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Effects of Harvest Regulations and Post-release Hooking Mortality on Walleye Populations in South Dakota

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EFFECTS OF HARVEST REGULATIONS AND POST-RELEASE HOOKING MORTALITY ON WALLEYE POPULATIONS IN SOUTH DAKOTA

BY

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THESIS ACCEPTANCE PAGE

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This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABSTRACT

EFFECTS OF HARVEST REGULATIONS AND POST-RELEASE HOOKING MORTALITY ON WALLEYE POPULATIONS IN SOUTH DAKOTA

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Harvest regulations are commonly implemented to manipulate fisheries stocks. By regulating the size and number of fish that are harvested by anglers, managers are able to meet the goals and needs of regions. However, these management actions come with the potential for negative consequences. Overexploitation due to less restrictive harvest regulations can cause collapses in fisheries populations. In addition, indirect consequences such as hooking mortality brought on by length-based regulations can also be detrimental to populations. In this study, I investigated the effects of various harvest regulations on Walleye populations in three western South Dakota irrigation reservoirs: Angostura, Belle Fourche, and Shadehill. A jaw-tagging study was initiated to estimate angler exploitation in each reservoir. Shadehill had the highest exploitation in 2018 and Angostura had the highest exploitation in 2019. Sagittal otoliths were sampled from Walleye to estimate growth and mortality in each reservoir. Walleye in Angostura exhibited the highest growth rates and highest estimates of mortality. From Fisheries Analysis and Modelling Simulator (FAMS) simulations, yield (kg) was highest for every reservoir when modeled with a 381 mm minimum length limit (MLL). Results from this

study reveal that Angostura Reservoir contains a highly productive Walleye population that experiences significant angler exploitation. I also evaluated the effects of capture depth and water temperature on Walleye hooking mortality. The study was split into two angling seasons: an ice fishing season that was conducted on Lake Sharpe and Lake Oahe in February of 2020, and an open water season on Belle Fourche Reservoir in July of 2020. After angling, Walleye were placed into holding pens to monitor post-release mortality. During the ice fishing season, hooking mortality of Walleye was 20%. No mortalities occurred during the open water season. The variables capture depth, fishing season, and air exposure were the most influential variables on mortality. Walleye were generally caught from deeper depths and exposed to air for longer periods of time in winter compared to summer. Results from this study indicate that hooking mortality needs to be considered when implementing length-based regulations, especially in lakes where Walleye angling occurs at depths greater than 10 m.

CHAPTER 1: INTRODUCTION

Walleye *Sander vitreus* anglers are generally harvest-oriented and can impact populations, age and size structure, biomass, and production (Fayram 2003; Colby and Baccante 1996). Applying appropriate management regulations is crucial in sustaining quality sport fisheries. Fisheries managers need to understand both biotic and abiotic factors and how they influence fish populations. These influences on fish populations can be observed through dynamic rate functions such as growth and mortality.

Fish growth is driven primarily by water temperature and prey availability (Venturelli et al. 2010; Meerbeek et al. 2002). Walleye in colder, northern latitudes grow slower and live longer than their warmer, southern counterparts where growth is fast and life is short (Beverton 1987). A two-fold variation in growth rates among Quebec and Ontario Walleye populations was found due to differences in food availability (Venturelli et al. 2010). Walleye abundance and growth increased after introductions of Gizzard Shad *Dorosoma cepedianum* into Angostura Reservoir, South Dakota (Ward et al. 2007). Rainbow Smelt *Osmerus mordax* have also been shown to increase Walleye growth rates (Fincel et al. 2014) and increase catches of big Walleye (Johnson and Goettl 1999). In addition, Walleye growth rates are subjected to density dependence. Nate et al. (2011) found that average length at age was inversely related to adult population density in Walleye. After experimentally-held exploitation rates of 35%, average adult biomass was 34% lower and 3 to 6 year old Walleye mean total length increased significantly in Big Crooked Lake, Wisconsin (Schmalz et al. 2011).

Two sources of mortality exist in angler-exploited systems: natural and angling. Walleye natural mortality rates of 39 to 53% per year were estimated in an unexploited

impoundment in Pennsylvania (Kocovsky and Carline 2001). Walleye natural mortality rates decrease with age in response to increased angling mortality (Hansen et al. 2011). Angler exploitation rates of North American Walleye populations range from 3 to 55.6%, with a median exploitation rate of 21% (Baccante and Colby 1996). Site specific angler exploitation on Lake Oahe, South Dakota ranged from 15 to 39% from 2013 to 2016 (Felts 2018).

Hooking mortality, or the mortality associated from the catch and subsequent release of fish, constitutes a secondary component of angling mortality. North American non-tournament Walleye hooking mortality ranges from 1.1 to 31% (Fletcher 1987; Payer et al. 1989; Reeves and Brusewitz 2007; Talmage and Staples 2011). Its impacts are typically seen in catch and release fisheries where length-based regulations dictate which fish can be harvested and which must be released. Due to this, these regulations can potentially harm populations. During the 1990's, Alberta implemented length-based regulations in response to collapsing Walleye stocks due to overfishing. Following implementation, summer post-release hooking mortality of Walleyes averaged 44% and ranged from 27 to 79%; post-release mortality was estimated to be less than 1% prior to regulation changes (Sullivan 2003).

Managers may enact regulations on what fish can be harvested to limit harvest and prevent overfishing. Growth overfishing occurs when fish are harvested before they reach a size to attain maximum yield. Growth overfishing can be prevented with minimum length limits (MLL) (Quist et al. 2010) as they protect the smaller stock of populations from being harvested. Recruitment overfishing occurs when too many fish are harvested so that they are unable to replace themselves in the population. In brown

trout *Salmo trutta*, MLL's caused recruitment overfishing by focusing harvest on adult fish, limiting recruitment (Sanchez-Hernandez et al. 2016). While similar results were found in a study involving MLL's on northern pike populations, harvest slot limits were effective in preventing recruitment overfishing (Arlinghaus et al. 2010).

Minimum length limits are a common length-based regulation managers use to maximize the average size of harvested fish by protecting fish below a certain size (Brousseau and Armstrong 1987). The Walleye population in Lake Francis Case, South Dakota saw significant increases in abundance and proportional size distribution (PSD) following the implementation of a partial-year 356 mm MLL (Stone and Lott 2002). Similar results were seen on Meredith Reservoir, Texas following the implementation of a 407 mm MLL as both total and legal-size abundance of Walleyes increased, paired with decreases in walleye growth rates (Munger and Kraai 1997). By contrast, Walleye population abundance, age structure, and size structure saw no improvements following MLL implementations on three Minnesota lakes (Isermann 2007).

In addition to MLL's, protected slot limits (PSL) are another common length-based regulation. By protecting fish within a given range of total lengths, the PSL is designed to increase harvest of fish below the slot to maintain or improve growth and recruitment into and through the slot leaving fish available above the slot (Brousseau and Armstrong 1987). The current knowledge regarding the effects of PSL's on fish populations is limited, particularly with Walleye. Protected slot limits have been shown to increase population size and proportional size distribution (PSD) in Largemouth Bass *Micropterus salmoides* populations (Wilde 1997). Following a PSL implementation on a Smallmouth Bass *Micropterus dolomieu* population in Elkhorn Creek, Kentucky, a large

increase in density of PSL-length fish was observed followed by a decline, probably due to other factors (Buynak and Mitchell 2002). Slot limits on various Northern Pike *Esox lucius* populations in Minnesota lakes led to a general increase in size structure (Pierce 2010).

Hooking mortality rates can be increased due to elevated rates of catch and release angling brought on by length-based regulations. Water temperature and capture depth have been shown to influence hooking mortality in fish (Graeb et al. 2005; Talmage and Staples 2011). During tournament conditions, Walleye hooking mortality rates significantly increase when water temperatures exceed 18°C (Hoffman et al. 1996; Graeb et al. 2005). Hooking mortality of Walleye and Sauger *Sander canadensis* increases significantly in depths exceeding 9 m (Schreer et al. 2009; Meerbeek and Hoxmeier 2011). Walleyes caught in 12.2 m have over an 18% chance of mortality (Talmage and Staples 2011).

In South Dakota, the Missouri River bisects the state along the Northwestern Glaciated Plains ecoregion (east of the Missouri River, ER) and the Northwestern Great Plains ecoregion (west of the Missouri River, WR). As a result of glaciation, the topography of ER contains numerous natural lakes and wetlands (Johnson and Higgins 1997). In contrast, the unglaciated WR has few natural lakes and wetlands. Additionally, WR doesn't receive as much precipitation as ER (Norton et al. 2014). Due to this, the few WR lakes and reservoirs have become regionally important. In addition to fishing recreation, the three most popular Walleye fisheries in western South Dakota double as irrigation reservoirs. Managed by the U.S. Bureau of Reclamation for the purpose of irrigation, Angostura, Belle Fourche, and Shadehill reservoirs can experience large

drawdowns during peak usage summer months. Belle Fourche Reservoir alone provides irrigation water to over 23,000 hectares of farmland in western South Dakota (McCune 2001).

Walleye management strategies contrast between ER and WR. Much of ER Walleye fisheries follow the South Dakota statewide harvest and length limits: a four fish daily limit with one over 508 mm in length. However, the aforementioned Walleye populations in the WR reservoirs are all managed using length-based regulations. Angostura and Shadehill Reservoirs are managed with a 381 mm MLL and a four fish daily limit. This regulation is designed to protect smaller fish from harvest leading to increased average fish sizes. In South Dakota, satisfaction of five criteria are required to implement a 381 mm MLL: 1. Fast growth (381 mm by age-4); 2. Periods of high exploitation; 3. Low natural mortality; 4. Low probability of winterkill; and 5. Sporadic or limited natural recruitment requiring frequent stocking (Lucchesi and Blackwell 2009). Belle Fourche Reservoir is the only waterbody in South Dakota that enforces a PSL on Walleye. Fish caught under 381 mm and over 457 mm may be harvested, with one over 457 mm and a four fish daily limit. Regarded as an experimental regulation, the PSL is designed to increase pressure on sub-381 mm fish which will improve size structure (Lucchesi and Blackwell 2009).

Anglers spend a combined 200,000 hours between these three reservoirs in a given year, with Walleye being the primary targeted species (SDGF&P; Unpublished SDGF&P data). Currently, angler exploitation and its impact on the Walleye populations with present regulations is unknown on these reservoirs. Additionally, if post-release hooking mortality is significant, the effectiveness of the PSL on Belle Fourche will be

diminished, leading to negative impacts on the population. The objectives of my study are to: 1. Estimate effects of water temperature and capture depth on hooking mortality of Walleye in Belle Fourche Reservoir; and 2. Obtain information on growth, mortality, and angler exploitation to model current and potential future regulation changes for the Walleye populations in Angostura, Belle Fourche, and Shadehill irrigation Reservoirs.

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CHAPTER 2: EFFECTS OF CAPTURE DEPTH AND WATER TEMPERATURE ON WALLEYE HOOKING MORTALITY

Abstract

Length-based regulations are a common tool that fisheries managers use to limit fishing mortality by regulating the size of fish that are harvested. Nonetheless, mortality associated with catch-and-release angling brought about by length-based regulations may negatively impact a fishery. In this study, I evaluated effects of capture depth and water temperature on hooking mortality of Walleye *Sander vitreus* in three South Dakota reservoirs. The study was split into two angling seasons: an ice fishing season that was conducted on Lake Sharpe and Lake Oahe in February of 2020, and an open water season on Belle Fourche Reservoir in July of 2020. After angling, Walleye (n=130) were placed into holding pens for 12 to 72 h to monitor post-release mortality. During the ice fishing season, hooking mortality of Walleye was 20%. In contrast, no hooking-related mortalities were observed among Walleye during the summer season. Using logistic regression and AIC model selection I found that capture depth, fishing season, and air exposure were the most influential variables on mortality. Walleye were generally caught from deeper depths in winter (10.9 m, SE=0.16), compared to summer (6.7 m, SE=0.33) and were exposed to air longer during winter (83.9 s, SE=8.22) versus summer (55.3 s, SE=2.49). I observed a sharp increase in probability of mortality (P_m) with capture depth where P_m ranged from 3% (10 m) to 38% (12 m). Results from this study indicate that hooking mortality needs to be considered when implementing length-based regulations, especially in lakes where Walleye angling occurs at depths greater than 10 m.

Introduction

Length-based harvest regulations are a common tool that fisheries managers use to manipulate fish stocks. Using these regulations, managers can limit harvest mortality and regulate the size of fish that are harvested. Length-based regulations are implemented to prevent overharvest and help sustain the quality of fishing (Brousseau and Armstrong 1987). However, due to size restrictions, the increased release of non-legal fish can impact a fishery due to hooking mortality. Following implementation of length-based regulations in Alberta, Canada, post-release hooking mortality of Walleye averaged 44% during the summer and ranged from 27 to 79%. In contrast, hooking mortality of Walleye prior to size restrictions was estimated to be less than 1% (Sullivan 2003). Similarly, a study of Walleye populations in Mille Lacs Lake, MN showed that hooking mortality was as high as 51.7% and was attributed to the implementation of a restrictive harvest slot of 406 to 457 mm along with observed catch rates of 0.75/hour (Reeves and Bruesewitz 2007).

Hooking, landing, handling, and subsequent release of fish can be a variable and substantial source of mortality in fishes. For example, North American Walleye hooking range from 1.1% to 31% (Fletcher 1987; Payer et al. 1989; Reeves and Brusewitz 2007; Talmage and Staples 2011). Factors such as capture depth, water temperature, hooking location, bleeding injuries, landing net design/mesh, and passively-fished baits are known to influence hooking mortality in fishes (Barthel et al. 2003; Schreer et al. 2009; Graeb et al. 2005; Millard et al. 2005; Schisler and Bergersen 1996).

Water temperatures and capture depth have been shown to influence Walleye hooking mortality (Graeb et al. 2005; Talmage and Staples 2011). During tournament

conditions when water temperatures exceeded 18°C, hooking mortality rates were estimated as high as 79 to 80% (Hoffman et al. 1996; Graeb et al. 2005). Capture depths of 12 m can cause probability of mortality to increase from 18 to 50% (Talmage and Staples 2011; Schreer et al. 2009). Saugers *Sander canadensis* experience significant increases in hooking mortality in capture depths greater than nine meters (Meerbeek and Hoxmeier 2011).

In South Dakota, Walleye is the most sought after sportfish and most anglers are harvest oriented. In 2010, 82% of resident anglers fished for Walleye and 1.4 million Walleye/Sauger were harvested within South Dakota (Gigliotti 2011). South Dakota Game, Fish, and Parks has implemented several regulations depending on the goals and needs of the fishery. Lake Oahe and Lake Sharpe, two mainstem Missouri River impoundments, have differing Walleye regulations. Lake Oahe, follows the statewide regulation of a four fish daily limit with one over 508 mm. In contrast, Lake Sharpe has a 381 mm minimum length limit (MLL), that is lifted during July and August, and one over 508 mm on Walleye, This partial-year exemption is to reduce hooking mortality during months of high water temperatures (Lucchesi and Blackwell 2009). The only 381 to 457 mm protected slot limit (PSL) in South Dakota is implemented on Belle Fourche Reservoir, an irrigation reservoir located in western South Dakota. This regulation is designed to increase harvest on sub-381 mm fish, with an overall goal of improving size structure (Lucchesi and Blackwell 2009).

Although the influence of capture depth and water temperatures on post-release hooking mortality of Walleye have been documented (Talmage and Staples 2011; Graeb et al. 2005), the potential interactive effects between depth and water temperature have

not. Total length of fish has been shown to influence hooking mortality, but the preciseness is poorly studied in Walleye (Loftus et al. 1988; Reeves and Bruesewitz 2007). The goal of the protected slot limit on Belle Fourche is to concentrate harvest on smaller fish, thus improving overall population size structure (Lucchesi and Blackwell 2009). However, if post-release hooking mortality of 381 to 457 mm fish is significant and(or) varies by season, negative impacts to the population could render the protected slot ineffective. My objective for this study was to estimate effects of capture depth and water temperature on post-release hooking mortality of Walleye in Belle Fourche Reservoir, Lake Oahe and Lake Sharpe.

Methods

Study Area – Winter hooking mortality trials were conducted on Lakes Oahe and Sharpe, two main-stem Missouri River impoundments in South Dakota. Lake Oahe has a surface area of 149,734 ha, a mean depth of 19 m, and a max depth of 62 m. Lake Sharpe has a surface area of 23,020 ha, a mean depth of 9.5 m, and a max depth of 24 m. Prey base for Walleye in Lake Oahe include Rainbow Smelt *Osmerus mordax* and Gizzard Shad *Dorosoma cepedianum* (Fincel et al. 2014); Gizzard Shad and Rainbow Smelt serve as Walleye forage in Lake Sharpe (Wuellner et al. 2010). The Walleye harvest regulation on Lake Oahe is a four fish daily limit with one over 508 mm. In contrast, Lake Sharpe has a four fish daily limit with a 381 mm MLL, which is removed to no length restrictions during July and August, and one over 508 mm on Walleye. Summer hooking mortality trials took place on Belle Fourche Reservoir, an irrigation reservoir located near Belle Fourche, SD. It has a surface area of 2,658 ha, a mean depth of 7.6 m, and a max

depth of 18.3 m. Prey base for Walleye consists of Gizzard Shad and Yellow Perch. It has a daily harvest limit of four fish and a 381 to 457 mm PSL with one over 457 mm.

Winter Hooking Mortality Trials – From February 10 to 20, 2020, winter hooking mortality trials took place on Lake Sharpe near Fort Thompson, SD. Following warming events that led to unsafe ice conditions on Lake Sharpe, trials were moved to Whitlock Bay on Lake Oahe from March 3 to 6, 2020. Anglers were instructed to target both shallow (less than 10 m) and deep (greater than 10 m) waters using active vertical jigging with artificial lures baited with minnows.

Summer Hooking Mortality Trials – From July 6 to 16, 2020, summer hooking mortality trials took place on Belle Fourche Reservoir. Two angling methods were used: trolling using artificial crankbaits, and active vertical jigging using artificial baits. Due to Belle Fourche being a shallower reservoir, the target depths changed from the winter hooking mortality trials on the Missouri River. During the week of July 6, anglers were instructed to target Walleye in less than 8 m of water. The following week, July 13, anglers targeted Walleye in water depth greater than 8 m.

Hooking Mortality Protocol – The data collection protocol was identical for both seasons and consisted of four time intervals. Stopwatches and smart phones were used to keep track of handling times. The first interval began once an angler set the hook into a Walleye and ended once the Walleye was pulled through the ice or landed in a net. During the second interval, a size 12 monel jaw tag with a unique identification number (National Band and Tag Company, Inc. Newport, KY) was attached to the fish. Hooking location (mouth, gills, or throat), depth of capture (m), capture date, symptoms of barotrauma (e.g. bulging eyes, prolapsed swim bladder, egg extrusion) and signs of

bleeding were noted and the fish were placed into a cooler of ambient temperature lake water, ending the interval. Interval three was the transportation of fish to holding pens. Upon arrival, the fish was removed from the cooler, starting interval four, and placed into a holding pen, ending the handling protocol.

Holding pens were 2 m x 2 m x 10 m deep, constructed from 6.35 mm white nylon delta mesh with 7.93 mm black polyester rope borders (Christensen Net Works, Everson, WA). When inactive, nets were tied shut to prevent escapement. During the open water season, a 2 m x 2 m square, 38 mm schedule 40 polyvinyl chloride frame was attached to the top of the pen, along with four brightly-colored bullet floats. During both seasons, identical PVC frames were attached to bottom of pens to aid in rigidity. Holes were drilled into the frame and two weights were tied on opposite corners to aid in submersion. Pens were placed in 6.0 to 8.5 m of water so the frame would remain in contact with benthic sediment.

On a given sampling week, holding pens were deployed on Monday and pulled Friday morning. Holding pens were emptied and survival of Walleye determined. Mortality was defined as absence of opercular movement and/or presence of rigor mortis. After survival was determined, unique jaw tag number was noted and total length was measured to the nearest mm.

Statistical Analyses – I used multivariate logistic regression to explore factors (variables) associated with Walleye mortality (R function “glm,” specifying “family = binomial”; R Core Team 2015). The global regression model was expressed as,

$$log_e\left[\frac{p_m}{(1-p_m)}\right] = \beta_0 + \beta_1(CD) + \beta_2(TL) + \beta_3(LV) + \beta_4(B) + \beta_5(H) + \beta_6(AE) + \beta_7(TP) + \beta_8(D) + \beta_9(S)$$

p_m is equal to probability of mortality, CD is depth of capture, TL is total length, LV is landing velocity (depth of capture/landing time), B is presence of bleeding, H is hooking location, AE is air exposure, TP is time in pen, D is net pen density, and S is season.

I evaluated potential multicollinearity among variables by examining the variance inflation factor (i.e., VIF >5; Paul 2006). Backward Akaike information criterion (AIC) model selection was used to find the most parsimonious model. Afterwards, I used the Hosmer and Lemeshow goodness of fit test ($p > 0.05$) to assess model fit. I calculated odds ratios by taking e to the i^{th} logistic regression coefficient to assess importance of individual variables in final model (e^{β_i}; Rich et al. 2003). I used the lower bound (positive coefficient) or upper bound (negative coefficient) of confidence intervals (95%) for odds ratios to assess biological significance of variables (Rich et al. 2003). I calculated evidence ratios using model weights (w_i) for top models ($\Delta AIC_c < 2.0$) to provide additional evidence for inferences concerning the actual best model (Burnham and Anderson 2002). To determine overall predictor variable support, I summed AICc weights (Σw_i) from top models that included each variable (MacKenzie et al. 2006).

Results

During winter hooking mortality trials, 58 Walleye were captured. Two Saugers were also captured and survived post-release; these fish were included in net pen density calculations but were excluded from mortality analysis. Of the 58 Walleyes, two were excluded from final analysis due to incomplete data (missing hooking location, presence

of bleeding), and one due to being held under non-experimental conditions (caught and held for 15 minutes before tags arrived; this Walleye subsequently died). During the summer hooking mortality trials, 103 Walleye were captured. Twenty-eight Walleye were excluded from analysis due to pen escapement (24), incomplete data (2), and mortalities caused by becoming physically entangled with the net pen (2).

From both seasons, total length of captured Walleye ranged from 217 to 516 mm (mean=388.90, SE=6.043). Walleye were caught in depths ranging from 2.4 to 14.0 m (mean=8.5, SE=0.3). Landing velocities ranged from 0.06 to 1.28 m/s (mean=0.28, SE=0.02). Air exposure times ranged from 26 to 432 seconds (mean=67.42, SE=3.95). On average, fish caught through the ice were smaller in total length, caught in deeper depths, exposed to air for longer periods of time, held in pens for longer, and landed at higher velocities than their open water counterparts (Table 2.4).

During the ice fishing season 11 mortalities were observed (20%), and from the open water season I observed zero mortalites (0%). The most parsimonious logistic model (top model) was found using an AIC (Akaike Information Criterion) backwards selection logistic regression model. Candidate models revealed that Walleye hooking mortality was influenced by capture depth, fishing season, and air exposure (Table 2.1). Capture depth had a positive relationship with probability of mortality, and air exposure had a negative relationship with probability of mortality (Table 2.2). The top model passed the Hosmer-Lemeshow goodness of fit test (X^2=1.61, df=8, p-value=0.99), meaning the model offers adequate fit for the data. I found no evidence of multicollinearity between independent variables in the global model (VIF < 5). The top

model included only capture depth (CD; Table 2.1); thus, the probability of mortality (p_m) for Walleye was positively related to capture depth as,

$$p_m = \frac{e^{(-17.67+1.43*(CD))}}{1 + e^{(-17.67+1.43*(CD))}}$$

A 1 m increase in capture depth was associated with at least a 90% increase in the probability of mortality (1.90/1; Table 2.3).

Discussion

My results revealed a sharp increase in probability of mortality at capture depths exceeding 10 m. A study conducted on the St. Lawrence River found Walleye had 50% probability of mortality at capture depths of 9.5 m (Schreer et al. 2009). Additionally, a Rainy Lake study saw an increase of mortality around 10 m of capture depth, as probability of mortality doubled from 9 to 12 m (Talmage and Staples 2011). At 9 m I found probability of mortality to be less than 1%, but at 11 m probability rose to over 12%. All 11 mortalities were caught in water exceeding 10 m. The two deepest caught fish in the study (14.02 m) had a 91.5% probability of mortality and subsequently died.

A likely mechanism for hooking mortality of fish caught in deep water is barotrauma. Barotrauma is the physical injuries associated with rapid decompression as fish are brought up from deep depths during angling. This can cause several harmful injuries: prolapsed swim bladder, hemorrhaging, loss of equilibrium, and bloating (Schreer et al. 2009; Eberts et al. 2018; Rummer and Bennett 2005; Gravel and Cooke 2008). In previous marine and freshwater hooking mortality studies, barotrauma rates in fish varied from 20 to 80% (Rummer and Bennett 2005; Brown et al. 2010; Gravel and Cooke 2008). A Walleye ice angling study on Lake Nipissing revealed a 22.2% rate of

barotrauma, however barotrauma didn't significantly affect mortality relative to absence of barotrauma (Twardek et al. 2018). I observed a total barotrauma incidence of 13.4%. Only fish caught during the ice fishing season exhibited symptoms of barotrauma and of the 11 total mortalities, 64% had symptoms of barotrauma.

The likelihood of barotrauma is also dependent on the rate of ascent. Model simulations of Bottlenose Dolphin *Tursiops truncatus* physiology and behavior showed that a reduced ascent rate to the surface is successful in returning excess N_2 to lungs and reduces N_2 supersaturation in blood and tissues (Fahlman et al. 2006), reducing barotrauma symptoms. While an ascent rate of 0.28 m/s reveals no decompression sickness in human divers, an ascent rate of 0.15 m/s reduces venous bubble formation in blood (Carturan et al. 2002). In a hooking mortality study on Australasian Snapper *Pagrus auratus* ascent rates of 0.4 m/s had no influence of mortality (Stewart 2008). Ascent rates of 1.0 m/s caused 80% barotrauma incidence on Red Snapper *Lutjanus campechanus*, which could lead to substantial mortality (Rummer and Bennett 2005). In my study, average landing velocities differed significantly between winter (0.48 m/s) and summer (0.15 m/s). It's likely that elevated landing velocities in the winter contributed to a higher instance of barotrauma during ice fishing.

Prolonged exposure to air after angling events introduce stressors and can potentially decrease survival in fish (Cooke et al. 2002; Danylchuk et al. 2007). Average air exposure times for winter (83.89 s) and summer (55.34 s) differed significantly. During the ice fishing season, anglers experienced air temperatures as low as two degrees Fahrenheit (NOAA 2020) which probably caused diminished dexterity of hands, leading to increased handling times during jaw tagging procedures of the Walleye compared to

summer months. Cold air temperatures can also magnify stressors on Walleyes if exposure is significant. Forty-five seconds of air exposure can change surface temperatures of Walleye, leading to freezing damage to the eyes and gills (Twardek et al. 2018). In my study, Walleye that died had significantly higher air exposure times than fish that survived.

Elevated water temperatures have been shown to affect fish survivability after angling. Walleye hooking mortality increases when surface water temperatures exceed 18°C (Hoffman et al. 1996; Graeb et al. 2005; Reeves and Bruesewitz 2007). Mortality rates of 100% have been observed during simulated tournament angling procedures with 24°C water temperatures (Loomis et al. 2013). All 75 fish involved in the summer season of my study survived angling and holding procedures. Fish were caught in surface temperatures exceeding 22°C, one third were caught in temperatures at or above 24°C, and the highest temperature observed during angling was 25.6°C.

Bleeding intensity can contribute substantially to mortality (Schisler and Bergersen 1996). Presence of bleeding occurred at a higher frequency during the summer angling season. I observed 17 fish to be bleeding following hook removal during the summer and one during the winter. This could be due to decreased metabolism and blood flow during the colder temperatures Walleye experience during the winter season (Egginton 1997). However, given that none of the fish that exhibited bleeding died, presence of bleeding did not influence hooking mortality

There were few instances of foul-hooking during the study. Five of the 130 total fish were foul-hooked: two during the winter season (both hooked in throat), and three during the summer season (two in gills, one in throat). The low frequency of foul-

hooking observed is most likely due use of active gears (crankbaits and vertical jigging). Passive fished baits result in high rates of injury, which leads to increased mortality (Schill 1996). All but two fish were caught using active gears. Those two fish didn't suffer foul-hooking/injury as a result of passive angling and were included in analysis. None of the foul-hooked fish in my study died from angling. As a result, hooking location wasn't a determining factor in hooking mortality.

Using net pens to monitor mortality is easy to implement and control, however the effects of confinement on fish over time on probability of mortality can play an unknown role (Diodati and Richards 1996). Typically, Walleye are held for a period of 120 h to monitor mortality (Reeves and Bruesewitz 2007; Talmage and Staples 2011). In my study, holding times in pens differed significantly between summer (57.6 h) and winter (72.0 h). Although most hooking mortality occurs within the first 24 h (Muoneke and Childress 1994), it's possible I would have seen an increase in mortality had the Walleye been held for longer periods of time. However, it would have been difficult to discern whether mortality was attributed to angling practices or stressors associated with prolonged confinement (Portz et al. 2006). Two fish during the open water season were found entangled with the net and subsequently died. Since there were no other mortalities during the open water season, confinement stress was controlled. Further, Walleye have been held in net pens for 12 d following angling and minimal mortality was documented (Fletcher 1987).

Crowding of fishes in holding pens can contribute to lowered survival rates (Portz et al. 2006). In my experiment, density of fish in net pens never exceeded 20 fish per pen (0.5 fish/m^3). Net pen densities were dynamic through sampling weeks as fish were

added daily. Average density of Walleye in net pens were not statistically different between summer (0.34 fish/m^3) and winter (0.35 fish/m^3) seasons.

In a meta-analysis by Hühn and Arlinghaus (2011), mortality rates between fish smaller or larger than a “typical” minimum size limit don’t differ. While Talmage and Staples (2011) found no relationship between Walleye total length and mortality, Schisler and Bergersen (1996) found a decrease in mortality with increasing total lengths of Rainbow Trout *Oncorhynchus mykiss*. Hooking mortality can increase with increases in total length as larger fish are fished to exhaustion (Reeves and Bruesewitz 2007). In my study, there was no relationship between total length and probability of hooking mortality.

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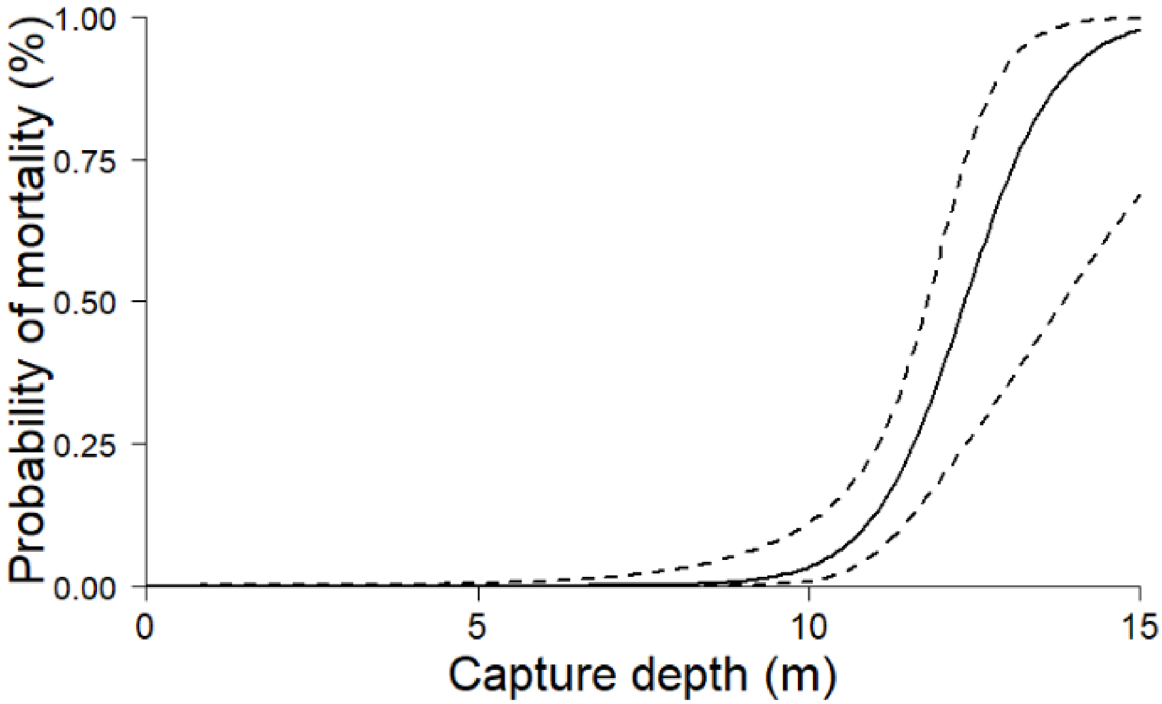

Figure 2.1. Probability of hooking mortality (p_m) of Walleye caught in Belle Fourche Reservoir, Lake Oahe, and Lake Sharpe in February and July of 2020 as a function of depth of capture (m) based on the top model including only capture depth (dashed lines indicate 95% confidence intervals)

Table 2.1. Number of model parameters (K), Akaike's information criterion (AICc) values, difference between AIC_c values, model weights (w_i), and evidence ratios for top logistic regression models evaluating probability of hooking mortality in Belle Fourche, Lake Oahe, and Lake Sharpe in February and July of 2020 (CD is capture depth, S is fishing season, AE is air exposure).

Model	K	AICc	ΔAICc	w_i	Evidence Ratio
CD	2	48.7	0.00	0.42	1.00
CD + *S*	3	49.1	0.40	0.34	1.21
CD + *S* + *AE*	4	49.8	1.10	0.24	1.73

Table 2.2. Relative influence of predictor variables in the top performing candidate models ($\Delta AIC_c < 2.0$) describing hooking mortality in Belle Fourche Reservoir, Lake Oahe, and Lake Sharpe in February and July of 2020. The Σw_i values represent the summed model Akaike's information criterion (AIC_c) weights of models that included the influential predictors.

Predictor variable	Relationship	Σw_i
capture depth	Positive	1.00
fishing season		0.58
air exposure	Negative	0.24

Table 2.3. Logistic model variables predicting probability of hooking mortality in Walleye in February and July of 2020 in Belle Fourche Reservoir, Lake Oahe, and Lake Sharpe.

	logistic coefficient	std error	scaling factor	scaled odds ratio	95% CI (LL, UL)	P > chi sq
intercept	-17.7	4.64				< 0.01
capture depth	1.44	0.41	1	4.21	1.90, 9.34	< 0.01

Table 2.4. Statistical differences in logistic regression model variables between the ice fishing season on Lake Oahe and Sharpe and the open water season on Belle Fourche Reservoir in 2020. Values in parentheses represent 1 standard error

Variable	Ice Fishing	Open Water	t-test p-value
air exposure (s)	83.89 (8.22)	55.34 (2.49)	0.001
landing velocity (m/s)	0.480 (0.03)	0.130 (0.006)	<0.001
capture depth (m)	10.92 (0.16)	6.65 (0.33)	<0.001
total length (mm)	342.2 (8.83)	423.1 (5.58)	<0.001
time in pen (days)	3.020 (0.117)	2.40 (0.104)	<0.001
density (fish/m^3)	0.350 (0.017)	0.340 (0.009)	0.616

CHAPTER 3: INFLUENCE OF HARVEST REGULATIONS ON ANGLER EXPLOITATION AND WALLEYE YIELD IN WESTERN SOUTH DAKOTA IRRIGATION RESERVOIRS

Abstract

Understanding population characteristics such as growth and mortality of a fishery is essential in developing appropriate management regulations. Incorrect harvest regulations can lead to undesired outcomes and negatively affect fish populations. In this study, I evaluated the effects of current harvest regulations on Walleye populations in three reservoirs in western South Dakota: Angostura, Belle Fourche, and Shadehill. In 2018, a jaw-tagging study was initiated to estimate angler exploitation in each reservoir. Shadehill had the highest exploitation in 2018 and Angostura had the highest exploitation in 2019. In addition, Walleye were randomly sampled and sagittal otoliths were collected to estimate growth and mortality in each reservoir. Walleye in Angostura exhibited the highest growth rates of the three reservoirs evaluated in this study. Total annual mortality (A) and the instantaneous rate of total mortality (Z) was also highest in Angostura. Fisheries Analysis and Modelling Simulator (FAMS) was used to model impacts of current and potential harvest regulations. For all reservoirs, yield (kg) was highest when modeled with a 381 mm minimum length limit (MLL). The highest yield was produced in Angostura given angler exploitation of 28.6% and a harvest regulation of 381 mm MLL. Results from this study reveal that Angostura Reservoir produces a highly productive Walleye population that experiences significant angler exploitation.

Introduction

Understanding population growth and mortality of a fishery is crucial for developing appropriate management regulations. Walleye growth is influenced by factors such as water temperature, length of growing season, population abundance, and food availability. Walleye in colder, northern latitudes grow slower than Walleye in warmer, southern latitudes (Beverton 1987; Quist et al. 2003a). On Big Crooked Lake in Wisconsin, Walleye growth increased after experimental regulations were implemented to enhance angler exploitation to 35% (Sass and Shaw 2018). Walleye growth increased following introductions of Gizzard Shad *Dorosoma cepedianum* into Angostura Reservoir, South Dakota, (Ward et al. 2007).

Two sources of mortality exist in angler-exploited systems: natural and angling. In an unexploited Walleye population in Pennsylvania, annual natural mortality was estimated at 39 to 53% (Kocovsky and Carline 2001). Natural mortality rates in Walleye have been shown to decrease with age, most likely in response to increased angling mortality as natural and angling mortality have an inverse relationship (Hansen et al. 2011). Angler exploitation rates of North American Walleye populations range from 3 to 56%, however few Walleye populations can sustain angler exploitation rates beyond 30% without losses to fishing quality (Baccante and Colby 1996). Site specific angler exploitation on Lake Oahe, South Dakota ranged from 15 to 39% from 2013 to 2016 (Felts 2018).

Walleye anglers are generally harvest-oriented and can impact populations, age structure, biomass, and production (Fayram 2003; Colby and Baccante 1996). To limit/control harvest of Walleye, managers enact regulations dictating which fish can be

harvested. Minimum length limits (MLL) are a common, length-based regulation managers use to maximize the average size of harvested fish by protecting fish below a certain size (Brousseau and Armstrong 1987). The Walleye population in Lake Francis Case saw significant increases in abundance and proportional size distribution (PSD) following the implementation of a partial-year, 356 mm MLL (Stone and Lott 2002). Similar results were seen on Meredith Reservoir, Texas following the enforcement of a 407 mm MLL as the abundance of total and legal-size Walleyes increased, but was accompanied by decreases in Walleye growth rates (Munger and Kraai 1997). By contrast, Walleye population abundance, age structure, and size structure saw no improvements following MLL implementations on three Minnesota lakes (Isermann 2007).

In addition to MLL's, protected slot limits (PSL) are another common length-based regulation. By protecting fish within a given range of total lengths, PSL's are designed to increase harvest of fish measuring below the slot to maintain growth and recruitment into and through the slot leaving fish measuring above the slot available for harvest (Brousseau and Armstrong 1987). The current knowledge regarding the effects of protected slot limits on fish populations is limited, particularly for Walleye. Protected slot limits have been shown to increase population size and proportional size distribution (PSD) in Largemouth Bass *Micropterus salmoides* populations (Wilde 1997). Following a PSL implementation on a Smallmouth Bass *Micropterus dolomieu* population in Elkhorn Creek, Kentucky, an increase in PSL-length fish density was observed followed by a decline, probably due to other factors (Buynak and Mitchell 2002). Slot limits on

Northern Pike *Esox lucius* populations in Minnesota lakes led to a general increase in size structure (Pierce 2010).

In South Dakota, the Missouri River bisects the state along the Northwestern Glaciated Plains ecoregion (east of the Missouri River, ER) and the Northwestern Great Plains ecoregion (west of the Missouri River, WR). As a result of glaciation, the topography of ER contains numerous natural lakes and wetlands (Johnson and Higgins 1997). In contrast, the unglaciated WR has few natural lakes and wetlands. Additionally, WR doesn't receive as much precipitation as ER (Norton et al. 2014). Due to this, the few WR lakes and reservoirs have become regionally important for a number of uses. In addition to fishing recreation, the three most popular Walleye fisheries in western South Dakota double as irrigation reservoirs. Managed by the U.S. Bureau of Reclamation for the purpose of irrigation, Angostura, Belle Fourche, and Shadehill reservoirs can experience large drawdowns during peak usage in summer months. Belle Fourche Reservoir alone provides irrigation water to over 23,000 ha of farmland in western South Dakota (McCune 2001).

In these western reservoirs, length-based regulations play an important role in controlling Walleye harvest. Walleye populations in Angostura and Shadehill reservoirs are managed by a 381 mm MLL, with one over 508 mm, and a four fish daily limit. This regulation is designed to protect smaller fish from harvest, leading to increased average fish sizes. In South Dakota, satisfaction of five criteria are required to implement a 381 mm MLL: 1. Fast growth (381 mm by age-4); 2. Periods of high exploitation; 3. Low natural mortality; 4. Low probability of winterkill; and 5. Sporadic or limited natural recruitment requiring frequent stocking (Lucchesi and Blackwell 2009). Belle Fourche is

the only waterbody in South Dakota that is regulated by a PSL on Walleye. Fish measuring less than 381 mm or greater than 457 mm may be harvested, with one over 457 mm, and a four fish daily limit. Regarded as an experimental regulation, the PSL is designed to increase pressure on sub-381 mm fish which will then improve overall size structure (Lucchesi and Blackwell 2009).

Anglers spend a combined 200,000 hours between these three reservoirs each year, with Walleye being the primary targeted species (SDGF&P; Unpublished SDGF&P data). Given the local value of these western Walleye fisheries, angler exploitation and its impact on the Walleye populations need to be better understood. Additionally, the 381 mm MLL regulations on Angostura and Shadehill Reservoirs, and the 381 to 457 mm PSL on Belle Fourche Reservoir and the effects on the Walleye populations need to be determined. The objective of this study was to obtain information on growth, mortality, and angler exploitation to model current and potential future regulation changes for the Walleye populations in Angostura, Belle Fourche, and Shadehill irrigation Reservoirs.

Methods

Study Sites – My study sites included three large irrigation reservoirs in western South Dakota. The largest, Belle Fourche Reservoir (2,658 ha), has a mean depth of 7.6 m and maximum depth of 18.3 m. Shadehill Reservoir (2,052 ha) has a mean depth of 6.7 m and a maximum depth of 18.9 m. Angostura Reservoir (1,956 ha) has a mean depth of 8.8 m and a maximum depth of 22.7 m. Gizzard Shad serve as primary forage in all three reservoirs. In addition to Gizzard Shad, Yellow Perch *Perca flavescens* is available as forage for Walleye in Belle Fourche and Shadehill.

Jaw Tagging Procedure –Walleye were sampled in April using fyke nets, gill nets, and electrofishing. Sex was determined by the extrusion of milt or eggs and total length of fish was measured to the nearest mm. Walleyes greater than 280 mm were tagged using size 12 monel jaw tags (National Band and Tag Company, Inc. Newport, KY). For fish measuring over 350 mm, jaw tags were attached to the upper maxillary bone. Jaw tags were attached to the lower maxillary bone of fish less than 350 mm. Tags were attached by making an incision with a knife and securing the ends of the tag through the flesh using pliers. During the 2018 pilot season, 500 fish were tagged per reservoir. In 2019, 1,000 fish were tagged per reservoir. To estimate angling reporting rate, 5% of the total fish tagged were tagged with $100 high-reward tags (Pollock et al. 2001).

Standard and reward tags were stamped with a unique tag number. In addition, high-reward tags were stamped with “REWARD $100”. Once caught, anglers could report tags in one of three ways: call the tag-reporting hotline, register the tag online, or report in person at a South Dakota Game, Fish, and Parks office.

Jaw tag data analysis – Reporting rates and exploitation rates were estimated for each reservoir using the Brownie et al. (1985) model as,

$$f = \lambda u$$

f is the tag recovery rate, λ is the reporting rate, and u is the exploitation rate. The reporting rate was then estimated as,

$$\lambda = \frac{R_s N_r}{R_r N_s}$$

where R_s is the number of standard tags returned, N_r is the number of high-reward tags released, R_r is the number of high-reward tags returned, and N_s is the number of standard

tags released. The reporting rate was used to correct angler exploitation rate by assuming 100% reporting rate for high-reward tags (Pollock et al. 2001).

Otolith Sampling – Walleye were sampled on Angostura, Belle Fourche, and Shadehill from April to May using fyke nets, gill nets, and electrofishing to collect sagittal otoliths. In 2018, 100 random Walleye from each reservoir were selected. In 2019, a maximum of 100 male and 100 female Walleye were randomly selected from each reservoir. Otolith preparation followed procedures of Beamish (1979). Otoliths were mounted in epoxy and two dorsal-ventral cuts were made next to the core using a low-speed diamond saw. Otoliths were photographed underneath a microscope using transmitted light. Consensus aging was performed among three readers on each otolith to reduce reader bias.

From aged otoliths, I estimated growth and mortality of Walleye populations from all reservoirs by pooling ampling years to supplement sample size. I made estimates of von Bertalanffy growth parameters were made in R using the package "FSA" (Ogel et al. 2019): L_∞ (asymptotic total length), K (growth coefficient), and t_0 (x-intercept). I used weighted catch curve regression analysis to calculate total mortality (A) and the instantaneous rate of total mortality (Z) for each reservoir. Regression analysis was used and included all age-groups with nonzero catch after the first fully recruited age class (Smith et al. 2012).

Yield Per Recruit Modeling – To model impacts of current and potential regulations changes, I used Fisheries Analysis and Modelling Simulator (FAMS; Slipke and Maceina 2014). I used estimates of von Bertalanffy growth parameters (L_∞, K, and t_0), conditional natural mortality (*cm*), and exploitation (*u*) for Walleye populations in each reservoir as input in the model. Weight was not measured for fish, so the standard coefficients of

slope (b) and x-intercept (a) from the length-weight relationship ($W=aL^b$) for Walleye were used in the models (Schneider et al. 2000). I modelled the impacts of angler exploitation on Walleye yield for two regulations: a 381 mm MLL and no length limit. Anglers will typically not harvest walleye measuring less than 305 mm total length (Potter et al. 2016; Felts 2018), so the no length limit regulation was coded in FAMS as a 305 mm MLL The current PSL on Belle Fourche was also evaluated using angling exploitation estimates from jaw tag returns.

Results

A total of 821 sagittal otoliths were collected from Walleye between 2018 (N=252) and 2019 (N=569) on Angostura, Belle Fourche, and Shadehill (Table 3.1). In Angostura, ages ranged from 2 to 8 and 2 to 13 in 2018 and 2019, respectively; in Belle Fourche, ages ranged from 2 to 12 and 3 to 13 in 2018 and 2019, respectively; and in Shadehill, ages ranged from 2 to 10 and 3 to 11 in 2018 and 2019, respectively.

Walleye in Angostura grow past the 381 mm MLL at approximately 2.5 years of age when they are legal to be harvested (Figure 3.1), however Walleye in Shadehill take approximately 4 years to reach harvestable size, given the same regulation (Figure 3.1). Walleye in Belle Fourche are available for harvest until age-3, where they remain protected by the slot limit until approximately age-7 (Figure 3.1). Walleye growth rate in Angostura was greater than that observed in Belle Fourche and Shadehill reservoirs (Figure 3.1). Mean total length of age-2 Walleye in all reservoirs was larger than the North American average for Walleye growth. After age-4, growth of Walleye in all three reservoirs slowed (Figure 3.1). Angostura reaches the highest theoretical maximum total length (L_∞), followed by Shadehill, and then Belle Fourche (Table 3.3).

Total annual mortality (A) and instantaneous rate of total annual mortality (Z) was highest in Angostura and lowest in Shadehill (Table 3.2). Shadehill had the highest survival (S), followed by Belle Fourche, and then Angostura (Table 3.2). Estimated conditional natural mortality (*cf*) was highest in Angostura and lowest in Shadehill (Table 3.2). Shadehill had the highest angler exploitation in 2018 (32.4%) and Angostura had the highest in 2019 (37.0%); Belle Fourche had the lowest exploitation during both years of tagging (Table 3.4). Tag reporting rate in 2018 was lowest in Shadehill and highest in Angostura, and in 2019 reporting rate was lowest in Angostura and highest in Belle Fourche (Table 3.4).

Walleye yield (kg) in all reservoirs was highest when conditional natural mortality was the lowest (*cm* = 0.1). Angostura had the highest estimated yields of any reservoir at an exploitation of 28.6% and modeled with a 381 mm MLL (Figure 3.4). Walleye yield in Shadehill was highest when modelled with a 381 mm MLL at an exploitation of 38.1% (Figure 3.5). Among the three regulations used to model Walleye yield in Belle Fourche, the highest yield was produced under the 381 mm MLL at an exploitation of 42.9% (Figure 3.2; Figure 3.3).

Discussion

High exploitation rates can have a negative impact on Walleye populations. Angler exploitation rates of North American Walleye populations range from 3 to 56%, with a median exploitation rate of 21% (Baccante and Colby 1996). Exploitation of 35% can lead to significant declines of adult Walleye abundance (Sass and Shaw 2018). On a previously unexploited Walleye population in eastern South Dakota, high exploitation of 75% substantially reduced the Walleye population in the first summer of angling

(Blackwell et al. 2019). Recommended angler exploitation rates should be approximately 75% of the instantaneous rate of natural mortality (Lester et al. 2014). Following this model, estimated angler exploitation on Angostura exceeded recommended sustainable exploitation rates in 2018 and 2019, anglers in Shadehill exceeded recommended exploitation in 2019, and angler exploitation on Belle Fourche was below the sustainable angler exploitation both years.

Growth rates of Walleye can vary between populations and are dependent on several factors. Gizzard Shad have been shown to increase growth rates in Walleye (Ward et al. 2007). Gizzard Shad are among the forage for Walleye in all three reservoirs; Angostura and Belle Fourche has a naturally reproducing population, whereas Shadehill receives maintenance stockings. Temperature can also play a role in growth as Walleye in colder, northern latitudes grow slower and live longer than Walleye in warmer, southern latitudes (Beverton 1987). Walleye populations in all three reservoirs had higher initial growth compared to the North American average for Walleye growth. This is probably due to the inclusion of northern populations of Walleye in the North American average estimate that grow slower than the populations in my study. Additionally, Walleye growth is subjected to density dependence as average length-at-age is inversely related to adult population density (Nate et al. 2011).

A number of factors could be responsible for the exceptional growth rate observed by the Walleye population in Angostura, compared to the Belle Fourche and Shadehill populations. Elevated water temperatures could've played a role as Angostura is the southernmost reservoir of those examined in this study. During the month of July 2020, the mean temperature for Pine Ridge, SD (77.1°F), approximately 50 miles SE of

Angostura, was higher than the mean temperature of Buffalo, SD (73.3°F), approximately 60 miles WSW of Shadehill (NOAA 2020). Additionally, increasing growth could be caused by reductions in abundance as estimates of mortality and angler exploitation were highest in Angostura. Estimated angler exploitation for Angostura in 2019 was 32%, slightly higher than the experimental exploitation of 35% on Big Crooked Lake which led to increased growth rates in Walleye, possibly due to density dependence (Sass and Shaw 2018).

In yield-per-recruit modelling, the more restrictive regulation (381 mm MLL) produce higher yields at lower conditional natural mortalities for all reservoirs. A study on a Kansas reservoir revealed similar results with maximum yield achieved given lower conditional natural mortalities, and more restrictive regulations (Serpan et al. 2017). Each population runs the risk of overfishing given low conditional natural mortality and the highest yields. Based on my estimates of conditional natural mortality for all reservoirs, I feel that the possibility of overfishing is minimal given the 381 mm MLL in each reservoir.

Angostura Reservoir produced the highest Walleye yield in all of my modeling scenarios, probably for a number of reasons. Mean annual air temperature accounts for most of the variability in maximum sustained yields (MSY) in fisheries populations as high air temperatures result in high fish yields (Schlesinger and Regier 1982). Angostura is the southernmost reservoir and is situated in a slightly warmer climate than Belle Fourche and Shadehill reservoirs (NOAA 2020). Variations in growth between waterbodies can also be due to factors such as lake productivity (Sass et al. 2004). The morphoedaphic index (MEI), a measure of fish productivity in northern temperate lakes

(Ryder 1965), is greater for Angostura reservoir (288.1) compared to Shadehill and Belle Fourche reservoirs (194.6 and 154.9, respectively).

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Table 3.1. Total number of sagittal otoliths collected from male and female Walleyes from Angostura, Belle Fourche, and Shadehill reservoirs, SD in 2018 and 2019.

	2018			2019		
Reservoir	Male	Female	Total	Male	Female	Total
Angostura	66	12	78	127	89	216
Belle Fourche	62	26	88	100	68	168
Shadehill	84	2	86	111	74	185

Table 3.2. Survival and mortality estimates based on weighted catch curve regression analysis from sagittal otoliths collected from Walleyes from Angostura, Belle Fourche, and Shadehill reservoirs, SD in 2018 and 2019: A (total annual mortality), Z (instantaneous rate of mortality), S (survival), and range of values for *cm* (conditional natural mortality) for 2018 and 2019.

Reservoir	A	Z	S	*cm*
Angostura	0.506	0.705	0.494	0.173-0.278
Belle Fourche	0.387	0.490	0.613	0.237-0.271
Shadehill	0.343	0.420	0.657	0.024-0.177

Table 3.3. Von Bertalanffy growth function coefficients for Walleye populations in Angostura, Belle Fourche, and Shadehill reservoirs, SD (2018 to 2019). Values in parentheses represent 1 standard error

Reservoir	L_∞	K	t_0
Angostura	574.1 (20.04)	0.2626 (0.042)	-1.756 (0.445)
Belle Fourche	500.9 (11.99)	0.266 (0.044)	-2.278 (0.678)
Shadehill	571.5 (50.59)	0.145 (0.051)	-3.815 (1.463)

Table 3.4. Angler exploitation rate and reporting rate estimates from jaw tags returns from Angostura, Belle Fourche, and Shadehill reservoirs, SD (2018 and 2019). Values in parentheses represent 1 standard error

	2018		2019	
Reservoir	Exploitation Rate	Reporting Rate	Exploitation Rate	Reporting Rate
Angostura	27.3	63.5 (0.06)	32.6	42.2 (0.02)
Belle Fourche	13.8	60.9 (0.05)	15.2	59.4 (0.02)
Shadehill	32.4	47.5 (0.03)	18.4	55.9 (0.03)

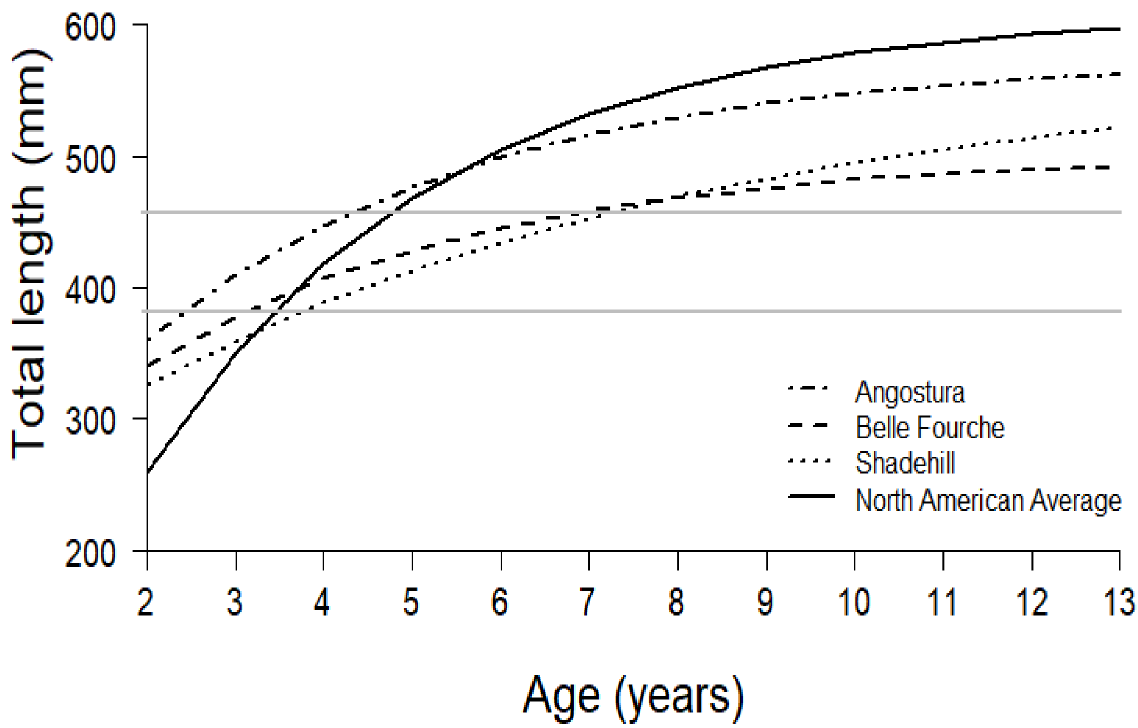

Figure 3.1. Von Bertalanffy growth curve of Walleye in Angostura, Belle Fourche, and Shadehill reservoirs. The North American Average for Walleye growth is depicted by the solid line (Quist et al. 2003a). Gray lines represent current length-based regulations of the 381 mm minimum length limit on Angostura and Shadehill reservoirs and the 381 to 457 mm protected slot limit on Belle Fourche Reservoir.

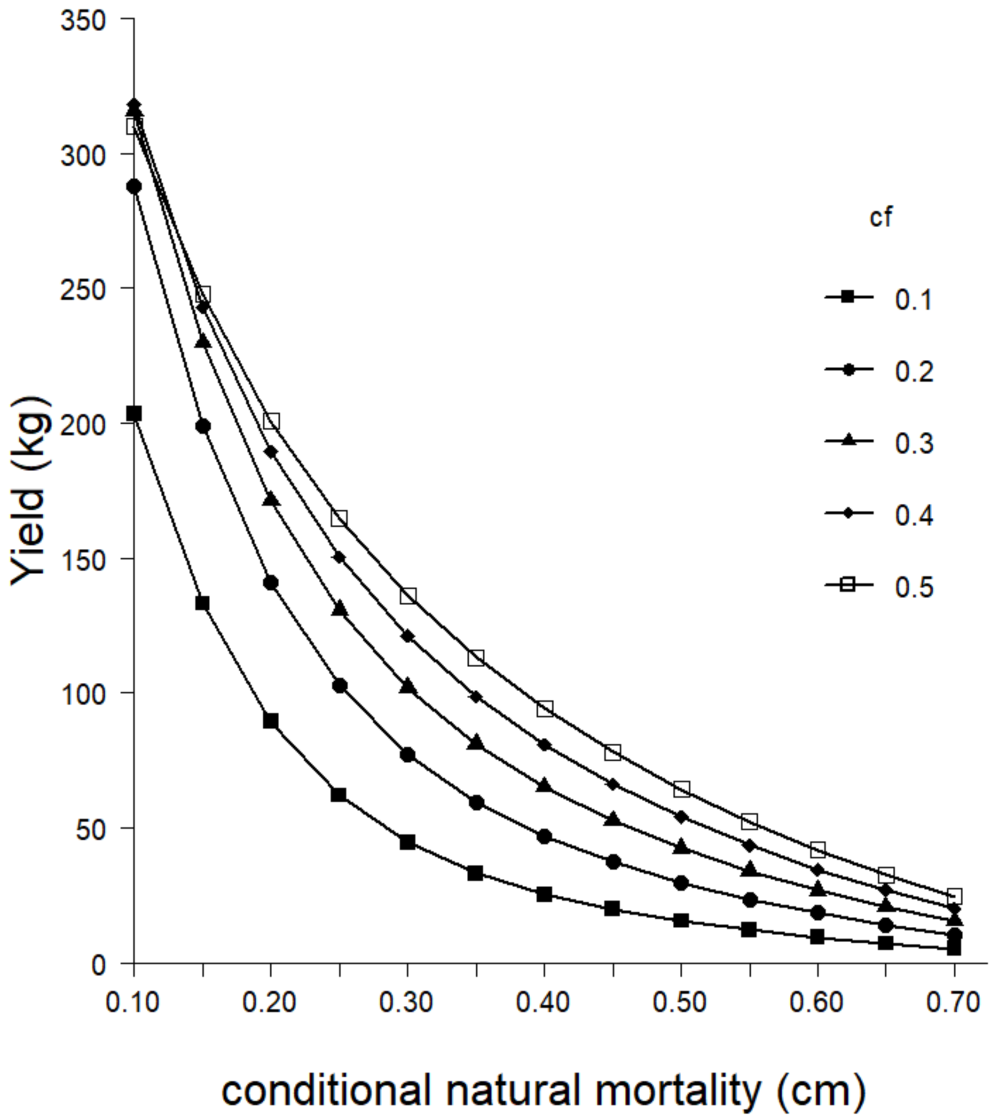

Figure 3.2. Estimated Walleye yield from yield-per-recruit modelling for Belle Fourche Reservoir under the protected slot limit (381 to 457 mm) through a range of conditional natural (*cm*) and conditional fishing (*cf*) mortalities.

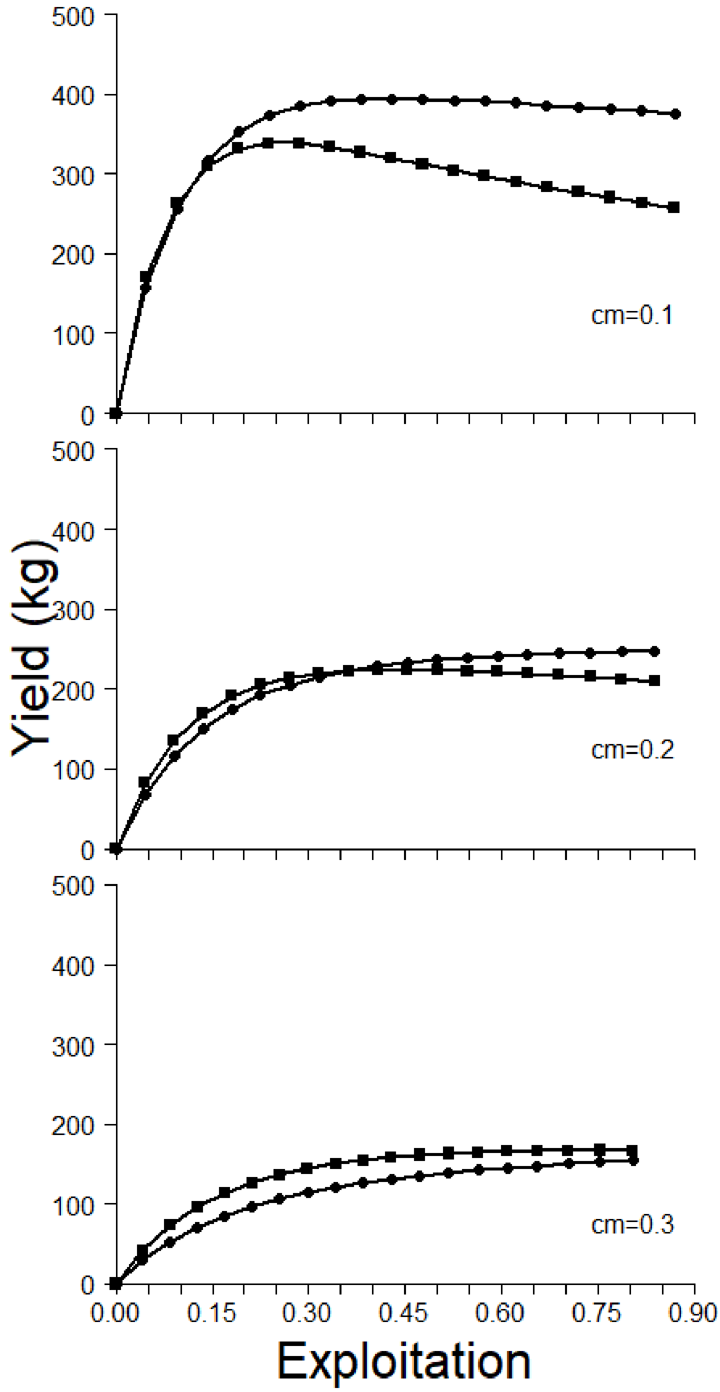

Figure 3.3. Estimated Walleye yield from yield-per-recruit modelling for Belle Fourche Reservoir under a 381 mm minimum length limit (circles) and no length limit (squares) through range of conditional natural mortalities (*cm*).

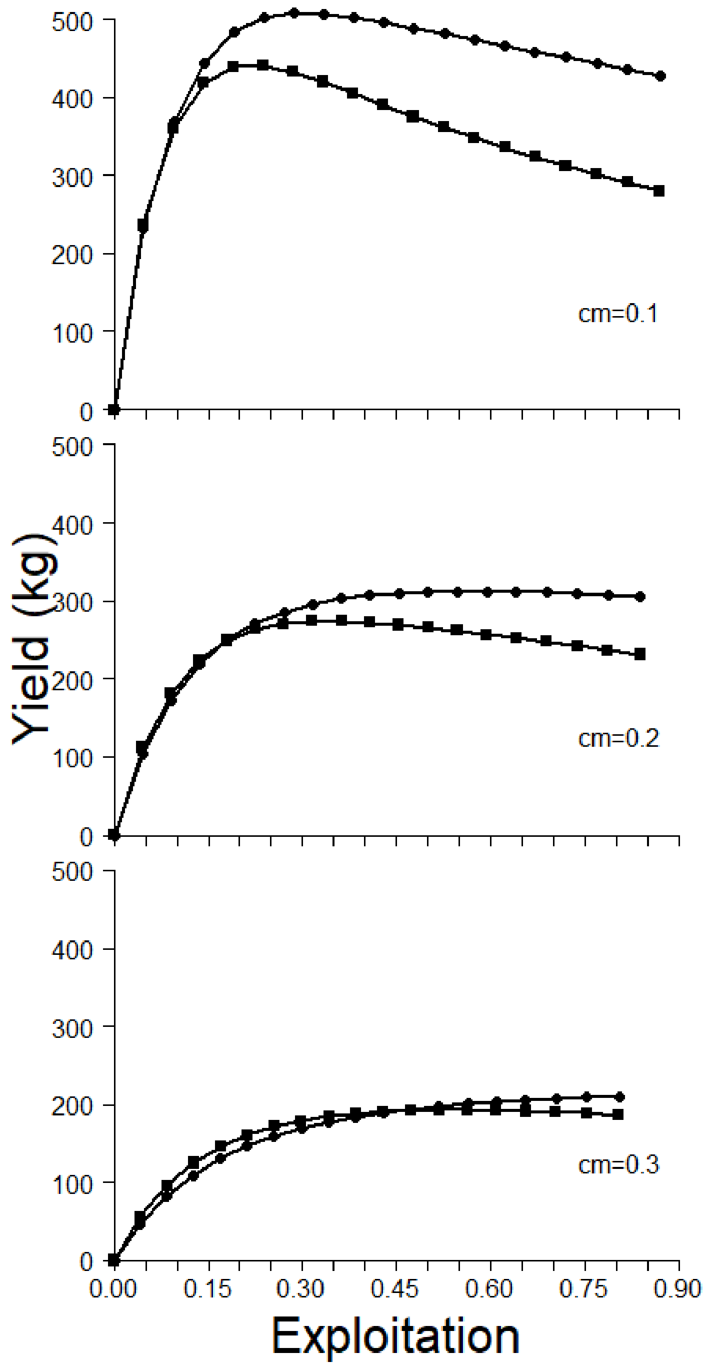

Figure 3.4. Estimated Walleye yield from yield-per-recruit modelling for Angostura Reservoir under a 381 mm minimum length limit (circles) and no length limit (squares) through range of conditional natural mortalities (*cm*).

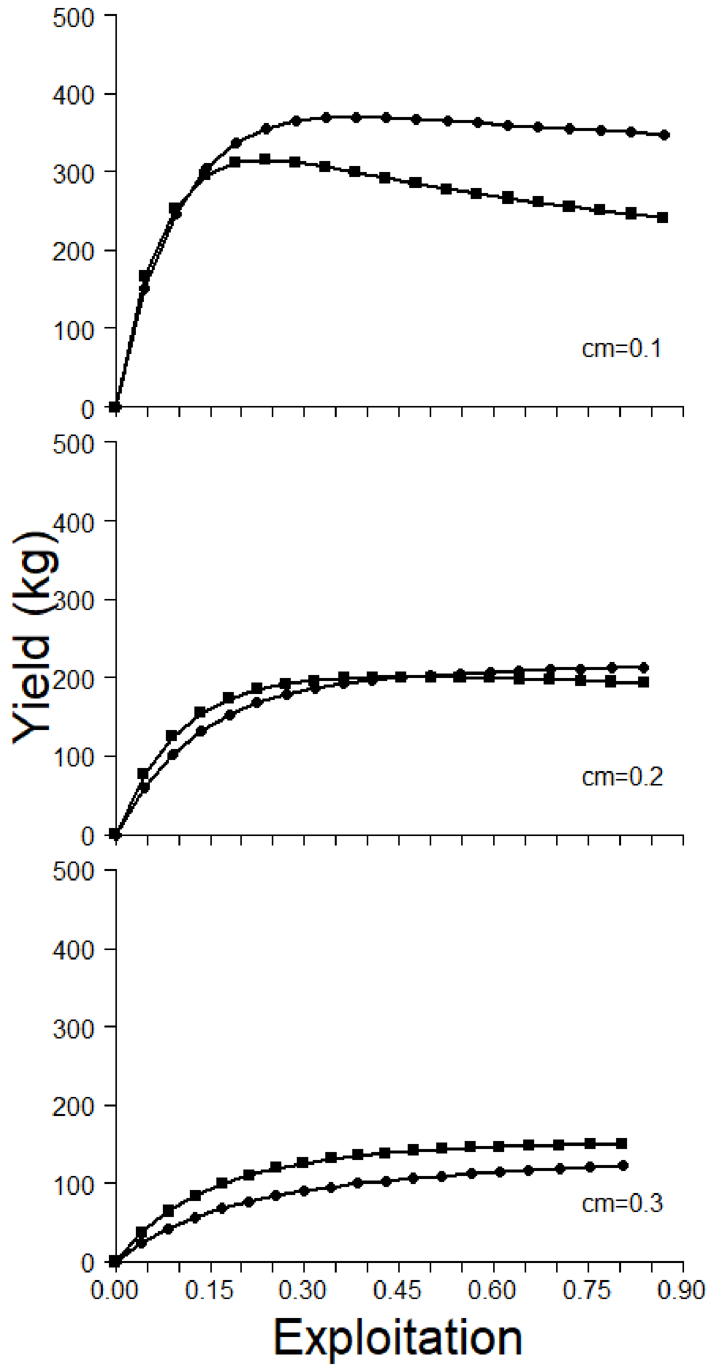

Figure 3.5. Estimated Walleye yield from yield-per-recruit modelling for Shadehill Reservoir under a 381 mm minimum length limit (circles) and no length limit (squares) through range of conditional natural mortalities (*cm*).

CHAPTER 4: MANAGEMENT RECOMMENDATIONS

Harvest regulations are a common tool that managers use to manipulate fish stocks to provide quality fisheries. However, negative impacts can result from inappropriate regulations on exploited populations. Overexploitation can occur from too liberal harvest restrictions and can lead to overfishing and collapses of populations. Hooking mortality brought on by length-based regulations due to catch and release angling can also have a negative impact on fish populations. If hooking mortality is substantial, collapses in fisheries can occur.

In this study, I examined the effects of regulations on Walleye populations in South Dakota. Angostura, Belle Fourche, and Shadehill are three irrigation reservoirs in western South Dakota. Walleye in Angostura and Shadehill reservoirs are currently under a 381 mm minimum length limit (MLL) and one over 508mm with four fish daily harvest limit. Belle Fourche is the only water body in the state of South Dakota that has a protected slot limit (PSL) of 381 to 457 mm and one over 457 mm with a four fish daily harvest limit on walleye.

Overall, Walleye hooking mortality was 20% during the ice fishing season. I saw an increase in probability of mortality occur when Walleye were caught in depths exceeding 10 m. Zero Walleye died following hooking mortality procedures during the open water season. Interestingly, fish caught during the summer season were subjected to water temperatures that exceeded stressful levels (>18°C) commonly observed in Walleye. However, these are potential underestimations of hooking mortality in Walleye as only active gears were used. Injuries, including bleeding and foul hooking, were

minimal in my study. Passively-fished gears increase the incidence of both of these in Walleye and thus, increase post-release mortality.

Angostura Reservoir produces a highly productive Walleye fishery likely due to a warmer climate and productive water quality. Angostura Walleye also receive a substantial amount of angler exploitation; nearly double that estimated for Belle Fourche or Shadehill. Due to this, the current 381 mm MLL regulation is most likely positively impacting the population in Angostura and is probably limiting harvest and preventing overfishing from occurring. If implemented, a more liberal harvest regulation could lead to growth overfishng of Walleye. The scarcity of Walleye fisheries in western South Dakota could exacerbate Walleye harvest in these three reservoirs by not providing alternate locations for Walleye angling. Additionally, angler effort is negatively related to fish populations and sustained high exploitation could continue while the Walleye population in Angostura falls to unsustainable levels. Because of this, I feel that current regulations on Angostura reservoir should remain in place.

It appears that the experimental PSL on Belle Fourche reservoir has achieved the management goal of increasing fishing pressure on sub-381 mm fish to increase size structure. Although angler exploitation is low-moderate, positive effects on growth can be seen early on as Walleye are reaching the lower limit of the PSL in only three years of age, potentially due to reductions in density. However, growth rates slow while in the slot and Walleye aren’t able to be legally harvested again until seven years of age. A majority (64%) of fish that were tagged were within the PSL, and this is probably leading to reductions in growth due to high densities of walleye.

Most Walleye anglers are harvest-oriented and the current PSL on Belle Fourche reservoir is hindering potential harvest yield (kg) from the Walleye population. From my modelling, if the regulation was changed to a no length limit, potential harvest gains could be double that under the PSL with little chances of overfishing. I feel that a regulation change to a no length limit regulation would allow anglers to fully utilize the potential of the Belle Fourche Reservoir Walleye fishery.

From my yield-per-recruit modelling in FAMS, Shadehill is the least productive reservoir. Walleye growth is slowest in Shadehill and fish take approximately four years to grow to the harvestable size of 381 mm. Shadehill also receives low-moderate angler exploitation, similar to Belle Fourche Reservoir. This could be due to its close proximity to Mobridge, SD on Lake Oahe, a very popular angling destination that has no length restrictions on Walleye harvest.

There is potential benefit to implement a more liberal, no length limit harvest regulation on Shadehill Reservoir. Slightly higher yields will be achieved in the events of higher conditional natural mortality rates, with little risk of overfishing. Additionally, increased harvest on sub-381 mm Walleye could free up resources and increase initial growth rates. This in turn could increase the production of the Shadehill Walleye population. Shadehill had the second highest morphoedaphic index (MEI) of the three reservoirs. It’s possible, that with the removal of the MLL on Shadehill and the subsequent increase in growth rates due to harvest, that the reservoir could support a more productive Walleye fishery. I feel that the removal of the 381 mm MLL would be beneficial and increase the value of the Walleye fishery in Shadehill Reservoir.

Given the results of this study, post-release hooking mortality should be minimal under these new regulation changes. In particular with Shadehill Reservoir, catch and release angling will be nearly non-existent with no length-based regulations. Being the most northern of the three reservoirs, it has the highest potential for ice fishing pressure and areas where catches greater than 10 m can occur (two of the most influential variables in probability of mortality in my study). Belle Fourche is a somewhat shallow reservoir, where catches of Walleye in greater than 10 m are rare. In addition, safe ice is not an annual guarantee, so the ice fishing season can be limited in years. Nonetheless, the no length harvest regulation I am proposing will cause little to no hooking mortality.

Angostura is the deepest and warmest of the three reservoirs examined in this study. Post-release hooking mortality during the winter is probably minimal on Angostura due to warmer water temperatures. However, hooking mortality during peak summer months has the possibility to be substantial due to the possibility of deep catches of Walleye exceeding 10 m. Even so, the interaction between high water temperatures and deep capture depths in Walleye isn’t well understood and will need to be further investigated to aid in the validity of the MLL on Angostura. Nonetheless, all reservoirs have the potential to experience large drawdowns during peak summer months for purposes of irrigation, thus potentially decreasing the likelihood of deep catches of Walleye for all fisheries.

Going forward, the interactions between deep capture depths and warm water temperatures on post release hooking mortality need to be further understood in South Dakota. The mean capture depth I achieved during sampling during the open water season was 6.7 m, far from the 10 m mark where I saw an increase in mortality

probability. Targeting fish much deeper using artificial baits and active gears, perhaps on a main stem Missouri River reservoirs used in my study would isolate the effects of depth on hooking mortality, particularly during peak summer months.