Based on the modal age of spawning female Walleye sampled at Wasi Falls from 1968 to 2017 (i.e., a spring Walleye age 6 would be age 5 in the previous years FWIN survey).

Mortality indicator – Annual adult (≥2 years old) mortality (%) estimated from age distribution using Robson-Chapman maximum likelihood indicator (Guy and Brown 2007). Compared to quartiles and median of Lake Nipissing Walleye mortality estimates 1972 to 2018[1]

Risk	Criteria	Description
Low	<41%	< Q_{25} – Mortality near F_{MSY} (i.e., F = M or A_{MSY} = 39%)[2]
Moderate	41% to 45%	Mortality above F_{MSY} but ≤ 1972-to-2018 median (Q_{50} = 45%)
High	46% to 50%	Mortality above 1972-to-2018 median but < Q_{75}
Excessive	≥51%	≥ Q_{75} – Mortality higher than F_{ext} (i.e., F = 2M or A_{ext} = 52%)

1. Annual adult mortality rates 1972 to 2018: lower (Q_{25}) quartile = 41%, upper (Q_{75}) quartile = 51%, and median (Q_{50}) = 45%
2. Lester et al. 2014.

Quality stock density indicator – Proportion of Walleye available to anglers

Risk	Criteria	Description
Low	≥45%	Plenty of fish available to anglers
Moderate	>34% but <44%	Some fish available to anglers
High	≤33%	Fewer fish available to anglers

Preferred stock density indicator – Proportion of large Walleye available to anglers

Risk	Criteria	Description
Low	≥15%	Plenty of large fish available to anglers
Moderate	>10% but <14%	Some large fish available to anglers
High	≤9%	Fewer large fish available to anglers

4.4 – Results

Results from the Bayesian model suggest that under the current harvest controls (i.e., 460mm minimum size limit and 2 fish limit for the recreational angling fisheries, and the measures stipulated in the Nipissing First Nation Fisheries Laws) the Lake Nipissing Walleye population has a high probability (>90%) of reaching its recovery target of $1.3B_{MSY}$ by the fall of 2019 (Figure 17). However, this must be interpreted as an optimistic prediction given the overestimation of growth and probably biomass during the last few years of the fitted time series (2014-2016). If the recovery is confirmed (with the 2019 FWIN survey) the suggested management direction should involve potential angling rules which will maintain the Walleye biomass $\geq 1.3B_{MSY}$ with considerations to trade-offs associated among the other indicators.

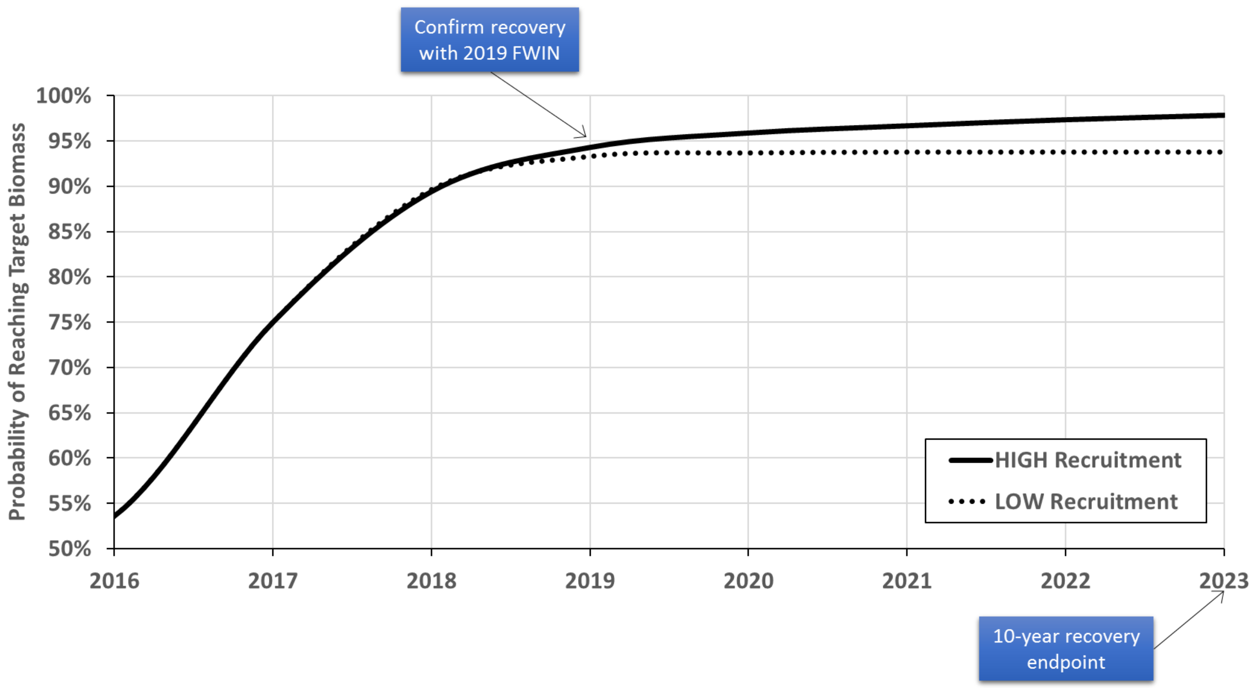
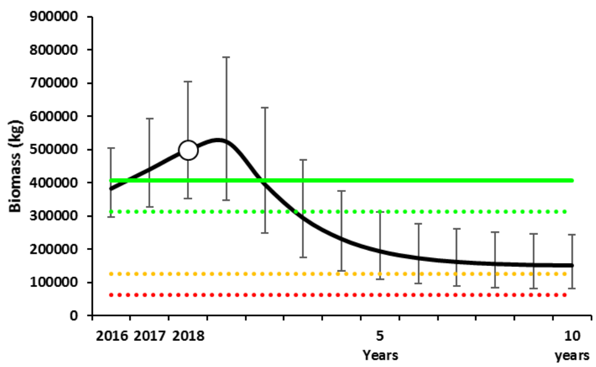


Figure 17. Cumulative probability of reaching the management recovery target biomass ($1.3B_{MSY}$) under either low or high recruitment. The probabilities were calculated from low recruitment (using MCMC values from 1999 to 2009) or high recruitment (using MCMC values from 2010 to 2016) (Figure 16).

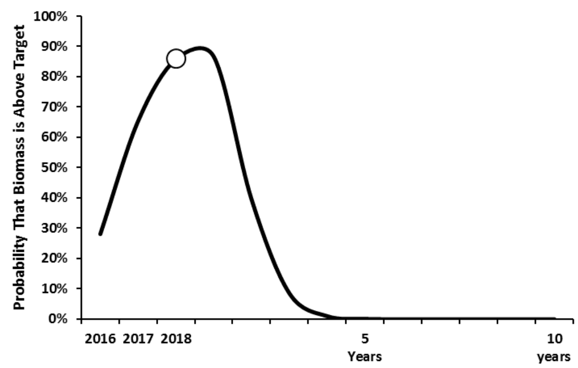
The results of the simulations from the 11 proposed regulations for the low and high recruitment pattern are summarized in Figure 18 and Table 7 using the indicators and criteria (table uses the colour codes only). The detailed results, for each indicator, from each of the 22 simulations are in Appendix 3.

Regulation: No size limit with 2 fish creel limit
Recruitment: LOW

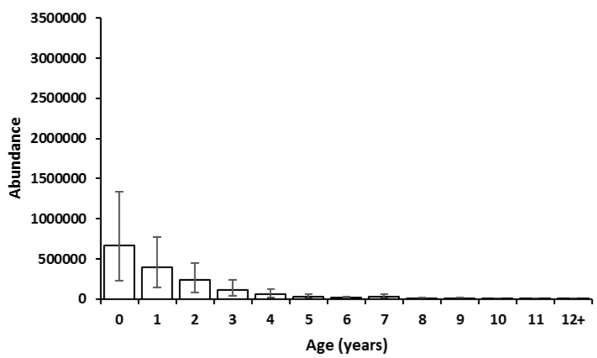
Biomass[1]



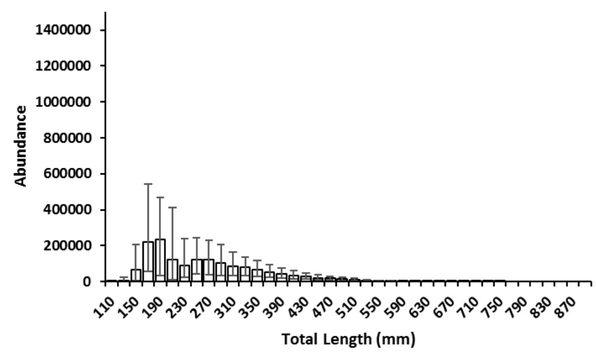
Probability of Achieving Management Target



Age Distribution



Size Distribution



1. Dotted red line is the limit reference point ($0.2B_{MSY}$), dotted orange line is the lower reference point ($0.4B_{MSY}$), dotted green line is the upper reference point (B_{MSY}), and solid green line is the management target ($1.3B_{MSY}$).

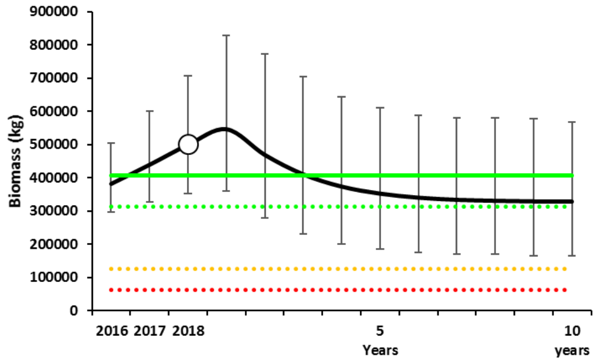
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	193516 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0010
Abundance (Number of Walleye ≥2 years old)	498794
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	44%
Quality stock density	39%
Preferred stock density	12%

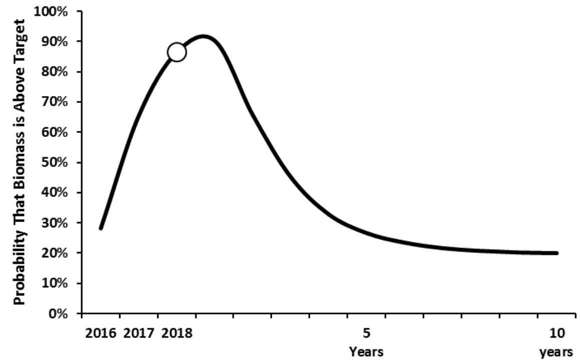
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment.

Regulation: No size limit with 2 fish creel limit
Recruitment: HIGH

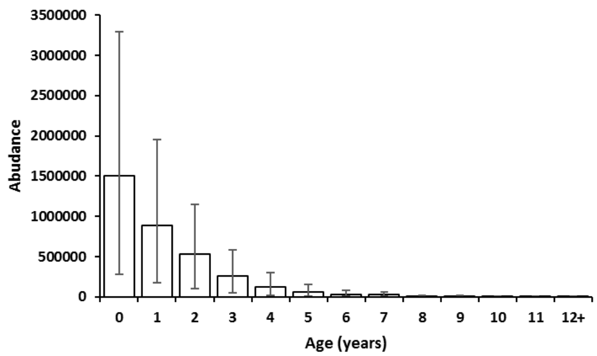
Biomass



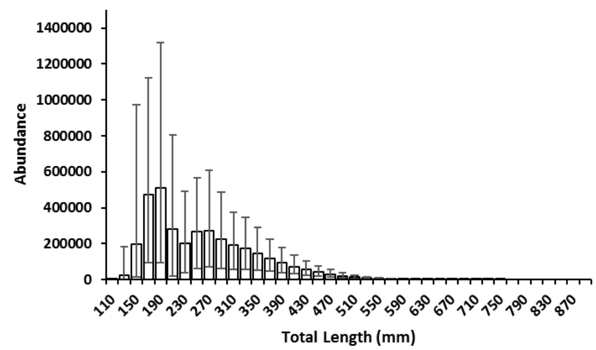
Probability of Achieving Management Target



Age Distribution



Size Distribution



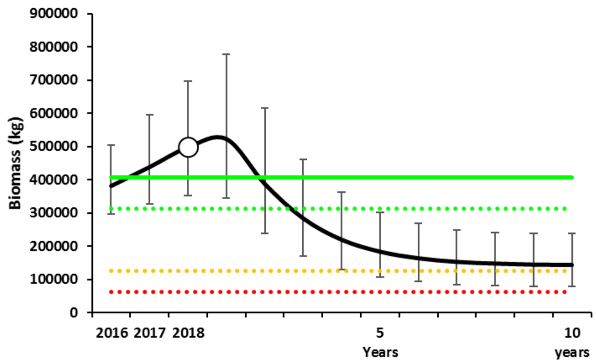
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	352870 kg
Probability that biomass will be above management target of 1.3B_{MSY}	0.2656
Abundance (Number of Walleye ≥2 years old)	1055408
Proportion of Adults (% of population ≥5 years old)	4%
Mortality (≥2 years old)	49%
Quality stock density	36%
Preferred stock density	9%

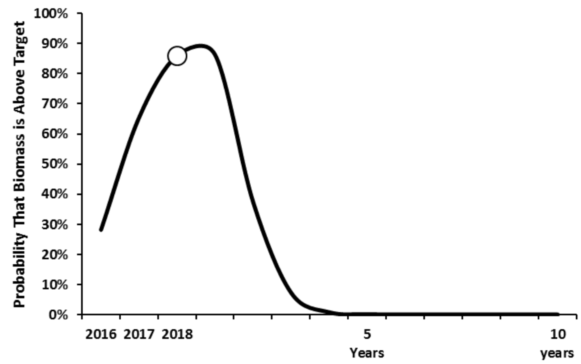
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm
Recruitment: LOW

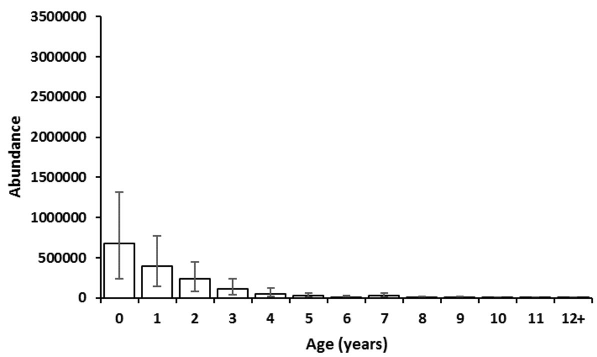
Biomass



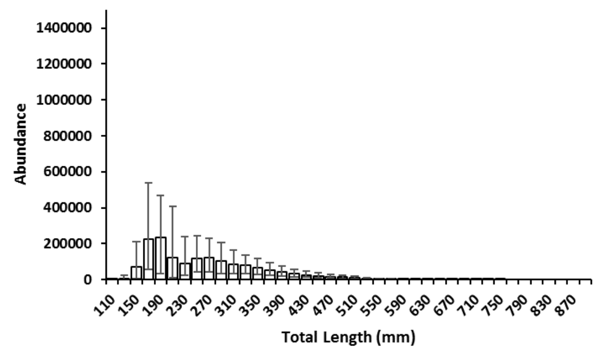
Probability of Achieving Management Target



Age Distribution



Size Distribution



Evaluation

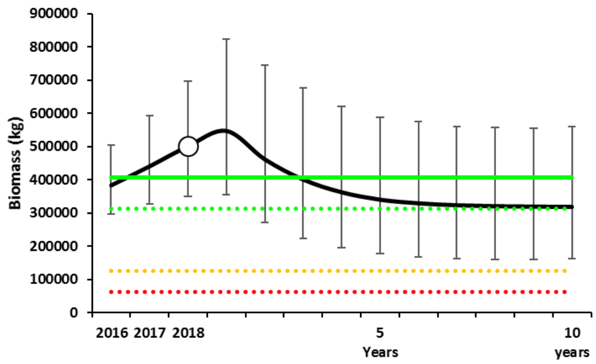
Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	185032 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0011
Abundance (Number of Walleye ≥2 years old)	488484
Proportion of Adults (% of population ≥5 years old)	5%
Mortality (≥2 years old)	45%
Quality stock density	38%
Preferred stock density	12%

Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

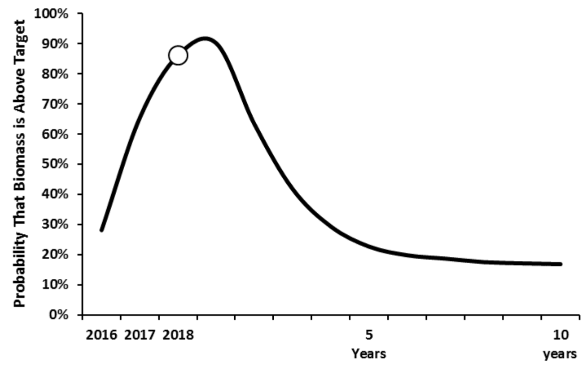
Regulation: Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm

Recruitment: HIGH

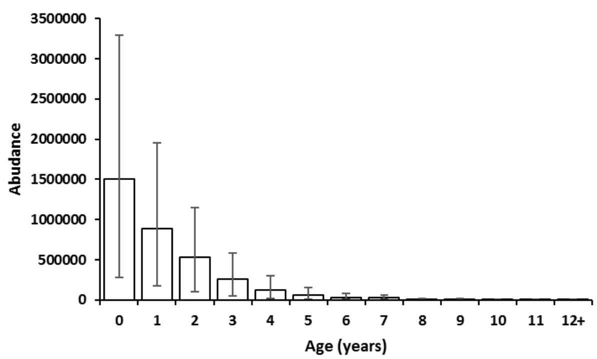
Biomass



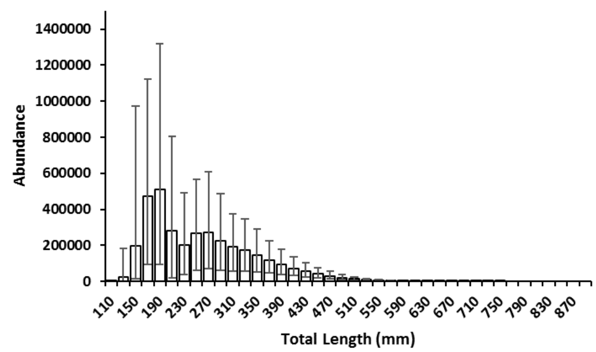
Probability of Achieving Management Target



Age Distribution



Size Distribution



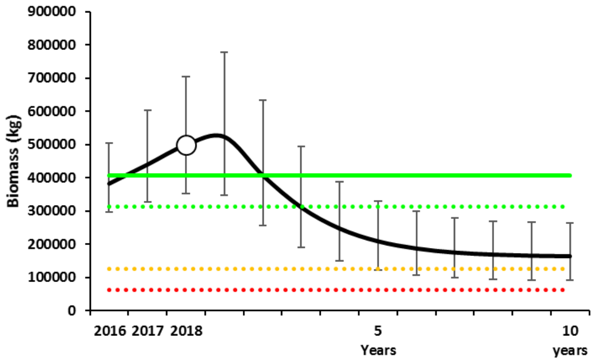
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	339456 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.2270
Abundance (Number of Walleye ≥2 years old)	1033200
Proportion of Adults (% of population ≥5 years old)	4%
Mortality (≥2 years old)	50%
Quality stock density	35%
Preferred stock density	8%

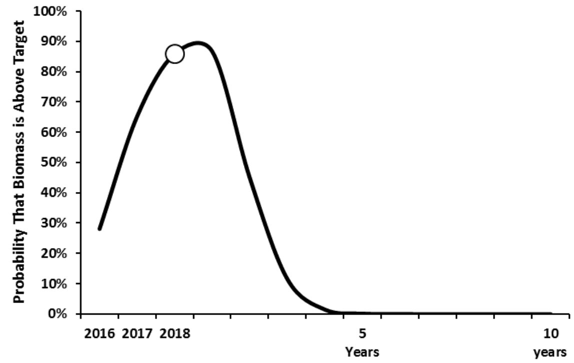
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm
Recruitment: LOW

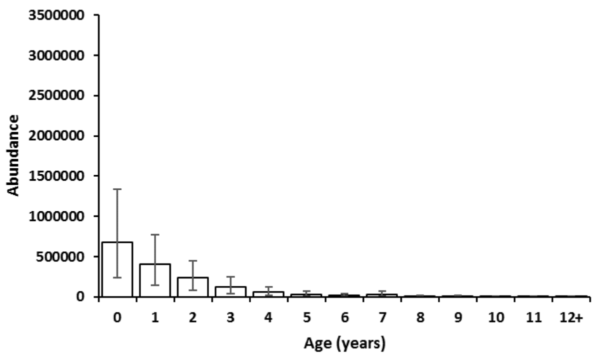
Biomass



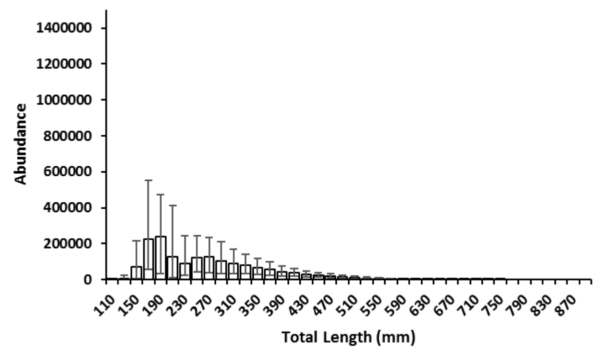
Probability of Achieving Management Target



Age Distribution



Size Distribution



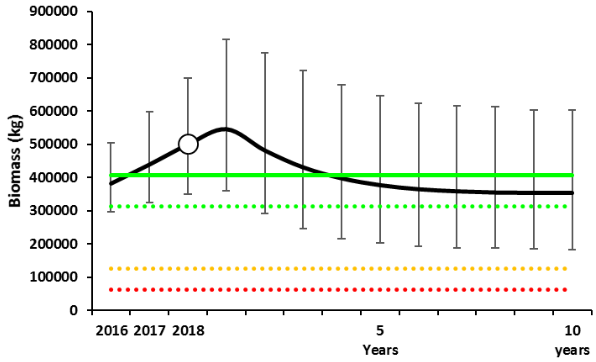
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	208982 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0020
Abundance (Number of Walleye ≥2 years old)	515889
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	42%
Quality stock density	41%
Preferred stock density	13%

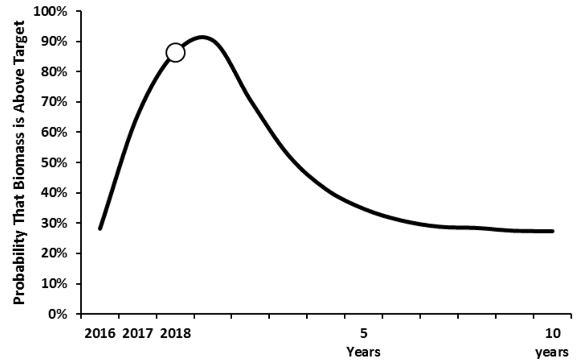
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm
Recruitment: HIGH

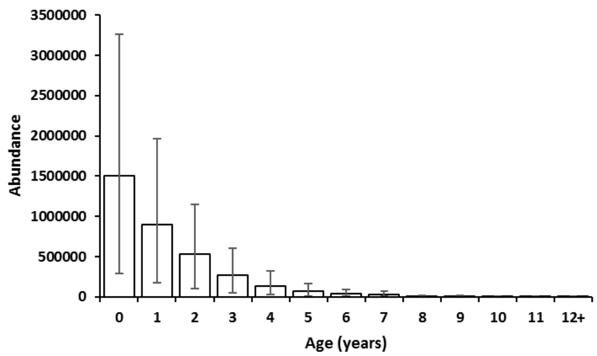
Biomass



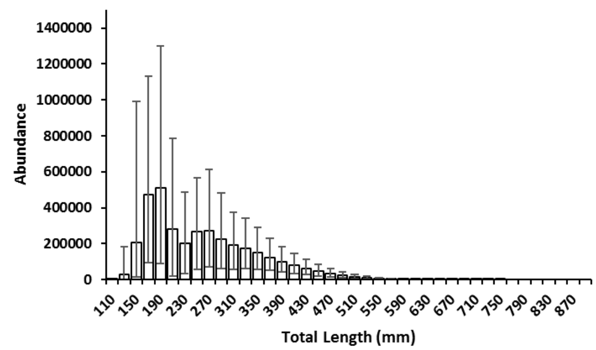
Probability of Achieving Management Target



Age Distribution



Size Distribution



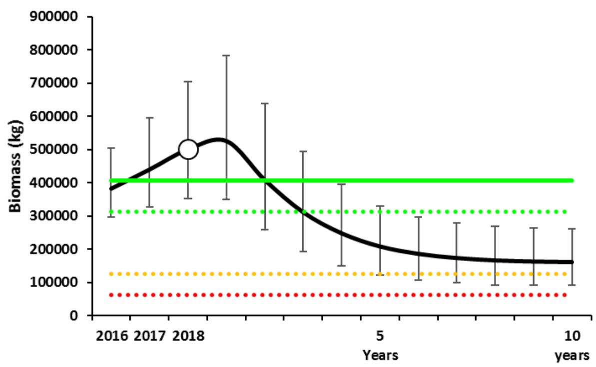
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	379338 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.3468
Abundance (Number of Walleye ≥2 years old)	1088007
Proportion of Adults (% of population ≥5 years old)	5%
Mortality (≥2 years old)	48%
Quality stock density	37%
Preferred stock density	9%

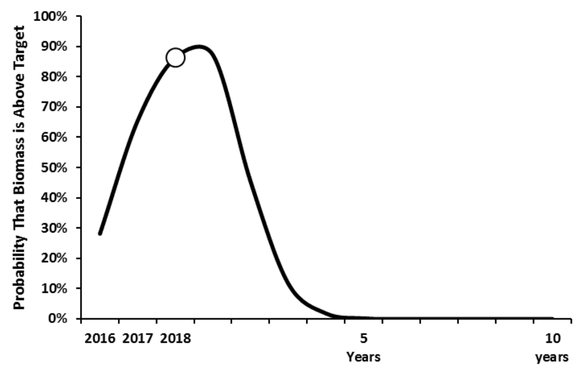
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400-to-600mm protected slot size limit with 2 fish creel limit
Recruitment: LOW

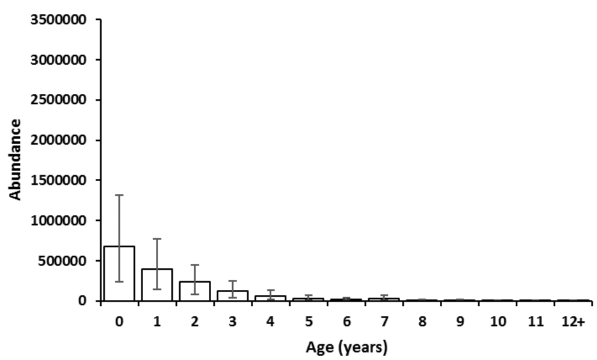
Biomass



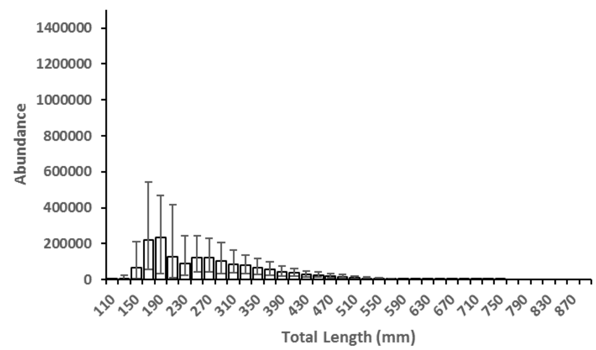
Probability of Achieving Management Target



Age Distribution



Size Distribution



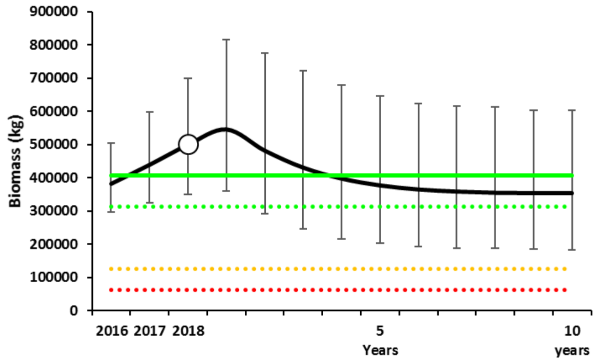
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	209395 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0022
Abundance (Number of Walleye ≥2 years old)	515204
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	42%
Quality stock density	41%
Preferred stock density	13%

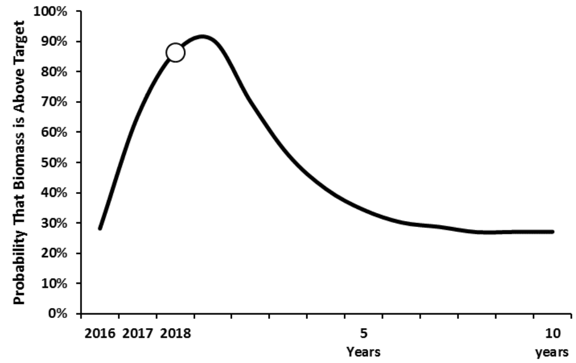
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400-to-600mm protected slot size limit with 2 fish creel limit
Recruitment: HIGH

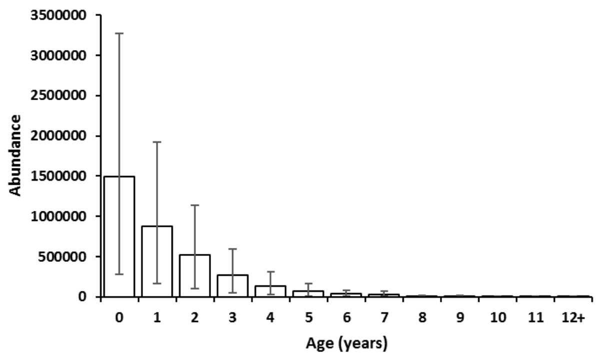
Biomass



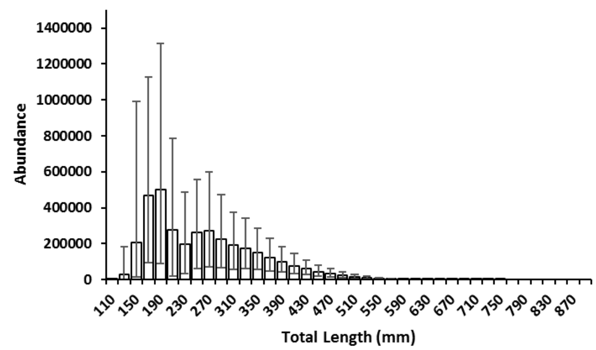
Probability of Achieving Management Target



Age Distribution



Size Distribution



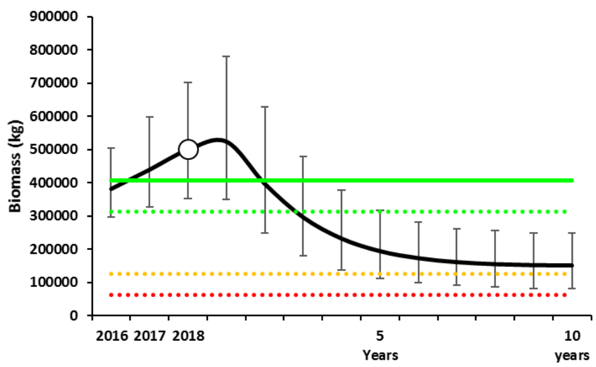
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	377514 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.3425
Abundance (Number of Walleye ≥2 years old)	1081720
Proportion of Adults (% of population ≥5 years old)	5%
Mortality (≥2 years old)	48%
Quality stock density	37%
Preferred stock density	9%

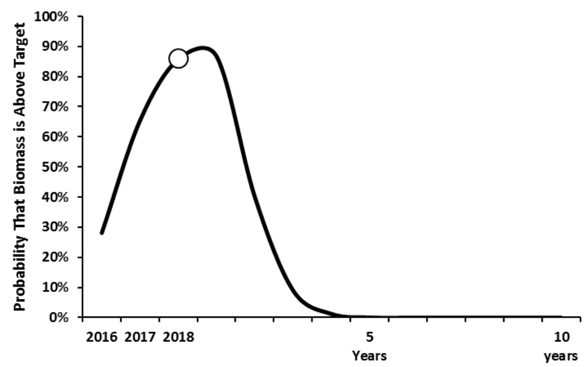
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: Current FMZ regulation – 430-to-600mm protected slot size limit with a 4 fish creel limit and only 1 fish >600mm
Recruitment: LOW

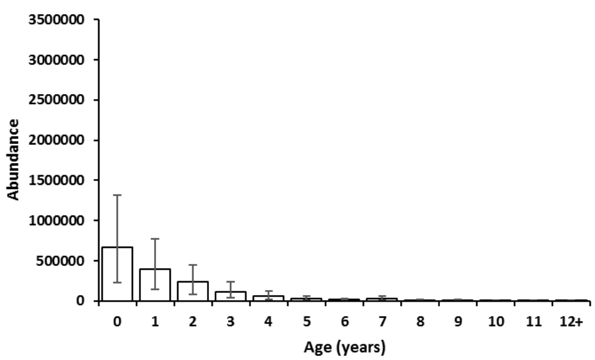
Biomass



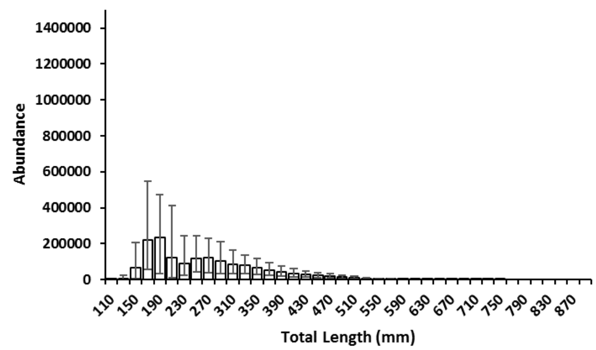
Probability of Achieving Management Target



Age Distribution



Size Distribution



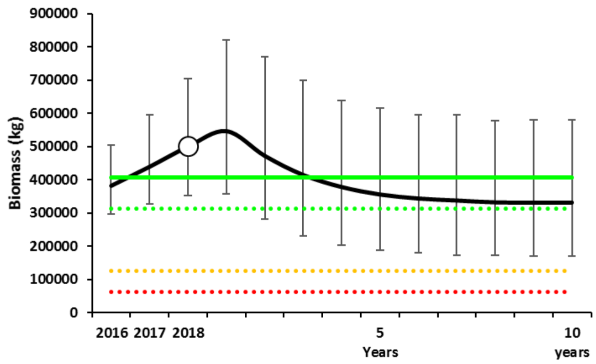
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	195637 kg
Probability that biomass will be above management target of 1.3B_{MSY}	0.0009
Abundance (Number of Walleye ≥2 years old)	500223
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	43%
Quality stock density	40%
Preferred stock density	12%

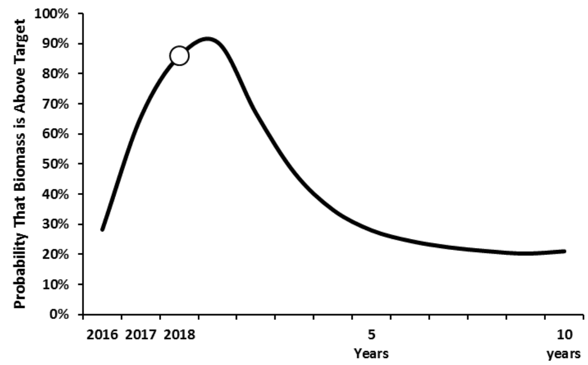
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: Current FMZ regulation – 430-to-600mm protected slot size limit with a 4 fish creel limit and only 1 fish >600mm
Recruitment: HIGH

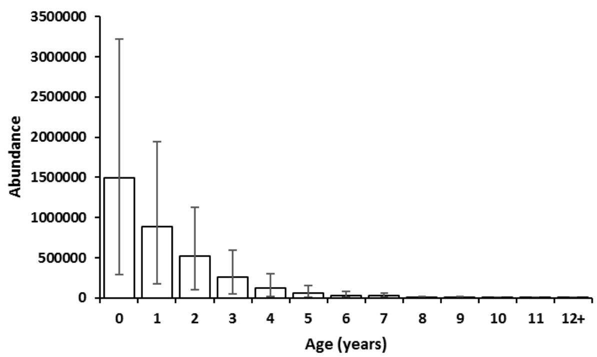
Biomass



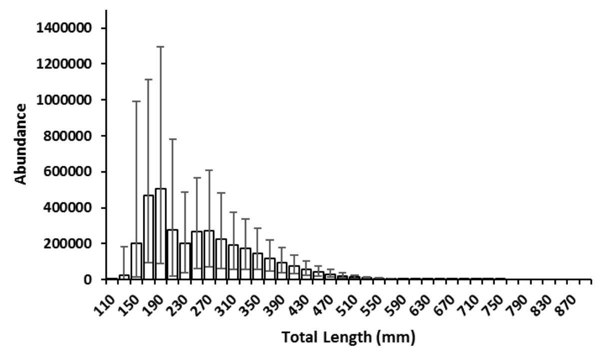
Probability of Achieving Management Target



Age Distribution



Size Distribution



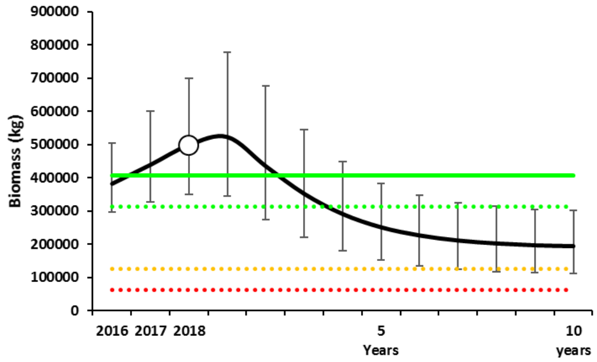
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	356230 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.2787
Abundance (Number of Walleye ≥2 years old)	1052711
Proportion of Adults (% of population ≥5 years old)	4%
Mortality (≥2 years old)	49%
Quality stock density	36%
Preferred stock density	9%

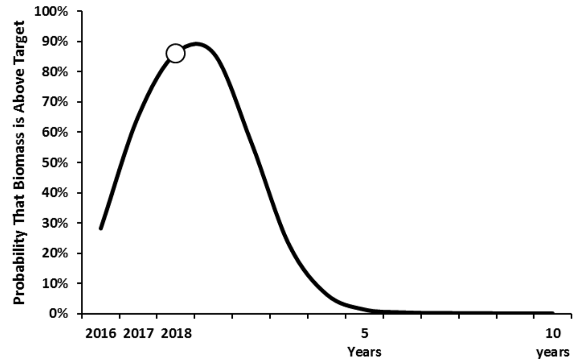
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400mm minimum size limit with 2 fish creel limit
Recruitment: LOW

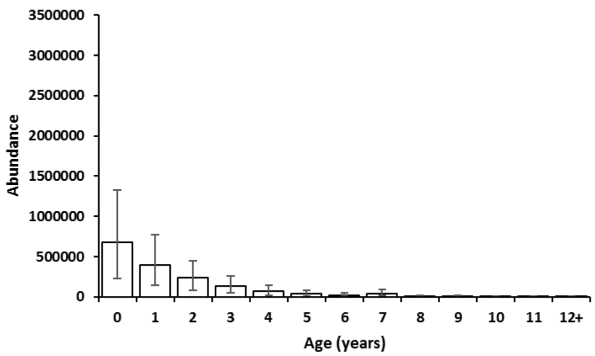
Biomass



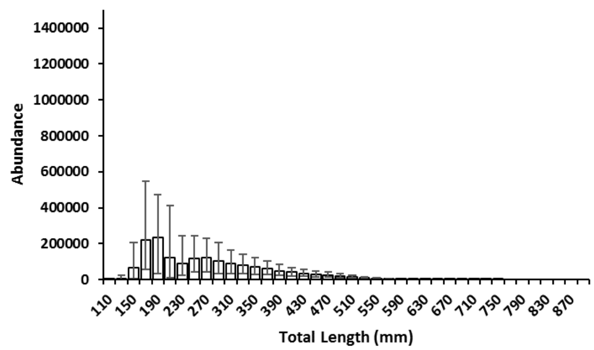
Probability of Achieving Management Target



Age Distribution



Size Distribution



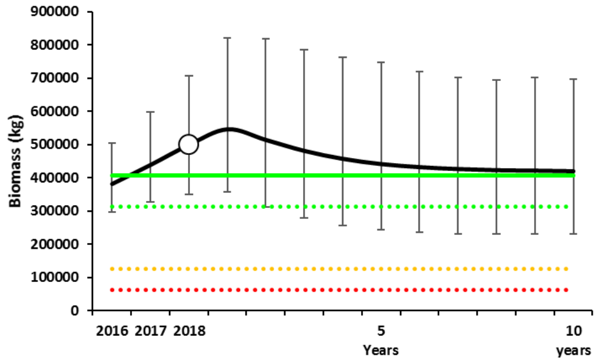
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	250816 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0132
Abundance (Number of Walleye ≥2 years old)	565317
Proportion of Adults (% of population ≥5 years old)	8%
Mortality (≥2 years old)	39%
Quality stock density	45%
Preferred stock density	16%

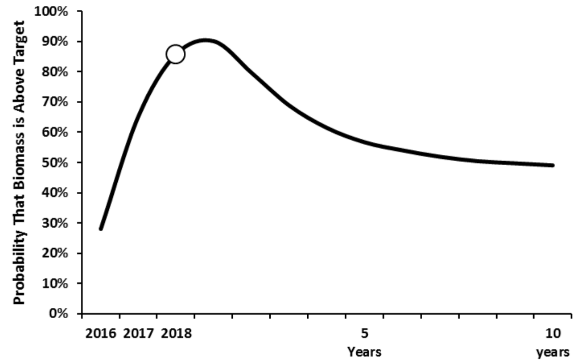
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400mm minimum size limit with 2 fish creel limit
Recruitment: HIGH

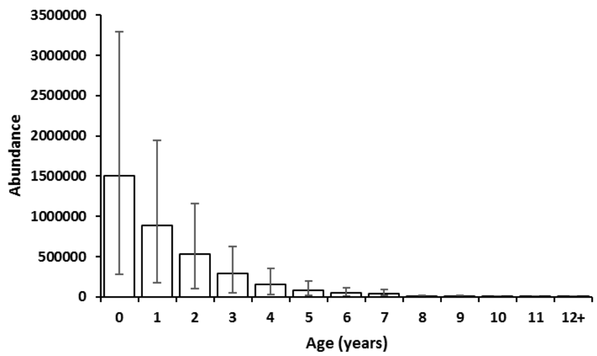
Biomass



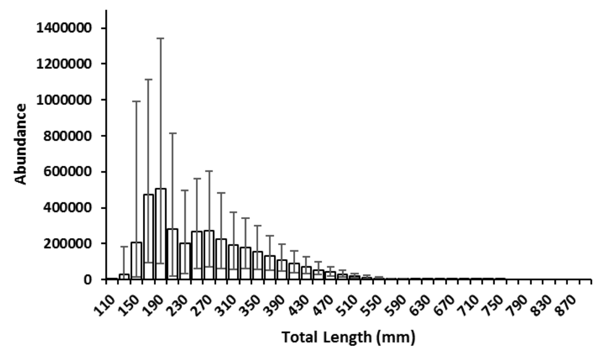
Probability of Achieving Management Target



Age Distribution



Size Distribution



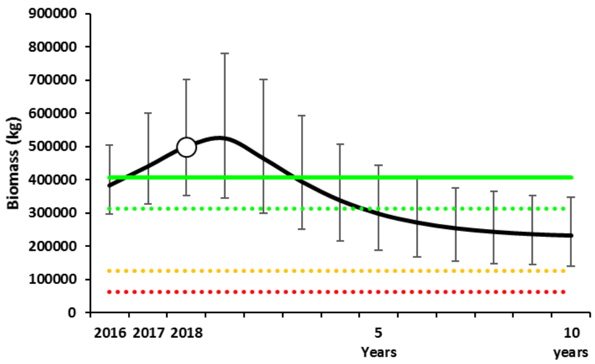
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	441993 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.5677
Abundance (Number of Walleye ≥2 years old)	1167846
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	45%
Quality stock density	40%
Preferred stock density	11%

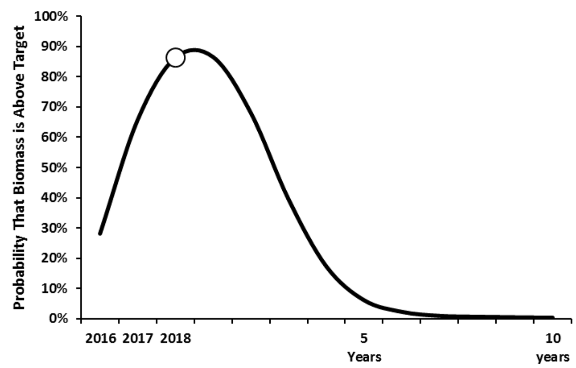
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit
Recruitment: LOW

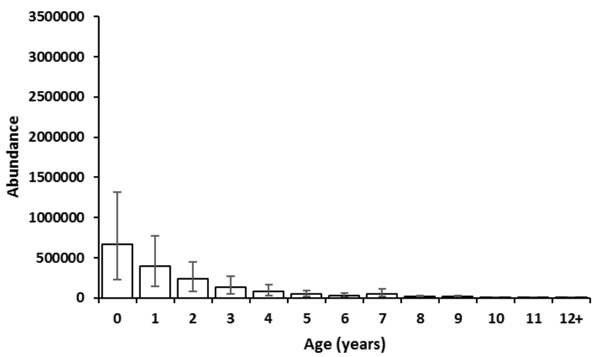
Biomass



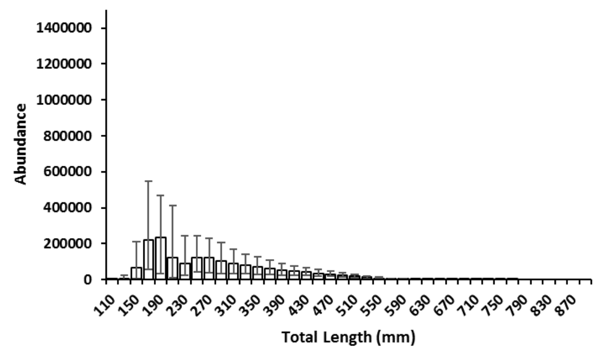
Probability of Achieving Management Target



Age Distribution



Size Distribution



Evaluation

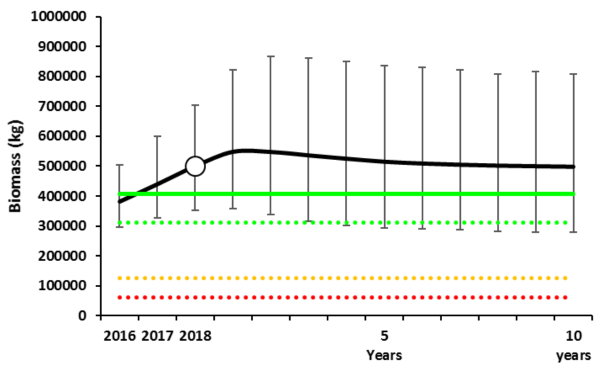
Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	297244 kg
Probability that biomass will be above management target of 1.3B_{MSY}	0.0612
Abundance (Number of Walleye ≥2 years old)	618401
Proportion of Adults (% of population ≥5 years old)	10%
Mortality (≥2 years old)	37%
Quality stock density	48%
Preferred stock density	18%

Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

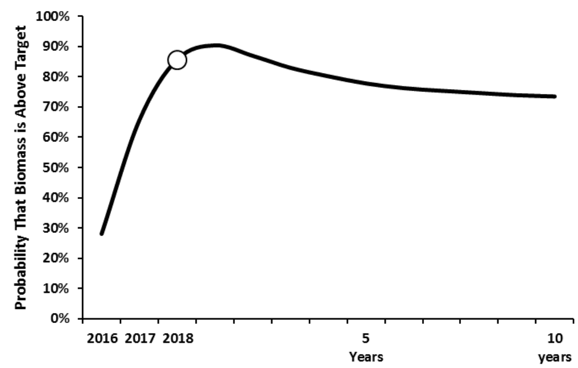
Regulation: Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit

Recruitment: HIGH

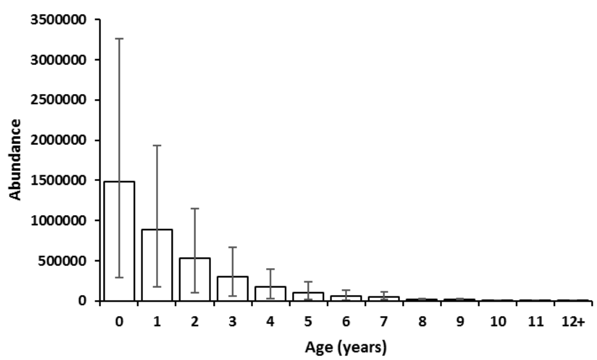
Biomass



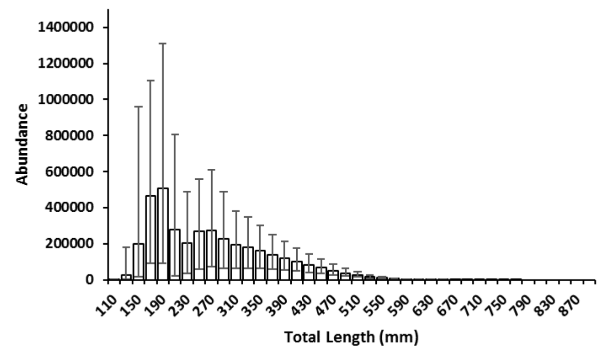
Probability of Achieving Management Target



Age Distribution



Size Distribution



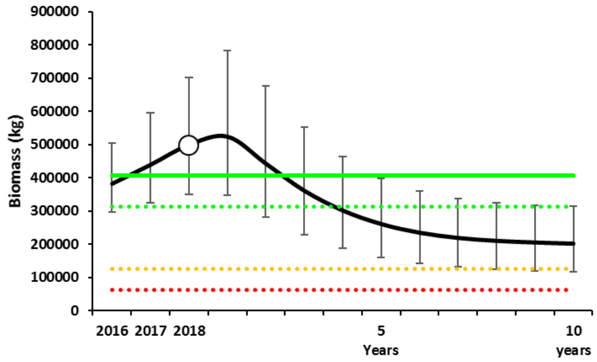
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	514354 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.7772
Abundance (Number of Walleye ≥2 years old)	1258938
Proportion of Adults (% of population ≥5 years old)	7%
Mortality (≥2 years old)	42%
Quality stock density	43%
Preferred stock density	13%

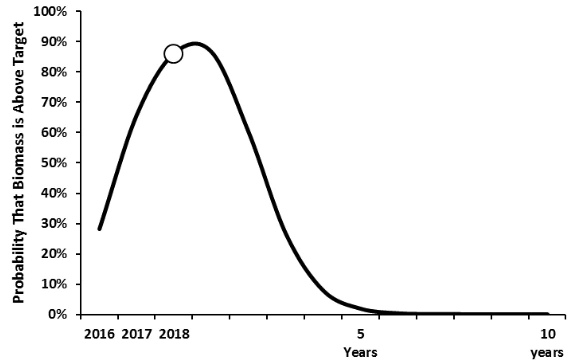
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

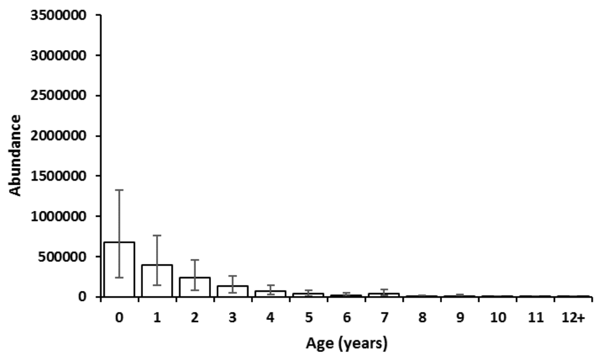
Biomass



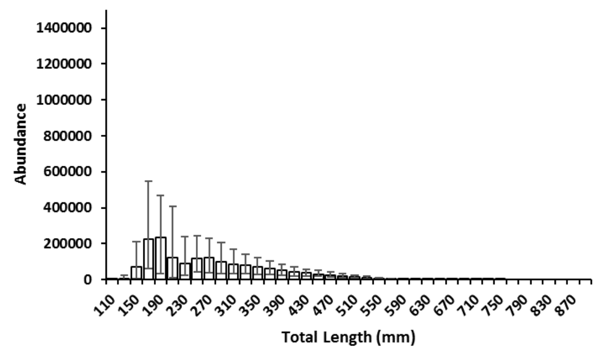
Probability of Achieving Management Target



Age Distribution



Size Distribution



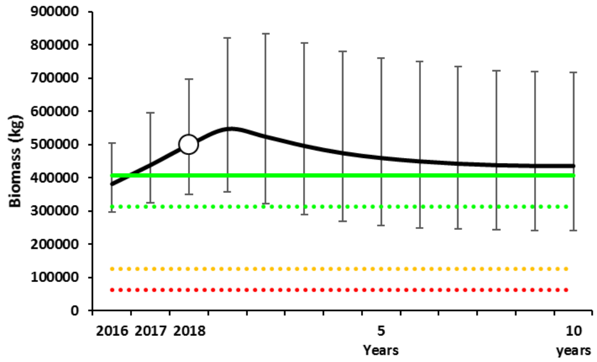
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	261324 kg
Probability that biomass will be above management target of 1.3B$_{MSY}$	0.0190
Abundance (Number of Walleye ≥2 years old)	573841
Proportion of Adults (% of population ≥5 years old)	8%
Mortality (≥2 years old)	38%
Quality stock density	46%
Preferred stock density	16%

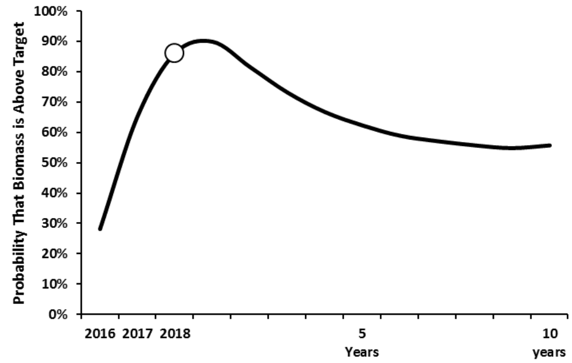
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

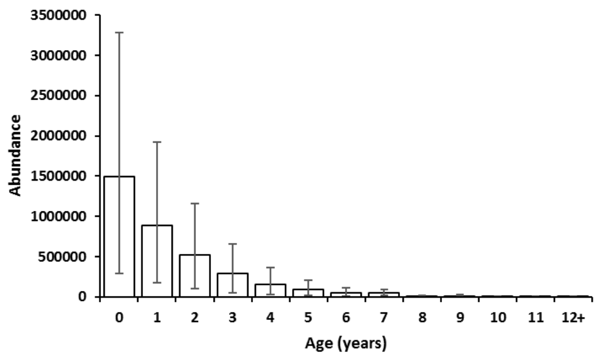
Biomass



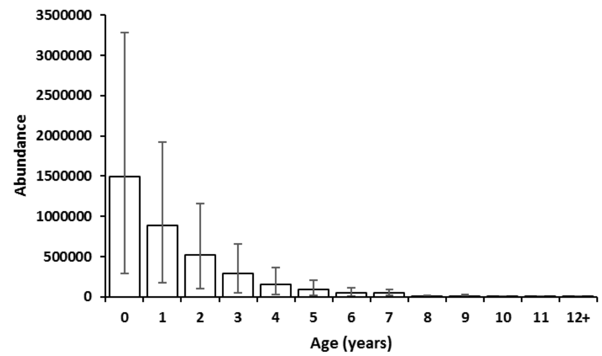
Probability of Achieving Management Target



Age Distribution



Size Distribution



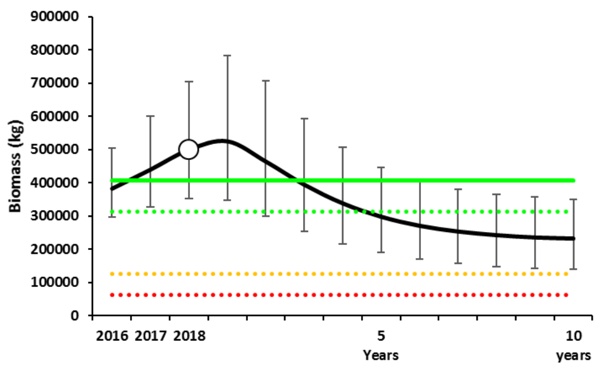
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	460208 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.6237
Abundance (Number of Walleye ≥2 years old)	1189066
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	44%
Quality stock density	41%
Preferred stock density	11%

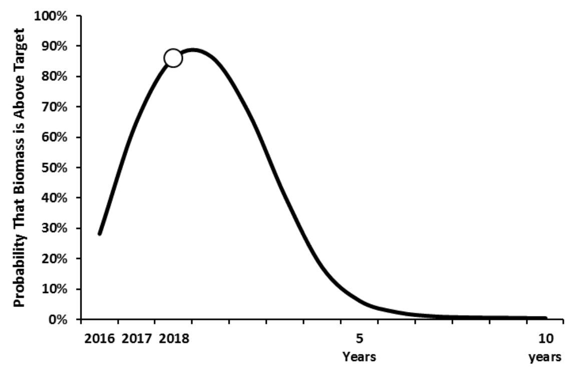
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

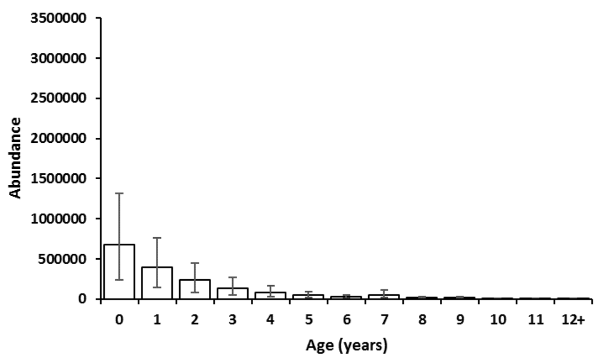
Biomass



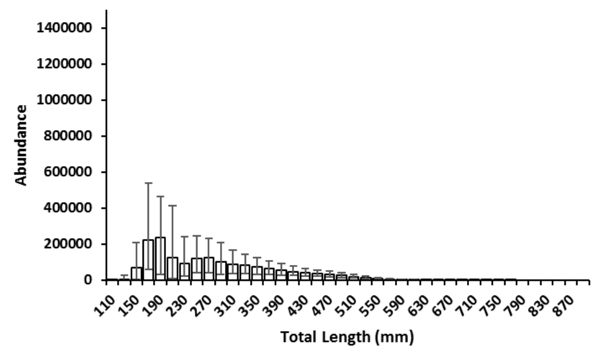
Probability of Achieving Management Target



Age Distribution



Size Distribution



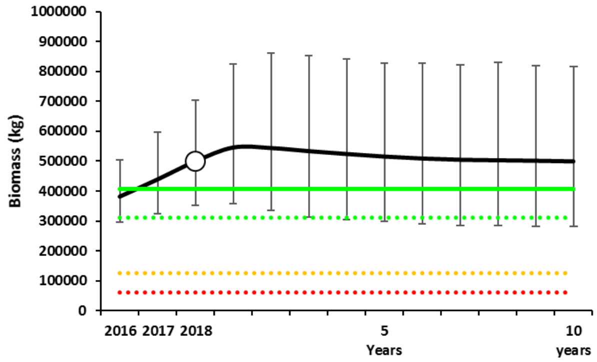
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	297965 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0603
Abundance (Number of Walleye ≥2 years old)	616515
Proportion of Adults (% of population ≥5 years old)	10%
Mortality (≥2 years old)	36%
Quality stock density	48%
Preferred stock density	18%

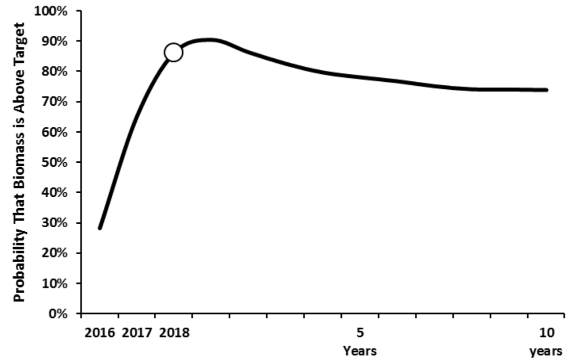
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

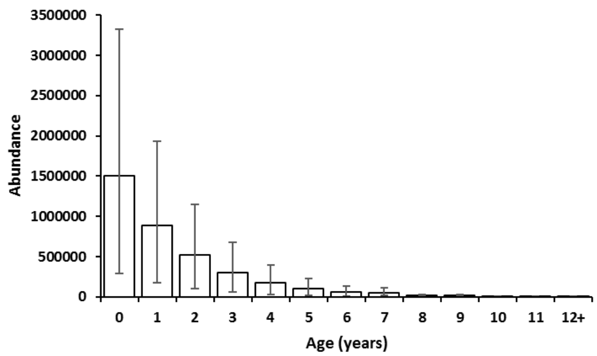
Biomass



Probability of Achieving Management Target



Age Distribution



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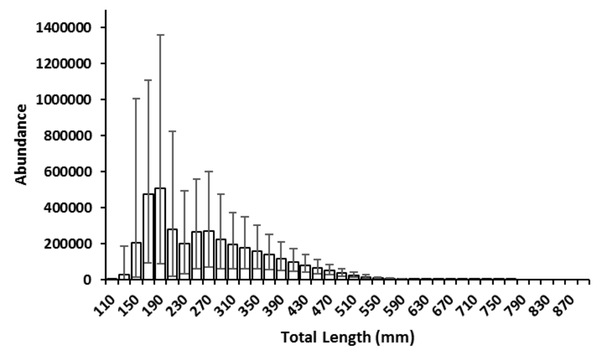


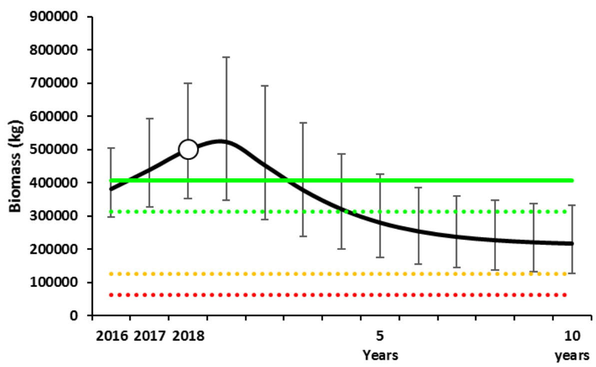
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	515329 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.7805
Abundance (Number of Walleye ≥2 years old)	1258611
Proportion of Adults (% of population ≥5 years old)	7%
Mortality (≥2 years old)	42%
Quality stock density	43%
Preferred stock density	13%

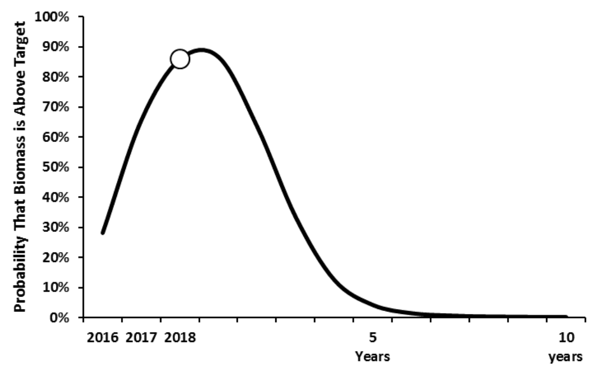
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

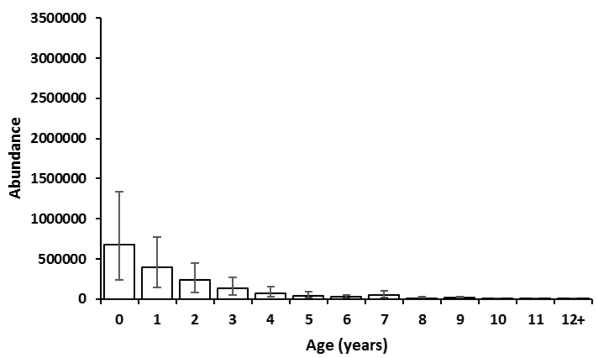
Biomass



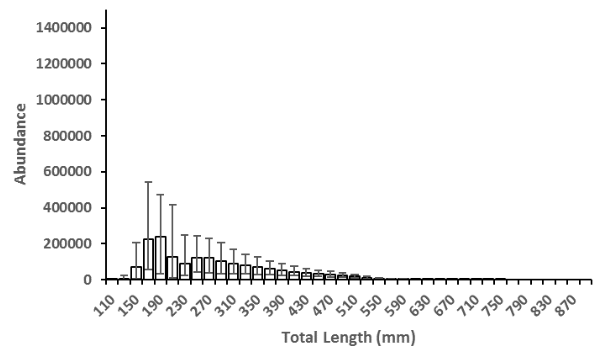
Probability of Achieving Management Target



Age Distribution



Size Distribution



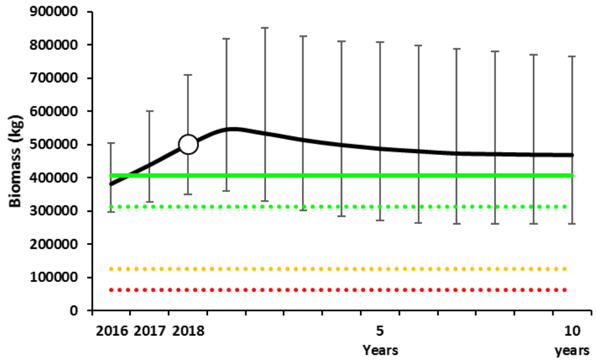
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	281079 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.0415
Abundance (Number of Walleye ≥2 years old)	598812
Proportion of Adults (% of population ≥5 years old)	9%
Mortality (≥2 years old)	37%
Quality stock density	47%
Preferred stock density	17%

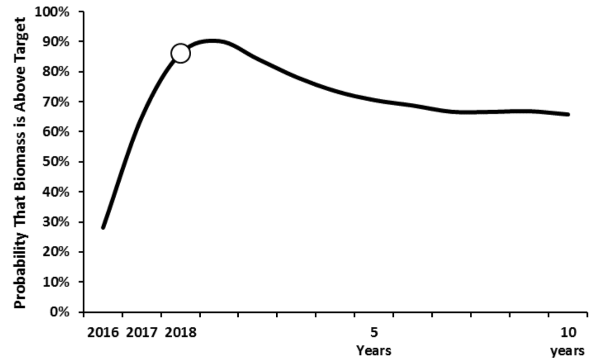
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

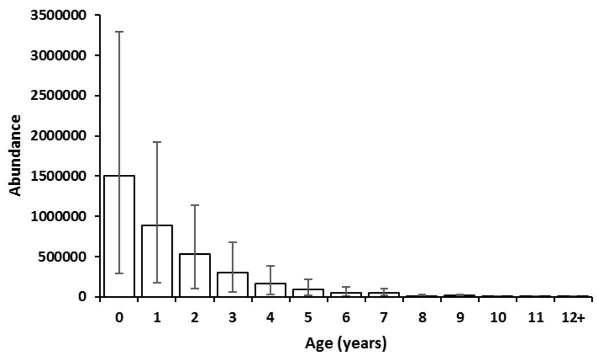
Biomass



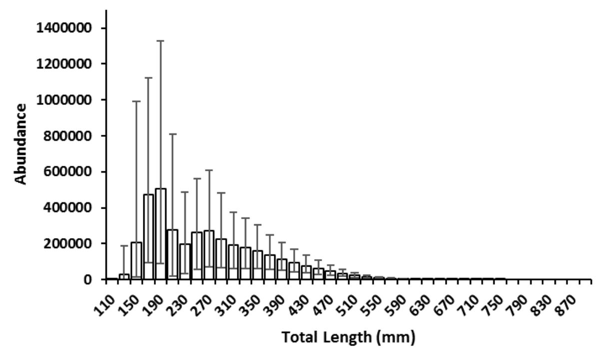
Probability of Achieving Management Target



Age Distribution



Size Distribution



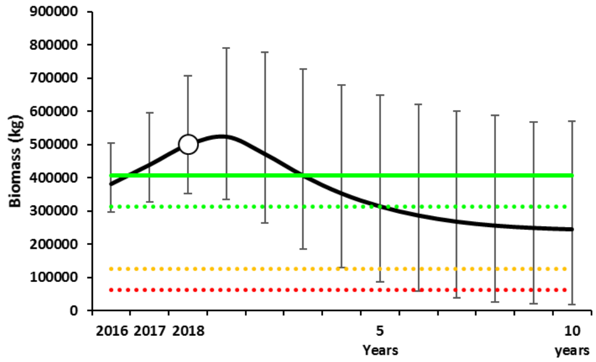
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	488251 kg
Probability that biomass will be above management target of $1.3B_{MSY}$	0.7061
Abundance (Number of Walleye ≥2 years old)	1226296
Proportion of Adults (% of population ≥5 years old)	6%
Mortality (≥2 years old)	43%
Quality stock density	42%
Preferred stock density	12%

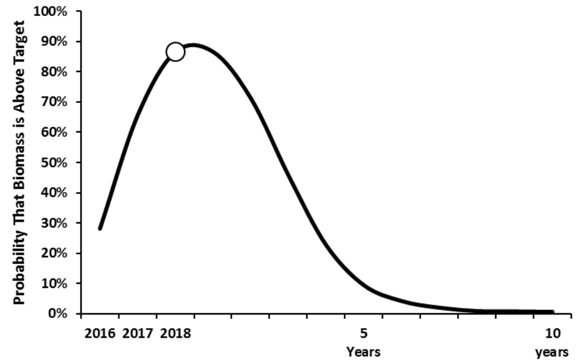
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

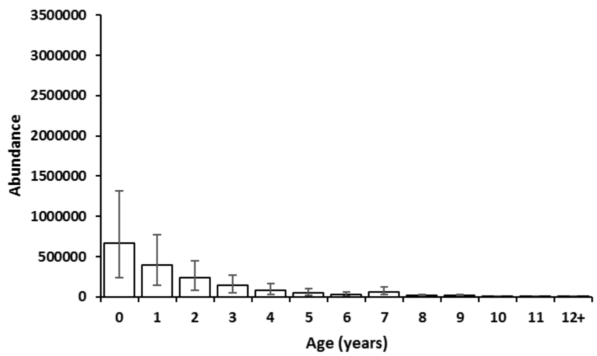
Biomass



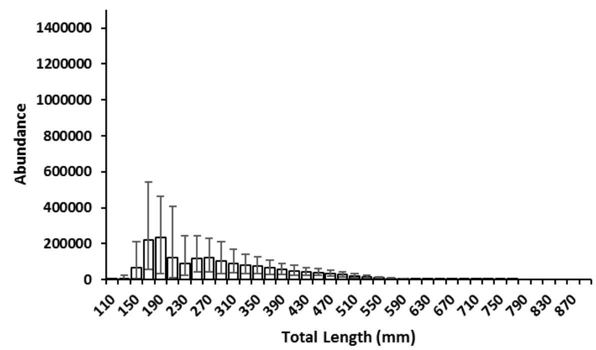
Probability of Achieving Management Target



Age Distribution



Size Distribution



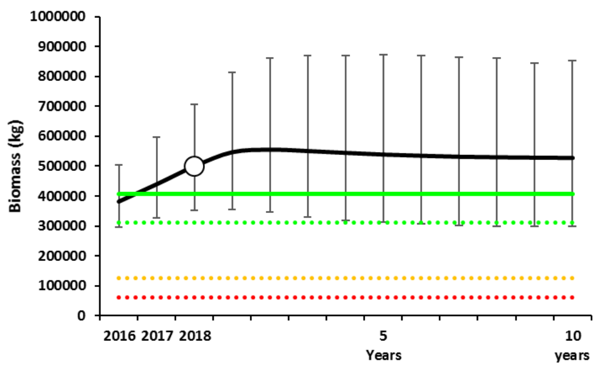
Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	314862 kg
Probability that biomass will be above management target of 1.3B_{MSY}	0.0948
Abundance (Number of Walleye ≥2 years old)	637652
Proportion of Adults (% of population ≥5 years old)	10%
Mortality (≥2 years old)	36%
Quality stock density	49%
Preferred stock density	19%

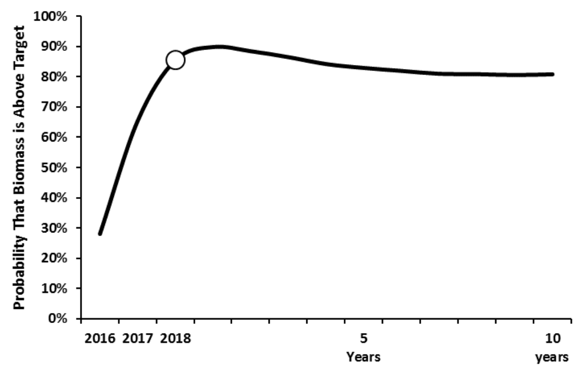
Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Regulation: 450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

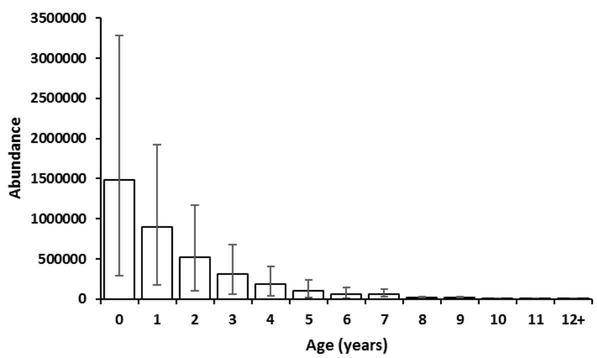
Biomass



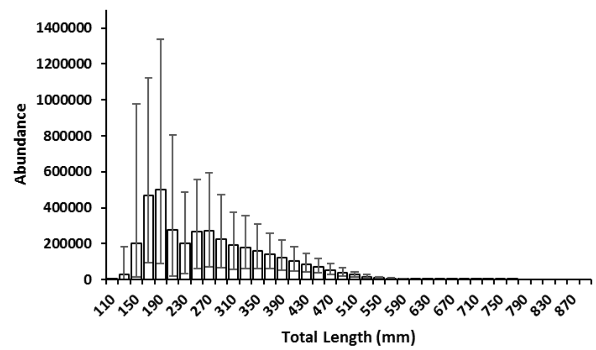
Probability of Achieving Management Target



Age Distribution



Size Distribution



Evaluation

Indicator	Estimate and Risk Criteria
Biomass (kg) of Walleye ≥350mm total length	538966 kg
Probability that biomass will be above management target of 1.3B_{MSY}	0.8293
Abundance (Number of Walleye ≥2 years old)	1285275
Proportion of Adults (% of population ≥5 years old)	7%
Mortality (≥2 years old)	41%
Quality stock density	44%
Preferred stock density	13%

Figure 18. Simulation results for 11 possible angling regulations with either low or high recruitment (continued).

Table 7. Performance indicators and risk criteria for 11 possible angling regulation simulations 5 years after implementation.

Angling Regulation	Recruitment Pattern	Biomass	Probability Above Target	Abundance ≥Age 2	% ≥Age 5	Adult Mortality	Stock Structure	
							Quality	Preferred
No size limit with 2 fish creel limit	LOW							
	HIGH							
Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm	LOW							
	HIGH							
2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm	LOW							
	HIGH							
400-to-600mm protected slot size limit with 2 fish creel limit	LOW							
	HIGH							
Current FMZ 11 regulation – 430-to-600mm protected slot size limit with 2 fish creel limit and 1 fish >600m	LOW							
	HIGH							
400mm minimum size limit with 2 fish creel limit	LOW							
	HIGH							
Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit	LOW							
	HIGH							
400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit	LOW							
	HIGH							
450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit	LOW							
	HIGH							
400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit	LOW							
	HIGH							
450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit	LOW							
	HIGH							

Given the high probability that the Lake Nipissing Walleye population will be declared recovered after the 2019 FWIN survey (Figure 17) and the current management target of $1.3B_{MSY}$, the best suite of angling regulations that may continue the recovery, if required, and possibly rebuild the population age- and size- structure are: maintaining the current 460mm minimum size limit with 2 fish creel limit or changing to either the 50mm (i.e., 400-to-450mm or 450-to-500mm) or 100mm (i.e., 400-to-500mm or

450-to-550mm) fishable (harvest) slot size limit options. The regulation with the lowest amount of risk is the 450-to-500mm fishable (harvest) slot size.

5 – Monitoring Requirements

Recruitment (i.e., survival of juvenile fishes to a defined stage or harvestable size) is critical for the sustainability of fish populations. Without sufficient recruitment, fish populations would be extirpated with or without exploitation. Recruitment to the adult stock can be defined as the product of egg deposition and the survival rate of juveniles (Walters and Martell 2004). As such, estimates of adult stock size that do not account for annual egg production (via fecundity) have often been poor predictors of recruitment. The exception being at low adult stock sizes where a direct, positive relationship between stock and recruitment has been observed (i.e., compensatory responses) as a result of density-dependent responses that increase juvenile survival (Beverton and Holt 1957).

The Lake Nipissing Walleye Bayesian model identified two recruitment patterns which greatly influenced the outcome of the various angling regulation simulations, as well as the risk associated with a potential management action. For example, given the range in mortality that has occurred from 2016 to 2018 (i.e., the first 3-year memorandum-of-understanding agreement between OMNRF and NFN) the future recruitment pattern clearly determines the success and longevity of the current management actions – 460mm minimum size limit and 2 fish creel limit (Figure 19).

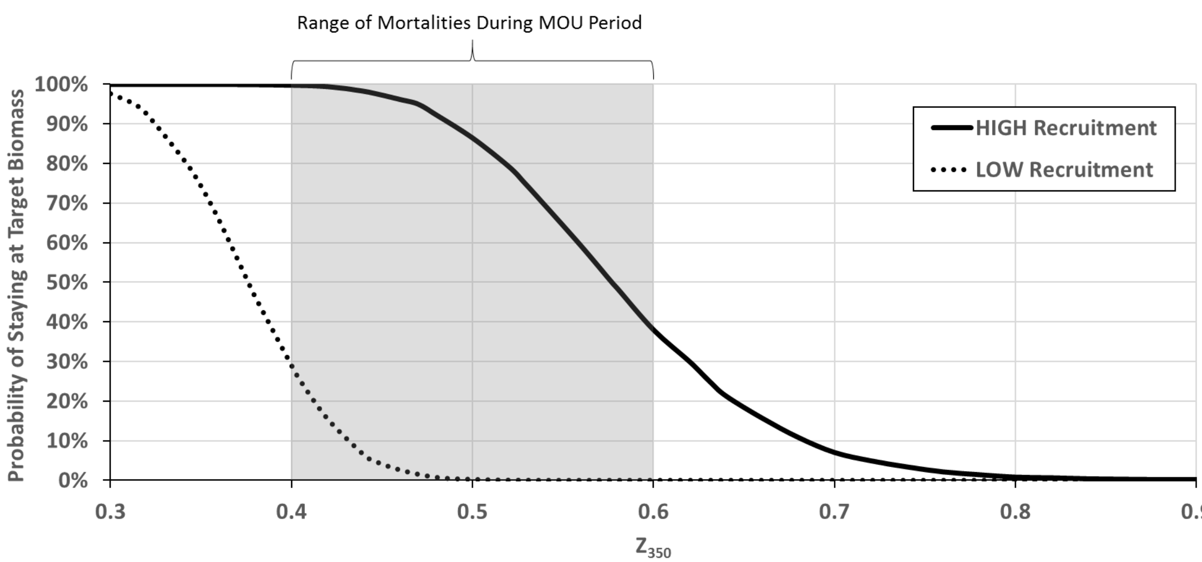


Figure 19. Probability that Lake Nipissing Walleye biomass will remain above the management target of $1.3B_{MSY}$ 5 years from now (i.e., 2023) and stay at-or-above the management target until 2050 as a function of the future recruitment pattern (low or high) and mortality rate (Z_{350}). The probabilities were calculated from the predictive Bayesian distribution assuming low recruitment (using MCMC values from 1999 to 2009) or high recruitment (using MCMC values from 2010 to 2016) (Figure 16).

Furthermore, the 1967 to 2018 time series indicates that in most years Lake Nipissing Walleye have experienced higher mortality rates when angling regulations were less restrictive (e.g., 1967 to 1998 – no size limit and 6 fish creel limit, and 1999 to 2013 – 400-to-600mm protected slot size limit and 4 fish creel limit with 1 fish >600mm) (Figure 20). The mortality (and biomass) estimates are for Walleye that have recruited to the fisheries (i.e., Walleye ≥350mm total length which, depending on growth rate, are 2 or 3 years old) so having an indication of the abundance of the smaller (and younger) pre-recruits (i.e., young-of-year, age-1, age-2) before entering the fisheries is paramount to assess the potential success or failure of future management actions on the lake.

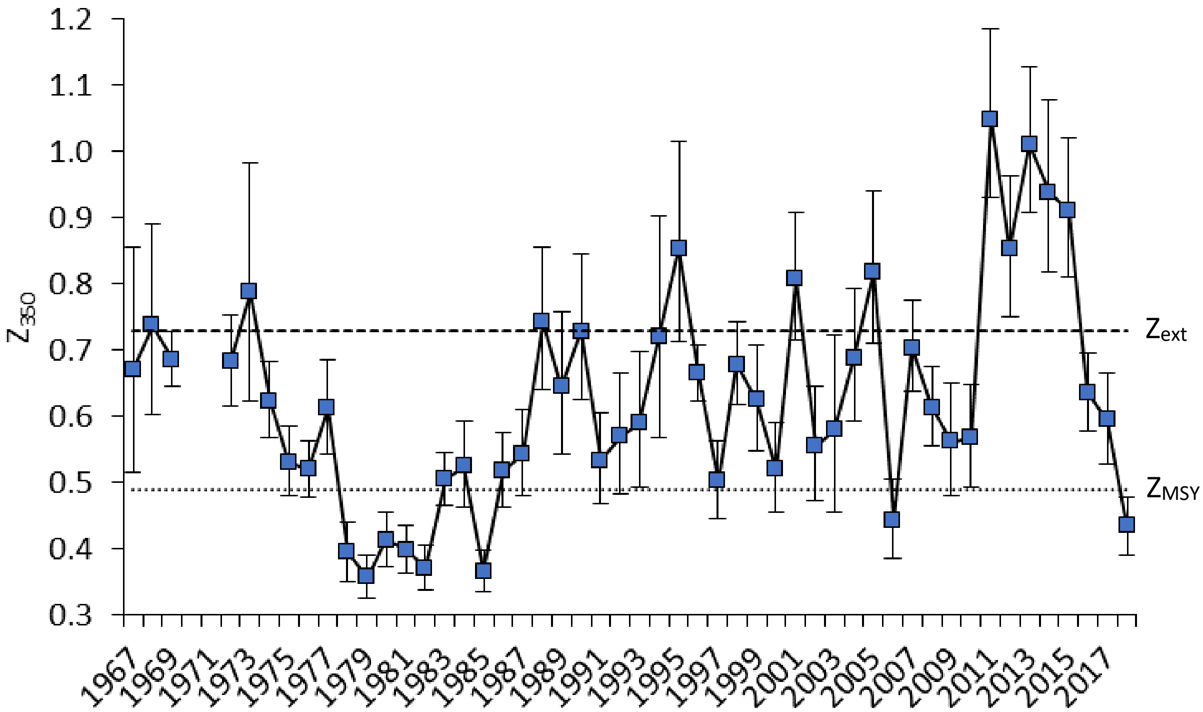


Figure 20. Adult (Z_{350}) Walleye mortality rates from 1967 to 2018 (estimate ±95% confidence interval). Z_{MSY} is the adult mortality rate at maximum sustained yield (F=M) and Z_{ext} is the maximum adult mortality rate that could be compensated from increases in pre-maturation growth rate (F=2M) (Lester et al. 2014).

Since the Bayesian model requires the data from the annual FWIN project, indicators of low and high recruitment patterns were developed for estimated catch rates (i.e. observed number•net^{-1}) of age-0 (i.e., young-of-year), age-1, and age-2. Estimates of indicators are based on the MCMC traces of the Bayesian model, assuming an encounter rate exponent β = 2. The distribution of maximum recruitment (R_{max}) estimates from multiple years is strongly trimodal, with an intermediate higher peak separating the clearly low from the clearly high recruitment peaks (Figure 21).

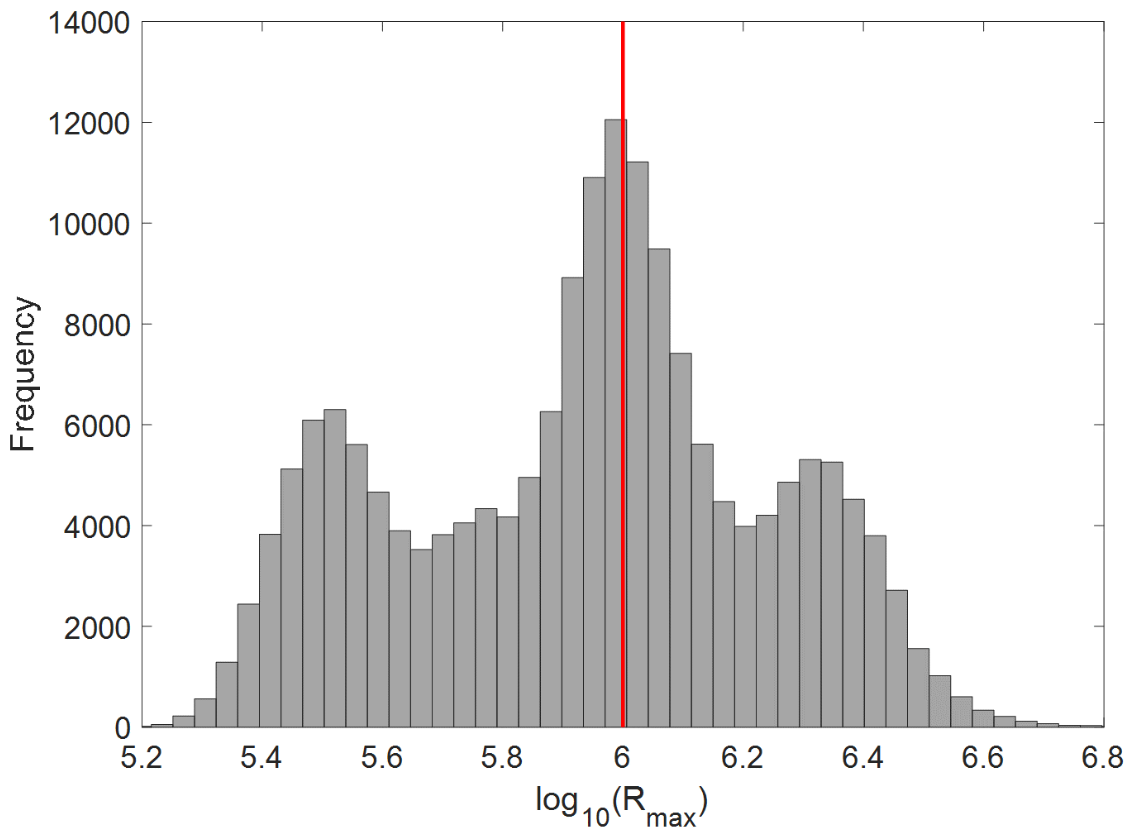


Figure 21. Distribution of maximum recruitment (R_{max}, in a $\log_{10}$ scale), pooling together the Bayesian traces for all years from 1999 to 2016. The red line marks a maximum recruitment of one million Age-0.

The center of this intermediate peak is very close to 10^6 (one million) Age-0 recruits and this was used as the reference number separating the low and high recruitment regions. To predict the Age-0 $FWIN_{CPUE}$ (number of Age-0•net^{-1}) associated with the reference value of one million Age-0 recruits, the observed Age-0 $FWIN_{CPUE}$ was regressed against R_{max} values across years. The time series from 1999 to 2016 (all years for which R_{max} could be estimated) was used in the regression. Similarly, Age-1 $FWIN_{CPUE}$ was regressed from 2000 to 2016 against R_{max} from 1999 to 2015 (i.e. there is a one-year lag from Age-0 recruited to Age-1), and Age-2-$FWIN_{CPUE}$ was regressed from 2001 to 2016 against R_{max} fr0m 1999 to 2014 (i.e., there is a two-year lag form Age-0 recruited to Age-2). The Bayesian estimation generated 10000 traces of the R_{max} time series and one regression was fit for each one of these traces for each age class. The regression lines are plotted in Figure 22.

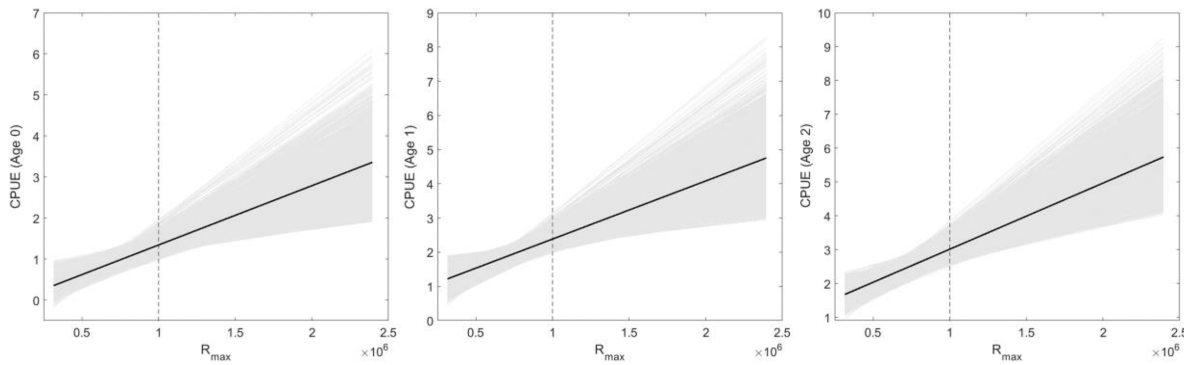


Figure 22. Linear regressions between maximum recruitment (R_{max}) and $FWIN_{CPUE}$ of Walleye Age-0 (A), Age-1 (B), and Age-2 (C). The superimposed gray lines are individual regressions from the distribution of R_{max} vectors (10000 regressions in total for each graph). The thick black lines are the mean regressions, and the vertical dashed lines mark the reference R_{max} of one million fish. Mean R^2 from regressions were: 0.64 (A); 0.47 (B); 0.54 (C).

The 10000 regressions generated a distribution of $FWIN_{CPUEs}$ predicted at the reference value $R_{max} = 10^6$. The distributions for the three age classes are presented in Figure 23.

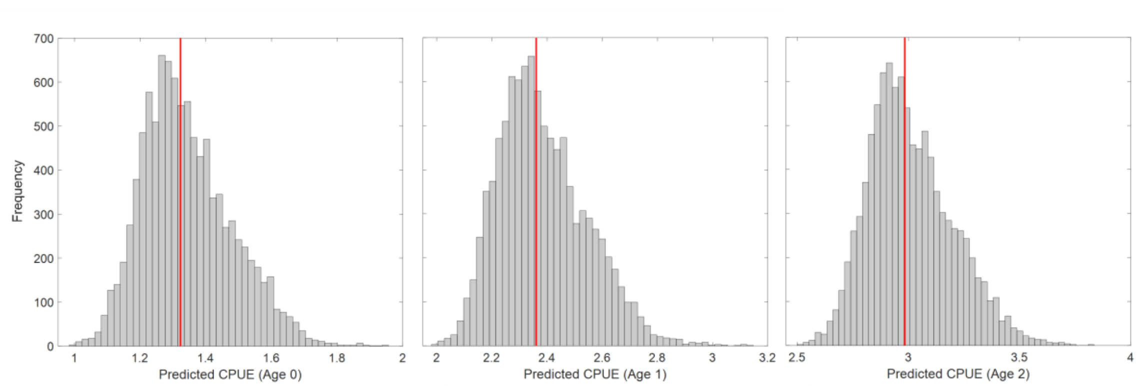


Figure 23. Distribution of $FWIN_{CPUEs}$ (fish•net^{-1}) predicted from linear regression with maximum recruitment (R_{max}), at $R_{max} = 10^6$ (one million fish). The red vertical lines mark the medians of the distributions: 1.32 Age-0•net^{-1} (A); 2.36 for Age-1•net^{-1} (B); 2.98 for Age-2•net^{-1}.

Based on the medians of distributions in Figure 3, the threshold between low vs high recruitment from the observed $FWIN_{CPUEs}$ would be:

> 1.32fish•net^{-1} for Age-0 Walleye, recruitment in the same year,
>
> 2.36fish•net^{-1} for Age-1 Walleye, recruitment one year before, and
>
> 2.98fish•net^{-1} for Age-2 Walleye, recruitment two years before.

Using these $FWIN_{CPUE}$ thresholds for Age-0, Age-1, and Age-2 Walleye provides a 3-year window to respond to potential changes in the recruitment pattern with the appropriate management action (assuming that an index netting stock assessment will be performed every year). Annual FWIN assessments should continue for 2-3 years after achieving the management target ($1.3B_{MSY}$).

Fishery monitoring tools differ, not only in the type and quality of data they collect, but also in their initial and ongoing operational costs, ease of use, transferability of results, and ability to meet the diverse needs of stakeholders. Although the specific monitoring goals and data requirements of the Lake Nipissing Management Plan (2014) will be the driving force behind the tools selected for the monitoring program, there are other considerations, such as the movement to another provincial standard index netting protocol – the Broad-scale Monitoring Program (Sandstrom et al. 2013). Ongoing net calibration efforts should in due course allow the Walleye monitoring program to transition from the FWIN to the large mesh gillnets of the provincial standard.

6 – Summary

This work has shown that the current management system should allow the Lake Nipissing Walleye population to reach its desired biomass recovery target in the near future. The simulated effects of a variety of alternate recreational angling rules were compared and there appear to be several options that can greatly decrease the risk to the resource while maintaining or increasing harvest into the near future. The model requires the annual data collected from the FWIN program on Lake Nipissing (at least until the Walleye population has reached the recovery target of $1.3B_{MSY}$).

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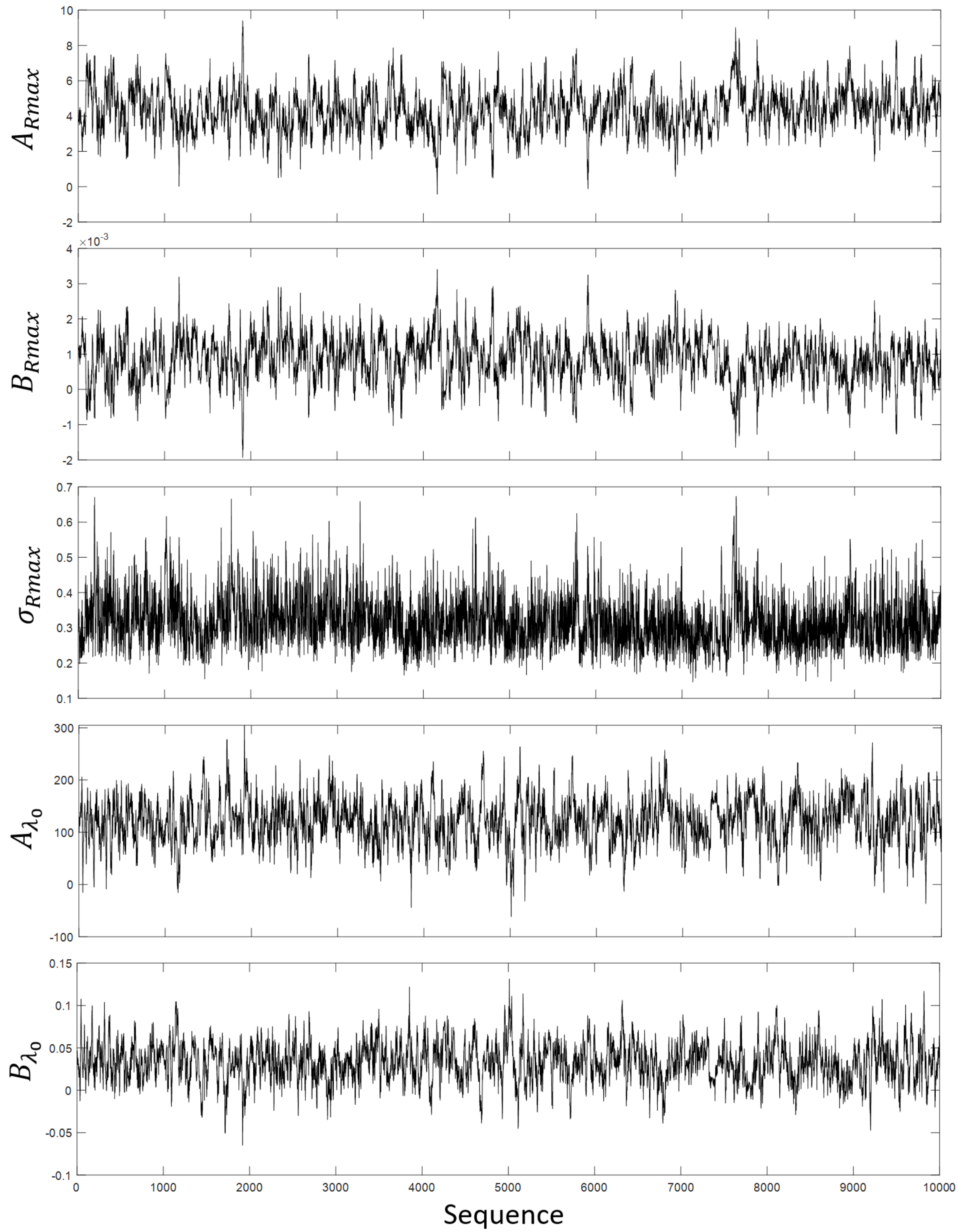
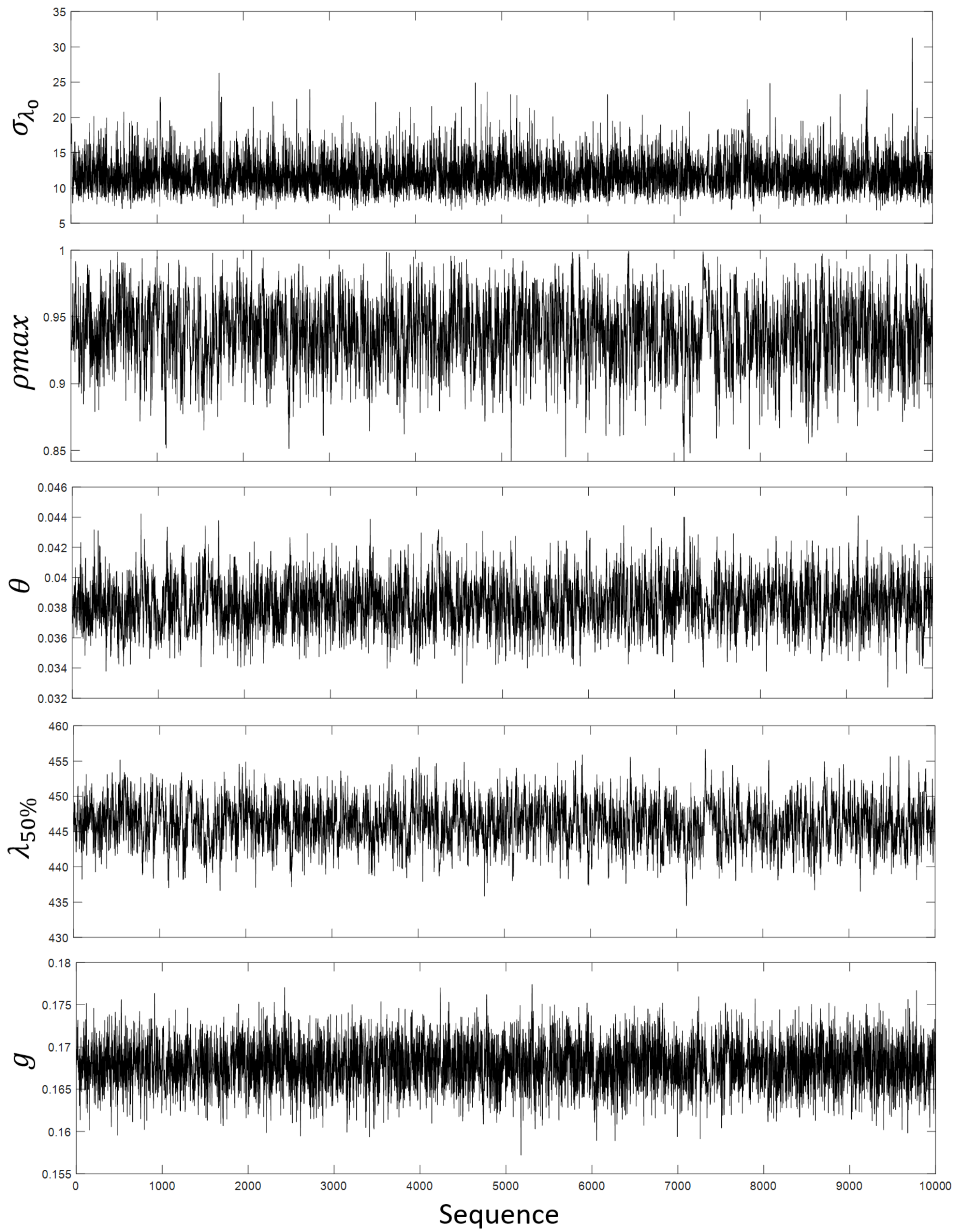
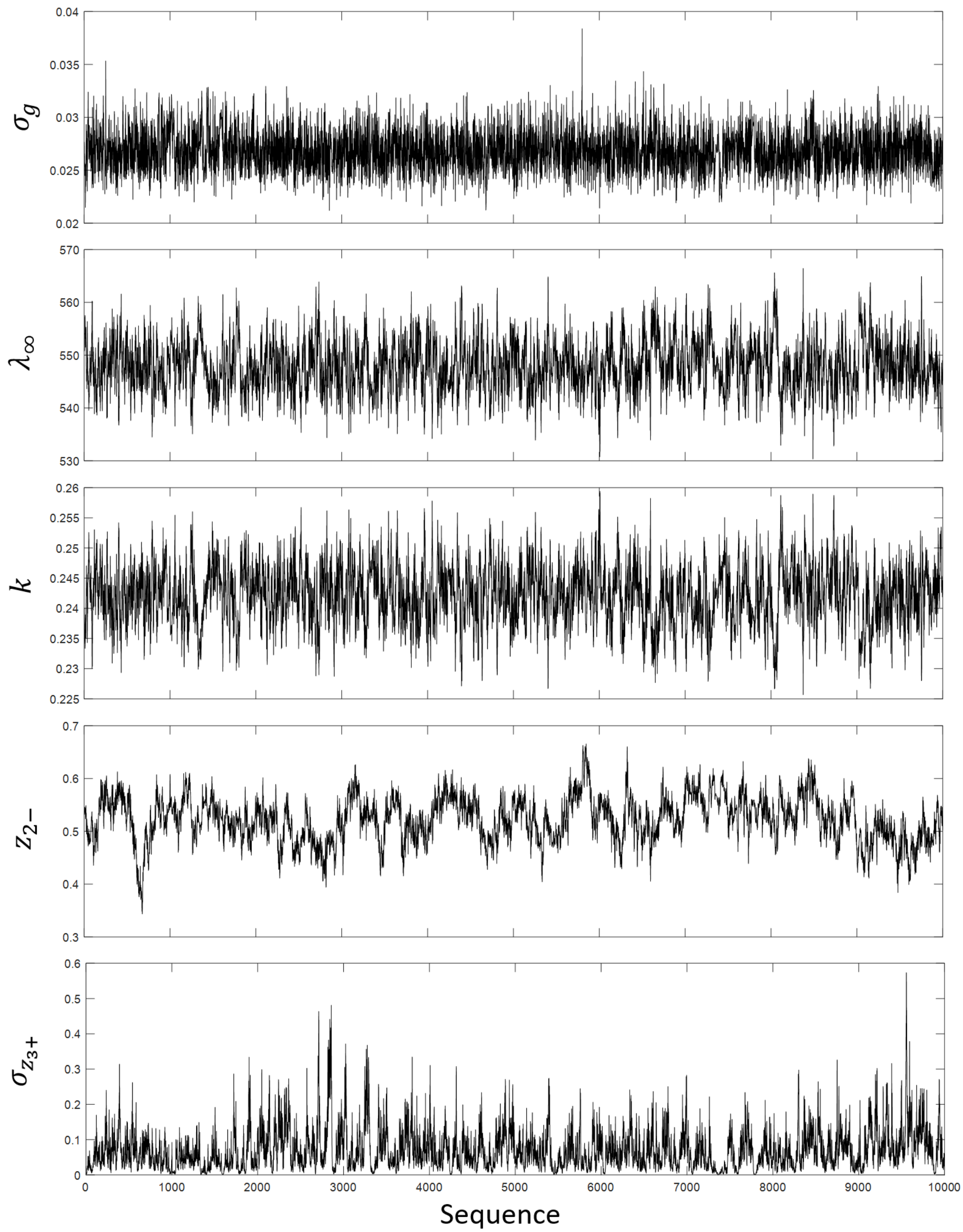
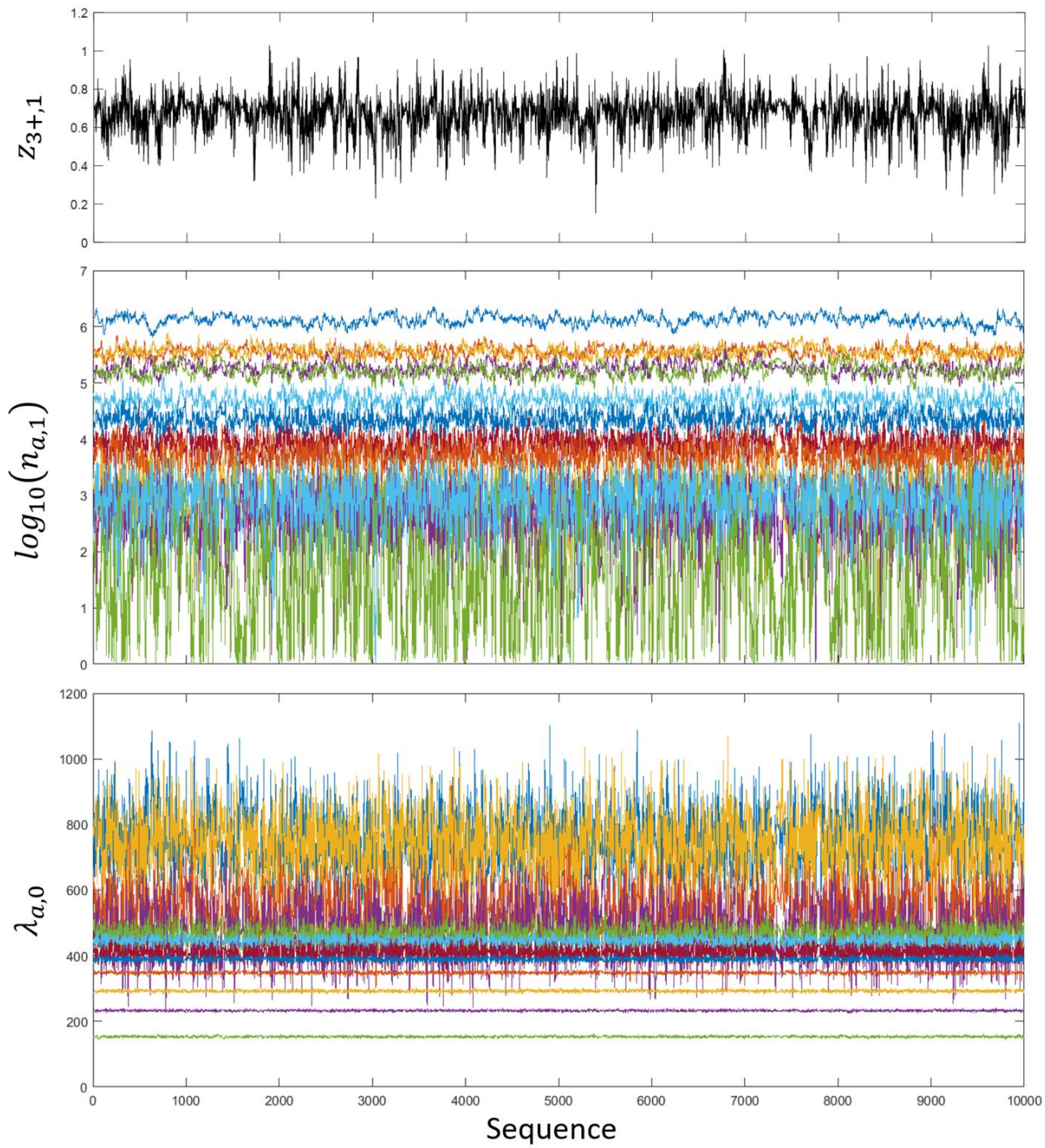
Appendix 1: Bayesian traces of estimated hyperparameters for $\beta = 2$.

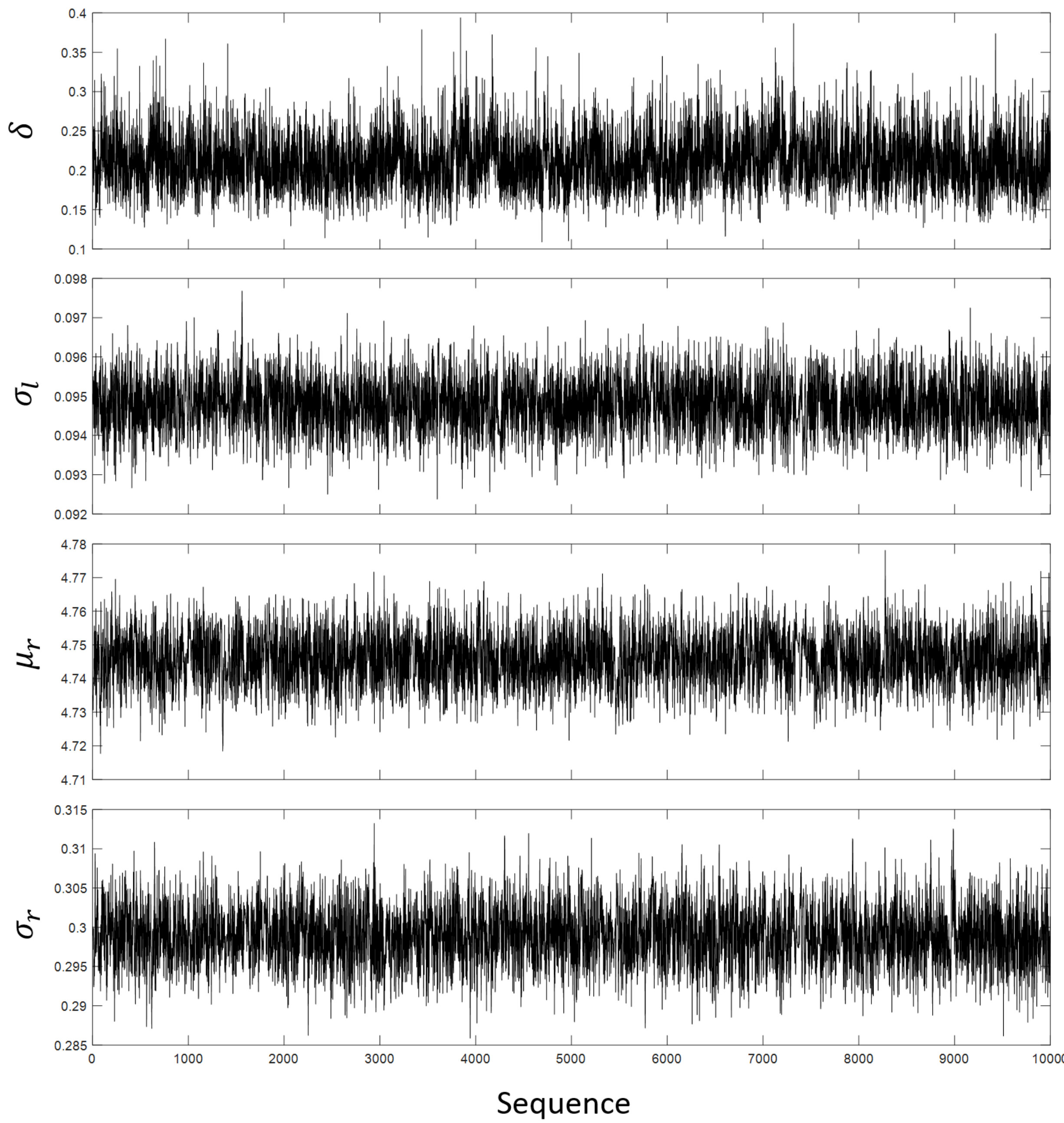




σ_{λ_0}
ρmax
θ
$\lambda_{50\%}$
g
Sequence


σ_g
λ_∞
k
z_{2-}
$\sigma_{z_{3+}}$
Sequence


$z_{3+,1}$
$log_{10}(n_{a,1})$
$\lambda_{a,0}$
Sequence



δ
σ_l
μ_r
σ_r
0.4
0.35
0.3
0.25
0.2
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0.1
0.098
0.097
0.096
0.095
0.094
0.093
0.092
4.78
4.77
4.76
4.75
4.74
4.73
4.72
4.71
0.315
0.31
0.305
0.3
0.295
0.29
0.285
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Sequence

Appendix 2: Lake Nipissing Walleye harvest (kg) from winter and open water angling fisheries, and Nipissing First Nation commercial fishery 1995 to 2018.

Year	Annual Walleye Harvest (kg) (recreation and commercial)	% Angling
1995	94674	76%
1996	122272	84%
1997	68787	69%
1998	64646	58%
1999	43522	48%
2000	51655	56%
2001	76447	52%
2002	107574	50%
2003	100472	30%
2004	67748	23%
2005	52422	31%
2006	58080	33%
2007	66066	24%
2008	59705	22%
2009	66744	21%
2010	44734	16%
2011	32723	40%
2012	42481	39%
2013	51122	42%
2014	36707	36%
2015	79574	11%
2016	48002	20%
2017	32386	25%
2018	41971	53%

Appendix 3: Simulation results for 11 proposed angling regulations with LOW and HIGH recruitment patterns.

Biological indicators and risk criteria.

Biomass indicator – Kilograms of Walleye ≥350mm total length

Risk	Criteria	Description
Low	$\geq B_{MSY}$	Biomass ≥ Upper reference point[1]
Moderate	$\geq 0.4B_{MSY}$ and $<B_{MSY}$	Lower reference point ≤ Biomass < Upper reference point
High	$>0.2B_{MSY}$ and $<0.4B_{MSY}$	Limit reference point ≤ Biomass < Lower reference point
Excessive	$\leq 0.2B_{MSY}$	Biomass < Limit reference point of harvest control rule

1. Reference points defined in harvest control rule where B_{MSY} = 312660 kg.

Management target indicator – Probability that biomass will be above management target of $1.3B_{MSY}$

Risk	Criteria	Description
Low	>66%	High probability that biomass is above management target
Moderate	40% to 65%	Reasonable probability that biomass is above management target
High	<40%	Low probability that biomass is above management target

Abundance indicator – Number of Walleye ≥2 years old in the population scaled to range in abundance[1]

Risk	Criteria	Description
Low	≥75%	Very high abundance
Moderate	≥50% and <75%	Above average abundance
High	≥10% and <50%$_Y$	Below average abundance
Excessive	<10%	Very low abundance

1. The 450-to-500mm fishable (harvest) slot size limit – 2 fish creel limit (high recruitment) scenario had the maximum abundance (N_{max} =1285275 Walleye ≥2 years old) while the current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm had the minimum abundance (N_{min} = 488484 Walleye ≥2 years old). Abundance indicator: $N_{criteria} = 1\text{-}(N_{max}\text{-}N_{sim})\bullet(N_{max}\text{-}N_{min})^{-1}$

Adult (i.e., spawning stock) indicator – % of age structure ≥5 years old[1]

Risk	Criteria	Description
Low	≥8%	High proportion of adult spawners in the population
Moderate	5% to 8%	Acceptable proportion of adult spawners in the population
High	<5%	Low proportion of adult spawners in the population

1. Based on the modal age of spawning female Walleye sampled at Wasi Falls from 1968 to 2017 (i.e., a spring Walleye age 6 would be age 5 in the previous years FWIN survey).

Mortality indicator – Annual adult (≥2 years old) mortality (%) estimated from age distribution using Robson-Chapman maximum likelihood indicator (Guy and Brown 2007). Compared to quartiles and median of Lake Nipissing Walleye mortality estimates 1972 to 2018[1]

Risk	Criteria	Description
Low	<41%	< Q_{25} – Mortality near F_{MSY} (i.e., F = M or A_{MSY} = 39%)[2]
Moderate	41% to 45%	Mortality above F_{MSY} but ≤ 1972-to-2018 median (Q_{50} = 45%)
High	46% to 50%	Mortality above 1972-to-2018 median but < Q_{75}
Excessive	≥51%	≥ Q_{75} – Mortality higher than F_{ext} (i.e., F = 2M or A_{ext} = 52%)

1. Annual adult mortality rates 1972 to 2018: lower (Q_{25}) quartile = 41%, upper (Q_{75}) quartile = 51%, and median (Q_{50}) = 45%
2. Lester et al. 2014.

Quality stock density indicator – Proportion of Walleye available to anglers

Risk	Criteria	Description
Low	≥45%	Plenty of fish available to anglers
Moderate	>34% but <44%	Some fish available to anglers
High	≤33%	Fewer fish available to anglers

Preferred stock density indicator – Proportion of large Walleye available to anglers

Risk	Criteria	Description
Low	≥15%	Plenty of large fish available to anglers
Moderate	>10% but <14%	Some large fish available to anglers
High	≤9%	Fewer large fish available to anglers

Regulation: No size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439866	326448	593990	0.6546
2018	498112	352176	703476	0.8588
2019 Regulation Change	523575	347292	776730	0.8663
2020	395258	249195	626245	0.3938
2021	293500	176680	469166	0.0847
2022	230493	135204	375760	0.0100
2023 5 years After Change	193516	110514	312668	0.0010

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	669857	232107	1331452
Age-1	400029	142036	772318
Age-2	237225	85245	452364
Age-3	115548	38504	239139
Age-4	56601	17643	124055
Age-5	27320	8218	61763
Age-6	13438	3795	31943
Age-7	27617	10361	61438
Age-8	6701	2703	14711
Age-9	7613	3276	15988
Age-10	2395	1054	4888
Age-11	2529	1132	5074
Age-12+	1808	874	3536
Abundance ≥Age-2	498794		
% ≥Age-5	6%		
Adult Mortality	44%		

Regulation: No size limit with 2 fish creel limit

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	37	0	339
120	4664	45	24668
140	68401	5570	207642
160	221772	58357	541163
180	234775	33775	469070
200	124347	10020	411163
220	90470	24799	241434
240	120841	43218	245533
260	124799	41005	229649
280	102493	32918	208833
300	87758	35858	166193
320	78994	33451	137965
340	67458	28329	119568
360	54771	24381	95907
380	43706	20596	75529
400	34753	16700	60493
420	27764	14030	48244
440	22384	11688	39059
460	17987	9523	31691
480	14009	7417	25200
500	10281	5369	18788
520	6978	3616	12867
540	4345	2223	8015
560	2480	1255	4602
580	1301	648	2430
600	631	309	1190
620	284	137	539
640	120	57	229
660	47	22	92
680	18	8	35
700	6	3	13
720	2	1	4
Quality Stock Density	39%		
Preferred Stock Density	12%		

Regulation: No size limit with 2 fish creel limit

Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439799	326166	600087	0.6538
2018	499696	351415	706980	0.8633
2019 Regulation Change	546808	359056	828306	0.9013
2020	469626	279227	772337	0.6558
2021	411059	230440	704966	0.4507
2022	374170	200406	643865	0.3275
2023 5 years After Change	352870	185253	610869	0.2656

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1500644	284753	3295552
Age-1	888907	171906	1955388
Age-2	532517	102801	1152386
Age-3	257192	48339	585035
Age-4	125321	22271	298225
Age-5	61606	10604	151869
Age-6	30094	4955	77159
Age-7	27560	10368	62151
Age-8	6736	2701	15122
Age-9	7637	3278	16004
Age-10	2399	1081	4858
Age-11	2534	1142	5075
Age-12+	1813	871	3563
Abundance ≥Age-2	1055408		
% ≥Age-5	4%		
Adult Mortality	49%		

Regulation: No size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	375	0	2961
120	26406	259	182998
140	199497	15227	972153
160	471430	94005	1121393
180	512161	92735	1317602
200	280471	21124	805045
220	200937	38035	490021
240	265864	61277	565215
260	273572	72428	609112
280	226385	64255	487702
300	194398	56731	376607
320	174198	57725	345430
340	148022	54932	290467
360	119663	47555	225095
380	94732	40318	177584
400	73762	32596	138551
420	56241	25937	104795
440	41894	20022	77832
460	30353	14861	56488
480	21186	10523	39859
500	14074	7102	26617
520	8803	4447	16700
540	5145	2602	9728
560	2801	1416	5268
580	1420	713	2663
600	672	334	1270
620	297	146	566
640	124	59	238
660	49	23	94
680	18	8	36
700	6	3	13
720	2	1	4
Quality Stock Density	36%		
Preferred Stock Density	9%		

Regulation: Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439079	326692	595493	0.6538
2018	498380	352023	697481	0.8596
2019 Regulation Change	523119	345592	776469	0.8615
2020	388577	239509	615627	0.3723
2021	285116	169632	460842	0.0717
2022	221119	128935	361640	0.0077
2023 5 years After Change	185032	106086	302250	0.0011

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	678089	235563	1316878
Age-1	397734	142139	766417
Age-2	236978	84985	452279
Age-3	113366	37743	234595
Age-4	54329	17086	120408
Age-5	25956	7804	60239
Age-6	12459	3453	30125
Age-7	25718	9471	58294
Age-8	6291	2474	14085
Age-9	7107	2969	14841
Age-10	2231	995	4535
Age-11	2362	1049	4825
Age-12+	1687	793	3298
Abundance ≥Age-2	488484		
% ≥Age-5	5%		
Adult Mortality	45%		

Regulation: Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm
Recruitment: LOW
(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	38	0	353
120	4760	44	24888
140	70035	5583	209496
160	226013	58809	538811
180	236984	33331	468267
200	124396	9829	409406
220	89970	24314	239116
240	120035	42709	242583
260	124195	41443	231941
280	102318	32914	208803
300	87669	36024	166108
320	78629	33719	137134
340	66727	28433	118583
360	53763	24269	94910
380	42547	20250	74422
400	33541	16281	59015
420	26563	13535	46480
440	21243	11155	37242
460	16959	8942	30280
480	13150	6879	23962
500	9624	4971	17888
520	6523	3325	12242
540	4059	2047	7664
560	2315	1156	4394
580	1215	599	2322
600	589	287	1136
620	265	128	513
640	112	53	219
660	44	20	88
680	17	7	33
700	6	3	12
720	2	1	4
Quality Stock Density	38%		
Preferred Stock Density	12%		

Regulation: Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439586	326951	592919	0.6540
2018	499677	351263	697054	0.8610
2019 Regulation Change	545859	356357	822566	0.9010
2020	460526	271477	744275	0.6319
2021	399887	223742	676597	0.4172
2022	361699	195670	620474	0.2933
2023 5 years After Change	339456	177632	588156	0.2270

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1492789	284979	3295652
Age-1	902487	174483	1966734
Age-2	527844	102255	1145391
Age-3	252000	46874	578482
Age-4	122187	21736	289753
Age-5	58177	9879	144224
Age-6	27771	4538	69908
Age-7	25602	9461	57350
Age-8	6268	2505	14240
Age-9	7089	2986	14703
Age-10	2227	982	4575
Age-11	2355	1036	4694
Age-12+	1681	796	3293
Abundance ≥Age-2	1033200		
% ≥Age-5	4%		
Adult Mortality	50%		

Regulation: Current provincial angling regulation – 4 fish creel limit with only 1 fish >460mm

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	397	0	2976
120	27829	266	183863
140	205696	15530	993124
160	469888	93701	1114775
180	503443	90416	1334549
200	276551	20738	805094
220	201858	37641	500203
240	269465	61855	566122
260	277150	73086	615861
280	227857	64125	493673
300	193899	58435	381421
320	172709	57746	341777
340	146121	54637	286016
360	117551	47177	220771
380	92526	39599	173327
400	71566	31981	133434
420	54144	24924	100820
440	39990	18866	74805
460	28737	13843	53646
480	19922	9840	37030
500	13169	6589	24719
520	8209	4109	15280
540	4789	2392	8924
560	2604	1295	4869
580	1320	652	2475
600	624	306	1174
620	276	133	523
640	115	54	218
660	45	21	87
680	17	8	33
700	6	3	12
720	2	1	4
Quality Stock Density	35%		
Preferred Stock Density	8%		

Regulation: 2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439859	326086	602573	0.6528
2018	498662	352257	703075	0.8591
2019 Regulation Change	523007	347297	777582	0.8657
2020	407206	257141	633625	0.4476
2021	311164	190927	493327	0.1147
2022	247441	149879	386899	0.0151
2023 5 years After Change	208982	123521	330507	0.0020

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	680627	233916	1336015
Age-1	402338	140612	770812
Age-2	236702	85574	451811
Age-3	118341	40188	243243
Age-4	60083	19491	127712
Age-5	30116	9155	67028
Age-6	15182	4463	35262
Age-7	31426	12029	69183
Age-8	7670	3176	16746
Age-9	8693	3786	17681
Age-10	2731	1251	5452
Age-11	2884	1326	5612
Age-12+	2061	1020	3949
Abundance ≥Age-2	515889		
% ≥Age-5	6%		
Adult Mortality	42%		

Regulation: 2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	37	0	347
120	4767	44	25159
140	70286	5571	214512
160	226545	59684	554073
180	237714	34225	471537
200	125293	9955	410257
220	91161	24733	244888
240	121612	42658	244391
260	125343	40936	232591
280	102696	33308	211232
300	87852	36228	169871
320	79302	33838	139591
340	68206	28854	120432
360	56012	25378	97965
380	45354	21839	78393
400	36680	18309	62663
420	29844	15602	50030
440	24486	13231	40828
460	19959	10903	33694
480	15703	8519	26837
500	11599	6230	20254
520	7905	4192	14009
540	4934	2592	8849
560	2820	1463	5093
580	1481	763	2692
600	718	366	1317
620	324	162	599
640	136	67	257
660	54	26	104
680	20	9	39
700	7	3	14
720	2	1	5
Quality Stock Density	41%		
Preferred Stock Density	13%		

Regulation: 2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439590	326534	598161	0.6562
2018	499237	350669	706607	0.8634
2019 Regulation Change	546630	359446	819757	0.9022
2020	482848	290337	784836	0.7033
2021	431876	243079	726832	0.5232
2022	398918	217955	679378	0.4111
2023 5 years After Change	379338	202634	654137	0.3468

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1503529	289190	3260108
Age-1	893170	171056	1962886
Age-2	528273	102333	1149914
Age-3	268047	49752	606377
Age-4	134259	24182	316388
Age-5	67921	11782	166116
Age-6	33963	5678	86383
Age-7	31460	12108	69598
Age-8	7696	3178	17038
Age-9	8703	3810	17670
Age-10	2734	1261	5378
Age-11	2888	1319	5618
Age-12+	2064	1024	3894
Abundance ≥Age-2	1088007		
% ≥Age-5	5%		
Adult Mortality	48%		

Regulation: 2 fish creel limit with 1 fish <460mm and 1 fish ≥460mm

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	390	0	2933
120	27418	262	184542
140	204589	15422	991912
160	473359	94416	1131509
180	509023	91372	1297609
200	279356	21125	788078
220	202126	36225	486514
240	267311	59749	568899
260	274024	71292	612291
280	225919	64255	483489
300	193847	58662	375183
320	174648	61316	341065
340	150190	57939	291728
360	123406	51069	230674
380	99331	42574	184339
400	78499	35337	144578
420	60660	28282	112003
440	45754	22213	84195
460	33525	16758	61863
480	23622	12080	43678
500	15808	8079	29285
520	9939	5128	18275
540	5831	3029	10684
560	3182	1655	5824
580	1616	836	2974
600	765	393	1415
620	339	172	633
640	141	70	268
660	55	27	107
680	21	10	41
700	7	3	15
720	2	1	5
Quality Stock Density	37%		
Preferred Stock Density	9%		

Regulation: 400-to-600mm protected slot size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439627	326678	596060	0.6542
2018	499715	352677	703096	0.8619
2019 Regulation Change	524698	349415	782778	0.8697
2020	408152	259544	637500	0.4508
2021	311782	192102	494827	0.1153
2022	248707	150079	395194	0.0182
2023 5 years After Change	209395	123248	330946	0.0022

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	674215	236498	1315462
Age-1	399410	142141	767289
Age-2	234906	83865	448951
Age-3	118717	40129	243556
Age-4	60608	19427	129184
Age-5	30323	9326	67902
Age-6	15118	4456	34993
Age-7	31425	12161	68806
Age-8	7686	3209	16725
Age-9	8721	3773	17780
Age-10	2738	1254	5438
Age-11	2893	1339	5681
Age-12+	2068	1032	3917
Abundance ≥Age-2	515204		
% ≥Age-5	6%		
Adult Mortality	42%		

Regulation: 400-to-600mm protected slot size limit with 2 fish creel limit
Recruitment: LOW
(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	36	0	355
120	4636	44	24751
140	68242	5525	209478
160	221596	59249	541634
180	236055	33899	466174
200	126516	9607	417743
220	91432	24558	244450
240	120789	43358	245401
260	124449	41667	230801
280	102073	34158	208399
300	87386	36540	166207
320	78976	33823	137193
340	68066	28977	119415
360	56024	25684	97557
380	45446	21928	77469
400	36795	18447	62078
420	29951	15766	49990
440	24568	13251	41430
460	20013	11051	34418
480	15735	8692	27451
500	11618	6402	20654
520	7916	4290	14206
540	4941	2655	8936
560	2824	1510	5135
580	1483	781	2716
600	720	374	1325
620	324	166	602
640	137	68	255
660	54	26	103
680	20	10	39
700	7	3	14
720	2	1	5
Quality Stock Density	41		
Preferred Stock Density	13		

Regulation: 400-to-600mm protected slot size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥$1.3B_{MSY}$ (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥$1.3B_{MSY}$
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439604	325682	598545	0.6521
2018	499796	350721	699659	0.8636
2019 Regulation Change	546173	360260	815343	0.9035
2020	482209	291907	775588	0.6984
2021	431128	246883	721612	0.5234
2022	398059	216974	678574	0.4113
2023 5 years After Change	377514	202558	647193	0.3425

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1489408	282353	3276479
Age-1	881006	169813	1921893
Age-2	524163	102659	1135758
Age-3	266034	49472	597511
Age-4	134646	23817	315809
Age-5	67437	11897	163145
Age-6	33988	5881	84579
Age-7	31401	11991	69398
Age-8	7677	3219	17036
Age-9	8701	3811	17775
Age-10	2730	1254	5378
Age-11	2882	1355	5581
Age-12+	2061	1024	3938
Abundance ≥Age-2	1081720		
% ≥Age-5	5%		
Adult Mortality	48%		

Regulation: 400-to-600mm protected slot size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	398	0	2971
120	27828	257	185258
140	204859	15038	991612
160	468188	92741	1125967
180	502854	91281	1312610
200	275881	20652	786854
220	199129	35393	486599
240	263661	60344	556151
260	270809	71913	598329
280	223798	66487	472531
300	192384	59673	373692
320	173415	60283	340425
340	149111	57410	288532
360	122515	50259	228738
380	98659	42854	184230
400	78050	34675	144736
420	60390	28175	110712
440	45596	22019	82940
460	33430	16601	60954
480	23562	11882	43062
500	15769	8086	28918
520	9915	5137	18237
540	5817	3027	10719
560	3175	1656	5875
580	1612	841	2976
600	763	396	1416
620	338	173	631
640	141	71	264
660	55	27	105
680	20	10	40
700	7	3	14
720	2	1	5
Quality Stock Density	37%		
Preferred Stock Density	9%		

Regulation: Current FMZ 11 regulation – 430-to-600mm protected slot size limit with 4 fish creel limit and only 1 fish >600mm

Recruitment: LOW

Biomass and Probability that it will be ≥1.3B$_{MSY}$ (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B$_{MSY}$
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439937	326575	597926	0.6550
2018	499695	352093	702665	0.8588
2019$_{\text{Regulation Change}}$	523966	349616	778957	0.8673
2020	397605	249092	628729	0.3992
2021	297274	180075	478896	0.0895
2022	233442	136488	377183	0.0125
2023$_{\text{5 years After Change}}$	195637	112857	317559	0.0009

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0$_{\text{Young-of-Year}}$	667705	232114	1320456
Age-1	396829	141402	772930
Age-2	235591	84771	452217
Age-3	116224	38936	239788
Age-4	57105	17991	124884
Age-5	27878	8298	62627
Age-6	13698	3895	32148
Age-7	28161	10654	63093
Age-8	6872	2811	14934
Age-9	7806	3339	16249
Age-10	2448	1101	4894
Age-11	2588	1167	5093
Age-12+	1851	893	3580
Abundance$_{\geq\text{Age-2}}$	500223		
% ≥Age-5	6%		
Adult Mortality	43%		

Regulation: Current FMZ 11 regulation – 430-to-600mm protected slot size limit with 4 fish creel limit and only 1 fish >600mm

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	38	0	358
120	4724	44	25133
140	68548	5501	207808
160	221386	58831	546494
180	233958	33317	472916
200	123439	9578	411527
220	89487	24345	243664
240	119739	42649	246145
260	123988	40945	232145
280	102105	32872	209846
300	87499	36233	167117
320	78704	33398	138265
340	67235	28533	117646
360	54719	24960	95225
380	43821	20921	75447
400	34984	16987	61158
420	28063	14218	48721
440	22707	11875	39335
460	18294	9741	32017
480	14274	7577	25384
500	10487	5513	18909
520	7124	3710	13047
540	4438	2287	8183
560	2534	1295	4698
580	1330	672	2471
600	645	321	1213
620	291	141	550
640	122	59	234
660	48	23	94
680	18	8	36
700	6	3	13
720	2	1	4
Quality Stock Density	40%		
Preferred Stock Density	12%		

Regulation: Current FMZ 11 regulation – 430-to-600mm protected slot size limit with 4 fish creel limit and only 1 fish >600mm

Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B$_{MSY}$ (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B$_{MSY}$
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439663	326333	596215	0.6553
2018	500021	351715	703929	0.8585
2019$_{\text{Regulation Change}}$	546713	358648	821367	0.9042
2020	472315	280929	769111	0.6669
2021	415027	231722	698749	0.4688
2022	378718	204085	639067	0.3465
2023$_{\text{5 years After Change}}$	356230	188375	614848	0.2787

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0$_{\text{Young-of-Year}}$	1488242	285974	3219475
Age-1	889116	172172	1946477
Age-2	524673	101971	1131705
Age-3	257786	48042	598359
Age-4	127174	22570	300976
Age-5	62375	10849	154636
Age-6	30857	5306	77625
Age-7	28207	10756	62868
Age-8	6906	2812	15461
Age-9	7822	3406	16033
Age-10	2458	1108	4958
Age-11	2595	1187	5121
Age-12+	1858	896	3576
Abundance$_{\geq\text{Age-2}}$	1052711		
% ≥Age-5	4%		
Adult Mortality	49%		

Regulation: Current FMZ 11 regulation – 430-to-600mm protected slot size limit with 4 fish creel limit and only 1 fish >600mm

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	385	0	2930
120	27029	260	184537
140	201774	15406	990890
160	468266	92795	1112065
180	504780	91865	1293179
200	276979	21167	782452
220	200600	37746	487544
240	265852	60006	568700
260	272945	72356	609998
280	225042	63992	483736
300	192448	58548	376416
320	172298	59529	337091
340	146879	55874	284409
360	119404	48535	221151
380	95059	40680	178279
400	74345	33015	139129
420	56879	26303	105242
440	42492	20247	78315
460	30865	15036	57456
480	21592	10738	40046
500	14370	7233	26490
520	8999	4562	16656
540	5265	2686	9764
560	2869	1462	5311
580	1455	736	2692
600	688	346	1280
620	305	151	576
640	127	62	241
660	50	24	96
680	18	9	36
700	7	3	13
720	2	1	4
Quality Stock Density	36%		
Preferred Stock Density	9%		

Regulation: 400mm minimum size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439642	327360	600839	0.6538
2018	499084	350226	699496	0.8613
2019$_{\text{Regulation Change}}$	523176	344225	777581	0.8597
2020	435033	275191	677420	0.5638
2021	351765	220458	544196	0.2271
2022	290824	180384	449513	0.0628
2023$_{\text{5 years After Change}}$	250816	152718	383754	0.0132

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0$_{\text{Young-of-Year}}$	672093	231093	1328582
Age-1	398002	141558	766417
Age-2	236750	85129	451711
Age-3	128131	44493	256632
Age-4	69333	22646	146395
Age-5	37543	12015	79968
Age-6	20207	6370	44450
Age-7	41553	16799	87973
Age-8	10142	4434	21050
Age-9	11504	5346	22471
Age-10	3611	1776	6865
Age-11	3817	1871	7128
Age-12+	2726	1465	5009
Abundance$_{\geq\text{Age-2}}$	565317		
% ≥Age-5	8%		
Adult Mortality	39%		

Regulation: 400mm minimum size limit with 2 fish creel limit

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	39	0	365
120	4787	44	25363
140	68985	5522	205804
160	222011	59006	545745
180	234886	32509	472966
200	124909	9412	410456
220	90453	24270	244682
240	120188	43320	244786
260	124320	41378	231018
280	102574	33242	206988
300	88472	36271	166618
320	80768	34490	139899
340	70835	30311	123162
360	59825	28018	101810
380	50064	24536	83520
400	41964	21517	69021
420	35443	19147	57661
440	30111	17030	49014
460	25229	14551	41422
480	20224	11604	33912
500	15112	8585	25570
520	10368	5887	17670
540	6496	3650	11176
560	3721	2087	6435
580	1957	1089	3394
600	950	523	1654
620	428	232	749
640	180	96	322
660	71	37	130
680	27	13	50
700	9	5	18
720	3	2	6
Quality Stock Density	45%		
Preferred Stock Density	16%		

Regulation: 400mm minimum size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439433	326147	598957	0.6539
2018	499443	351130	706074	0.8582
2019 Regulation Change	546164	358022	819969	0.9013
2020	514214	312955	817193	0.7972
2021	481438	279595	784457	0.6893
2022	457649	257326	762670	0.6153
2023 5 years After Change	441993	243192	747216	0.5677

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1500392	282524	3293529
Age-1	889008	171424	1939013
Age-2	526985	101042	1156358
Age-3	285934	53238	628519
Age-4	153801	28202	354897
Age-5	82713	14680	194829
Age-6	45128	7870	108397
Age-7	41538	16842	88952
Age-8	10128	4370	21143
Age-9	11479	5259	22385
Age-10	3608	1759	6894
Age-11	3812	1832	7154
Age-12+	2718	1441	4944
Abundance ≥Age-2	1167846		
% ≥Age-5	6%		
Adult Mortality	45%		

Regulation: 400mm minimum size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	394	0	2946
120	27601	260	181345
140	204657	15320	993915
160	471389	93345	1113661
180	507925	90648	1341939
200	279448	20467	811990
220	202154	35934	496338
240	266309	60037	560015
260	272260	71353	606065
280	224693	63329	482724
300	194125	58522	374113
320	177165	61678	343735
340	155354	59410	298462
360	130948	54325	241966
380	108512	48116	197976
400	88484	40433	160415
420	70651	33860	126841
440	55014	27505	98010
460	41450	21378	73322
480	29855	15618	52678
500	20296	10764	35684
520	12896	6930	22461
540	7616	4139	13244
560	4173	2282	7264
580	2124	1160	3730
600	1007	541	1768
620	446	237	792
640	186	96	333
660	73	37	133
680	27	13	50
700	10	5	18
720	3	2	6
Quality Stock Density	40%		
Preferred Stock Density	11%		

Regulation: Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439593	326263	599311	0.6586
2018	499232	352664	700979	0.8642
2019 Regulation Change	524064	346090	780093	0.8658
2020	463715	299586	701388	0.6804
2021	393637	251763	593094	0.3944
2022	337322	214762	505734	0.1731
2023 5 years After Change	297244	187521	444828	0.0612

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	672034	231406	1320465
Age-1	398325	140472	772595
Age-2	238458	84714	451771
Age-3	135800	47270	270967
Age-4	78117	26178	159875
Age-5	45019	14833	94513
Age-6	26277	8508	56125
Age-7	53661	22380	110639
Age-8	13115	5941	26383
Age-9	14833	7205	27777
Age-10	4667	2384	8650
Age-11	4929	2483	8979
Age-12+	3524	1935	6188
Abundance ≥Age-2	618401		
% ≥Age-5	10%		
Adult Mortality	37%		

Regulation: Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit
Recruitment: LOW
(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	37	0	340
120	4683	44	24188
140	68712	5417	209708
160	222316	58700	546333
180	235209	33114	468148
200	124967	9861	413970
220	90957	24594	246262
240	120882	43245	243805
260	124479	40855	231229
280	102533	33454	207036
300	88961	36389	167509
320	82122	35220	142067
340	73208	31679	127650
360	63275	29556	107256
380	54506	26893	89888
400	47240	24591	76597
420	41348	23057	65718
440	36307	21089	57217
460	31216	18503	49565
480	25465	15208	40785
500	19234	11447	31134
520	13279	7867	21743
540	8351	4923	13715
560	4793	2809	7925
580	2523	1456	4209
600	1226	700	2066
620	553	311	942
640	233	129	404
660	92	50	162
680	34	18	62
700	12	6	22
720	4	2	8
Quality Stock Density	48%		
Preferred Stock Density	18%		

Regulation: Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439992	326101	600385	0.6562
2018	499876	351155	705047	0.8560
2019 Regulation Change	547201	359347	822159	0.9027
2020	546621	337491	867461	0.8682
2021	535309	315382	860284	0.8288
2022	524308	300915	850799	0.8009
2023 5 years After Change	514354	294586	835934	0.7772

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1487836	287174	3259102
Age-1	891667	171843	1927559
Age-2	528378	102392	1153170
Age-3	302628	58042	671921
Age-4	174182	33845	395548
Age-5	100775	18601	234636
Age-6	58274	10538	137833
Age-7	53627	22597	109895
Age-8	13098	5912	26319
Age-9	14853	7147	28254
Age-10	4666	2343	8592
Age-11	4933	2520	8834
Age-12+	3525	1936	6146
Abundance ≥Age-2	1258938		
% ≥Age-5	7%		
Adult Mortality	42%		

Regulation: Current Lake Nipissing regulation – 460mm minimum size limit with 2 fish creel limit
Recruitment: HIGH
(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	378	0	2874
120	26536	259	179140
140	199219	15198	959232
160	467013	92926	1106139
180	506645	92291	1308832
200	278668	20285	807877
220	201439	35723	486312
240	266554	60752	557920
260	273686	73060	607821
280	226317	65591	489347
300	195973	62221	378734
320	180356	63576	347256
340	160812	62822	302350
360	138829	58767	251336
380	118372	53493	213168
400	99571	48192	175697
420	82054	41178	142108
440	65786	34323	113287
460	50781	27290	87521
480	37248	20554	64089
500	25646	14391	43603
520	16433	9326	27793
540	9758	5592	16408
560	5366	3058	8985
580	2737	1558	4591
600	1300	734	2194
620	577	319	983
640	240	130	416
660	94	50	166
680	35	18	63
700	12	6	23
720	4	2	8
Quality Stock Density	43%		
Preferred Stock Density	13%		

Regulation: 400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439473	324397	596287	0.6575
2018	499202	350556	701550	0.8604
2019 Regulation Change	523986	346262	783655	0.8652
2020	442783	282046	675982	0.5991
2021	361443	228971	553523	0.2635
2022	302037	187447	463354	0.0780
2023 5 years After Change	261324	161206	398733	0.0190

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	678837	233292	1330546
Age-1	395444	142556	760898
Age-2	233625	84173	452701
Age-3	129234	44797	255922
Age-4	72039	24063	148106
Age-5	39327	12570	83945
Age-6	21509	6739	47114
Age-7	44249	18261	93670
Age-8	10808	4800	22156
Age-9	12232	5761	23692
Age-10	3846	1915	7223
Age-11	4064	2027	7557
Age-12+	2908	1543	5259
Abundance ≥Age-2	573841		
% ≥Age-5	8%		
Adult Mortality	38%		

Regulation: 400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	38	0	361
120	4845	46	25296
140	70588	5717	212263
160	226434	59785	546364
180	236936	33699	470411
200	124224	9422	409060
220	89597	23894	241799
240	119250	42907	244233
260	123229	40704	228993
280	101498	32604	208946
300	87511	36324	167449
320	80168	34660	140821
340	70812	30746	124458
360	60384	28381	103127
380	51069	25201	85259
400	43254	22202	71362
420	36882	19917	59663
440	31582	17966	50964
460	26615	15340	43488
480	21416	12410	35533
500	16040	9209	26905
520	11019	6314	18664
540	6910	3923	11780
560	3959	2235	6771
580	2082	1164	3569
600	1011	560	1738
620	456	249	792
640	192	103	339
660	76	40	136
680	28	14	52
700	10	5	19
720	3	2	7
Quality Stock Density	46%		
Preferred Stock Density	16%		

Regulation: 400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥$1.3B_{MSY}$ (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥$1.3B_{MSY}$
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439133	325433	595166	0.6533
2018	499362	350780	696933	0.8621
2019 Regulation Change	547371	357599	820315	0.9000
2020	523986	322138	832850	0.8165
2021	496339	289925	805478	0.7323
2022	474682	269742	779525	0.6679
2023 5 years After Change	460208	256182	760356	0.6237

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1496995	288129	3285312
Age-1	882460	170196	1919696
Age-2	524584	102297	1161585
Age-3	291162	54087	657020
Age-4	158905	29442	362044
Age-5	87705	15880	206486
Age-6	48110	8325	116568
Age-7	44502	17935	94215
Age-8	10894	4763	22418
Age-9	12321	5691	23951
Age-10	3873	1880	7363
Age-11	4085	2049	7570
Age-12+	2924	1540	5305
$Abundance_{\geq Age\text{-}2}$	1189066		
% ≥Age-5	6%		
Adult Mortality	44%		

Regulation: 400-to-500mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	384	0	2944
120	27037	253	184977
140	202596	15217	998197
160	471635	93327	1120531
180	508123	90436	1308097
200	278288	20374	793144
220	200602	36155	493992
240	264167	60266	561039
260	270252	71477	597414
280	223378	64976	480865
300	193583	59828	378527
320	177520	62867	353521
340	156640	61019	303530
360	132984	55821	244863
380	111057	48958	202564
400	91324	42375	163696
420	73558	35505	129994
440	57742	28996	102152
460	43794	22854	77073
480	31697	17096	55608
500	21621	11826	37921
520	13769	7571	23999
540	8144	4528	14129
560	4468	2477	7719
580	2276	1255	3934
600	1080	586	1880
620	479	258	832
640	199	106	351
660	78	41	140
680	29	15	53
700	10	5	19
720	3	2	7
Quality Stock Density	41%		
Preferred Stock Density	11%		

Regulation: 450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439611	326508	599902	0.6526
2018	499349	352307	703617	0.8616
2019$_{\text{Regulation Change}}$	524463	347930	783271	0.8657
2020	463542	298348	706114	0.6833
2021	394119	253267	593894	0.4022
2022	338187	215843	505947	0.1692
2023$_{\text{5 years After Change}}$	297965	190779	445434	0.0603

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0$_{\text{Young-of-Year}}$	672569	234509	1314178
Age-1	398399	141437	762583
Age-2	235118	84934	451802
Age-3	135958	47566	265986
Age-4	79098	26657	161151
Age-5	45401	14805	93967
Age-6	26167	8312	54564
Age-7	53655	22530	110116
Age-8	13129	5963	26640
Age-9	14856	7160	28007
Age-10	4671	2354	8575
Age-11	4934	2513	8910
Age-12+	3528	1949	6205
Abundance$_{\geq \text{Age-2}}$	616515		
% ≥Age-5	10%		
Adult Mortality	36%		

Regulation: 450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	38	0	355
120	4737	45	24961
140	69079	5508	209410
160	222665	58164	540259
180	235141	33507	465145
200	124872	9887	412918
220	90768	24731	240557
240	120577	43013	243408
260	124187	41285	229561
280	102077	32120	207477
300	88250	36701	166140
320	81482	35448	141546
340	72909	31787	127140
360	63294	30141	107417
380	54697	27500	90296
400	47480	25227	76609
420	41561	23489	65936
440	36461	21612	57160
460	31309	18729	49180
480	25515	15289	40447
500	19259	11473	31048
520	13291	7856	21696
540	8357	4921	13735
560	4796	2788	7928
580	2525	1454	4182
600	1227	698	2052
620	553	310	937
640	233	127	399
660	92	49	161
680	35	18	61
700	12	6	22
720	4	2	8
Quality Stock Density	48%		
Preferred Stock Density	18%		

Regulation: 450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439411	325710	597288	0.6517
2018	499550	352422	703110	0.8619
2019 Regulation Change	545482	358638	824155	0.9045
2020	543679	334882	862162	0.8633
2021	533349	313097	853736	0.8253
2022	523956	304018	841546	0.7964
2023 5 years After Change	515329	299684	825952	0.7805

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1508424	286625	3320566
Age-1	884163	170266	1936653
Age-2	524626	101253	1144481
Age-3	304429	57923	678866
Age-4	175995	33506	396097
Age-5	100958	18724	227737
Age-6	57697	10374	134949
Age-7	53703	22798	109548
Age-8	13160	5929	26909
Age-9	14894	7153	28424
Age-10	4676	2372	8603
Age-11	4942	2508	8930
Age-12+	3531	1958	6174
Abundance ≥Age-2	1258611		
% ≥Age-5	7%		
Adult Mortality	42%		

Regulation: 450-to-550mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	399	0	3002
120	27940	260	186624
140	206949	15356	1004833
160	474948	93916	1105618
180	509424	91584	1357536
200	278864	20791	821978
220	200507	36089	494246
240	264846	59730	560449
260	271514	71016	599601
280	224336	63213	476594
300	194565	59837	373293
320	179619	63692	348305
340	160722	63797	304618
360	139191	58719	251773
380	118898	54498	209978
400	100028	48595	173710
420	82338	41887	140992
440	65904	34711	111952
460	50799	27385	86721
480	37229	20280	62981
500	25626	14212	43222
520	16423	9299	27568
540	9755	5597	16308
560	5366	3084	8972
580	2739	1563	4576
600	1301	734	2188
620	577	324	983
640	240	132	415
660	94	51	166
680	35	18	63
700	12	6	23
720	4	2	8
Quality Stock Density	43%		
Preferred Stock Density	13%		

Regulation: 400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B$_{MSY}$ (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B$_{MSY}$
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439765	326626	593441	0.6554
2018	499616	351862	698267	0.8585
2019$_{\text{Regulation Change}}$	524180	346530	777091	0.8658
2020	453735	289758	691674	0.6345
2021	378877	239696	579652	0.3331
2022	321377	201418	487749	0.1246
2023$_{\text{5 years After Change}}$	281079	175072	425350	0.0415

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0$_{\text{Young-of-Year}}$	680811	234967	1332855
Age-1	399475	141221	772567
Age-2	235967	84762	449525
Age-3	133837	46518	267628
Age-4	75399	25414	154275
Age-5	42538	13913	89450
Age-6	24015	7517	51864
Age-7	49244	20679	103688
Age-8	12078	5352	25158
Age-9	13663	6379	25990
Age-10	4292	2141	7954
Age-11	4536	2263	8290
Age-12+	3242	1764	5745
Abundance$_{\geq\text{Age-2}}$	598812		
% ≥Age-5	9%		
Adult Mortality	37%		

Regulation: 400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW
(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	38	0	352
120	4747	44	25061
140	69588	5487	208638
160	225129	58429	543019
180	238032	33748	471261
200	126395	9626	417164
220	91295	24577	246917
240	120945	42946	245856
260	124707	40748	231174
280	102556	33082	206690
300	88516	36284	167551
320	81390	35112	141178
340	72327	31617	126190
360	62189	29084	105742
380	53123	26208	88524
400	45531	23549	74705
420	39355	21638	63264
440	34153	19562	54538
460	29097	17001	47064
480	23593	13882	38920
500	17757	10417	29513
520	12235	7128	20560
540	7687	4460	12999
560	4410	2549	7488
580	2321	1330	3957
600	1128	640	1927
620	509	283	878
640	214	117	377
660	85	45	153
680	32	16	58
700	11	6	21
720	4	2	7
Quality Stock Density	47%		
Preferred Stock Density	17%		

Regulation: 400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439226	326729	599880	0.6496
2018	499522	350170	708062	0.8618
2019 Regulation Change	546405	359078	818788	0.9027
2020	534405	329997	850930	0.8426
2021	514714	302529	826572	0.7822
2022	499658	284941	810968	0.7361
2023 5 years After Change	488251	271155	807238	0.7061

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1505395	288855	3287430
Age-1	883339	170253	1923209
Age-2	526665	102544	1142583
Age-3	297629	56549	672913
Age-4	168148	31224	380353
Age-5	94029	17123	218805
Age-6	53062	9527	125952
Age-7	49135	20284	102031
Age-8	12027	5341	25402
Age-9	13596	6426	26429
Age-10	4270	2117	7917
Age-11	4513	2247	8289
Age-12+	3223	1742	5672
Abundance ≥Age-2	1226296		
% ≥Age-5	6%		
Adult Mortality	43%		

Regulation: 400-to-450mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	403	0	3074
120	28273	261	187558
140	208602	15309	989819
160	474811	94658	1124142
180	506688	90897	1325693
200	276569	20436	808545
220	198934	36292	487799
240	264230	59551	564219
260	272044	69898	607846
280	225294	64457	484380
300	195127	60265	377352
320	179116	62386	344457
340	158870	60284	302715
360	136172	55756	250695
380	115086	50609	208142
400	95801	44539	171153
420	78053	38487	137982
440	61899	31476	108113
460	47350	24791	81738
480	34499	18517	59083
500	23646	12965	40153
520	15108	8405	25730
540	8955	5037	15147
560	4919	2778	8390
580	2508	1411	4255
600	1190	662	2032
620	528	289	909
640	220	118	383
660	86	45	153
680	32	16	58
700	11	6	21
720	4	2	7
Quality Stock Density	42%		
Preferred Stock Density	12%		

Regulation: 450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: LOW

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	439652	325805	598008	0.6552
2018	499544	351852	699029	0.8643
2019$_{\text{Regulation Change}}$	524147	345778	776814	0.8645
2020	472290	303935	721462	0.7114
2021	407115	257622	613811	0.4566
2022	353738	224892	529827	0.2267
2023$_{\text{5 years After Change}}$	314862	200355	464000	0.0948

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0$_{\text{Young-of-Year}}$	670696	234395	1312629
Age-1	397210	142640	766900
Age-2	237954	84669	451739
Age-3	138872	48493	272319
Age-4	82045	27716	165445
Age-5	47659	15792	99152
Age-6	28239	9213	59278
Age-7	58269	24550	118175
Age-8	14237	6554	28727
Age-9	16127	7936	30391
Age-10	5067	2609	9222
Age-11	5356	2743	9668
Age-12+	3828	2134	6632
Abundance$_{\geq\text{Age-2}}$	637652		
% ≥Age-5	10%		
Adult Mortality	36%		

Regulation: 450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: LOW

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	36	0	343
120	4638	42	24231
140	68388	5402	210835
160	221955	59473	544527
180	234910	33448	463061
200	124782	9546	409370
220	90856	24265	242633
240	120480	43379	244341
260	123839	41208	231169
280	102008	33563	209426
300	88839	37398	168329
320	82599	35336	142322
340	74283	32262	128615
360	64802	30528	109371
380	56344	28341	91667
400	49310	26091	78760
420	43589	24513	68333
440	38617	22581	60092
460	33431	19812	52602
480	27403	16342	43492
500	20764	12337	33200
520	14365	8511	23101
540	9045	5333	14603
560	5196	3052	8473
580	2737	1595	4497
600	1330	765	2194
620	600	340	999
640	253	141	428
660	100	54	173
680	37	20	66
700	13	7	24
720	4	2	8
Quality Stock Density	49%		
Preferred Stock Density	19%		

Regulation: 450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit
Recruitment: HIGH

Biomass and Probability that it will be ≥1.3B_{MSY} (current management target)

Year	Biomass (kg) of Walleye ≥350mm total length			Probability that Biomass ≥1.3B_{MSY}
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval	
2014	371450	292546	456267	0.1919
2015	406449	321548	507841	0.4746
2016	382377	295754	503446	0.2814
2017	440123	326632	596288	0.6548
2018	500065	353252	706042	0.8553
2019 Regulation Change	546851	356570	813301	0.8985
2020	555043	346521	860057	0.8846
2021	550675	329766	869236	0.8650
2022	544509	319921	869546	0.8422
2023 5 years After Change	538966	311923	871508	0.8293

Abundance and Age Structure 5 years After Regulation Change

Age (year)	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Age-0 Young-of-Year	1487312	285413.5	3279221
Age-1	893340.6	171943.9	1919992
Age-2	523486.6	102978.6	1167431
Age-3	309221.1	59096.93	682432.4
Age-4	180890.1	34379.84	401252.6
Age-5	106648.4	19760.08	242862
Age-6	62469.14	11566.28	145338.5
Age-7	58014.1	24552.31	117882.4
Age-8	14202.63	6548.588	28951.65
Age-9	16116.96	7736.989	30487.8
Age-10	5061.27	2608.981	9198.348
Age-11	5344.891	2732.854	9566.681
Age-12+	3819.331	2132.552	6733.08
Abundance ≥Age-2	1285275		
% ≥Age-5	7%		
Adult Mortality	41%		

Regulation: 450-to-500mm fishable (harvest) slot size limit with 2 fish creel limit

Recruitment: HIGH

(continued)

Size Structure 5 years After regulation Change

Total Length (mm) Lower Boundary of 20mm Size Bins	Walleye Abundance (number)		
	Average	Lower 95% Confidence Interval	Upper 95% Confidence Interval
100	391	0	2983
120	27451	259	185723
140	203761	15173	979706
160	468377	93470	1124174
180	502573	90952	1335150
200	275795	20881	804817
220	200771	35813	489078
240	267057	60383	559145
260	274006	72490	596438
280	225741	64484	475170
300	195163	59490	376248
320	180367	63802	354275
340	162167	64353	310382
360	141408	60100	258227
380	121748	54717	219223
400	103325	49430	182915
420	85864	43622	148341
440	69379	36987	118358
460	53923	29578	90650
480	39772	22293	66141
500	27499	15740	45343
520	17674	10232	28950
540	10517	6139	17121
560	5792	3373	9469
580	2958	1717	4879
600	1405	810	2334
620	624	356	1047
640	260	146	441
660	102	56	177
680	38	20	67
700	13	7	24
720	5	2	8
Quality Stock Density	44%		
Preferred Stock Density	13%		