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Measurement Error in Fish Lengths: Evaluation and Management Implications

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Measurement Error in Fish Lengths: Evaluation and Management Implications

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ABSTRACT: *A fundamental aspect of fisheries science is measuring body length. Humans are inherently prone to error despite systems and provisions made to reduce it. We evaluated length measurement error (herein, referred to as "error") and digit preference from fish studies conducted on the Colorado River and Little Colorado River in Arizona. Empirical error estimates varied among fish species and generally increased with fish size. We identified a digit preference for numbers ending in zero and five, which was exacerbated with larger sizes. Error effects on growth estimates were largest for fish recaptured after a short time, and we suggest guarding against the error phenomenon by removing data from fish captured and recaptured within a minimum of 30 days. Human, situation, and specimen induced error factors are described. Fisheries professionals should be cognizant of error factors, especially in situations when high precision and accuracy are required and results have important management implications.*

Medición del error en la talla de los peces: evaluación e implicaciones para el manejo

RESUMEN: *un aspecto fundamental en las ciencias pesqueras es la medición de la talla corporal. Los humanos somos inherentemente propensos a cometer errores pese a los sistemas y medidas preventivas que se utilizan para reducirlos. En este trabajo se evalúa el error asociado a la medición de la talla (en lo sucesivo se le llamará "error") y la preferencia en el número de dígitos en los estudios ícticos llevados a cabo en el Río Colorado y el Río Coloradito, Arizona. Los estimados empíricos del error variaron entre especies de peces y en general se incrementaron conforme la aumenta la talla de los peces. Se identificaron preferencias en cuanto al número de dígitos para los números con terminación cero y cinco, lo cual se amplificó en los peces más grandes. Los efectos del error en las estimaciones de crecimiento fueron más grandes en el caso de los peces recién recapturados. Se sugiere tratar el fenómeno del error mediante la remoción de los datos provenientes de peces recapturados en los primeros 30 días después de su liberación. Se describen los factores de error humano, de medición y asociado al espécimen. Los profesionales de las pesquerías deben ser conscientes de los factores de error, especialmente en situaciones en las que se requieren precisión y exactitud y cuando hay implicaciones importantes para el manejo.*

INTRODUCTION

A fundamental aspect of fisheries science is measuring body length. Conventional measurements include total length (TL), standard length, and fork length (Anderson and Neumann 1996). Fish lengths can be measured with underwater cameras and laser-beam systems (Rochet et al. 2006), visual observation (Harvey et al. 2002), processing machines (White et al. 2006), and electronic measuring boards (Chaput et al. 1992). However, the most primitive and common method for measuring fish length is to use a board with a ruler adhered to the top surface and lengths are recited to a data recorder.

Humans are inherently prone to error despite systems and provisions made to reduce it (Reason 2000). Measurement error, defined here as the "inability to measure fisheries variables perfectly," is a type of uncertainty in fisheries population dynamics (Chen and Paloheimo 1998:9). Fisheries professionals should consider various factors that affect error rates and, more important, understand how error can influence the interpretation of fisheries data and, thus, management decisions.

Although studies comparing sport and commercial fishers' length measurements to those within the fisheries profession have been conducted (Ferguson et al. 1984; Page et al. 2004), few studies have evaluated length measurement error within the fisheries science profession. Our objectives were to (1) evaluate error for different fish species and size groups, (2) evaluate digit preference, and (3) demonstrate the necessity to remove data from fish captured and recaptured within a short time frame (e.g., 30 days) during growth studies.

METHODS

Length Measurement Error Evaluation

We evaluated a long-term fish monitoring database from various Colorado River and Little Colorado River studies conducted between Glen Canyon Dam (Lake Powell) and the inflow to Lake Mead in Arizona. The study area encompassed Glen, Marble, and Grand canyons and the Little Colorado River, which is a large tributary to the Colorado River. The Little Colorado River is the primary spawning and rearing grounds for the endangered Humpback Chub (*Gila cypha*) and other large-bodied native fish, including Flannelmouth Sucker (*Catostomus latippinis*) and Bluehead Sucker (*Catostomus discobolus*). The tailwater stretching 27 km below Glen Canyon Dam supports a recreational Rainbow Trout (*Oncorhynchus mykiss*) fishery.

The database contains over 750,000 individual fish records dating back to the late 1970s. More than 120,000 fish have been tagged with individually identifying marks (i.e., passive integrated transponder tags, numbered external anchor tags, and numbered coded wire tags). In addition to the species listed above, other species including Brown Trout (*Salmo trutta*) and Common Carp (*Cyprinus carpio*) have been tagged. Fish were captured using a variety of net types (e.g., hoop nets and trammel nets of various sizes and dimensions) and boat-mounted electrofishing (Coggins et al. 2006; Makinster et al. 2010, 2011). Total length (in millimeters) measurements were taken on measuring boards on shore or aboard research vessels during the day or night depending on the study requirements. Tagging protocols have varied across species and sizes, and generally fish less than 100 mm TL were not tagged with individual marks.

A portion of fish that received tags tended to get captured and recaptured within the same sampling event or soon thereafter. We only used data from fish that were marked or recaptured within a 3-day period of a subsequent recapture. We assumed that growth was negligible during this short time frame, which would not affect our estimates of error. The difference between the two independent measurements (i.e., the measurement at capture and the subsequent measurement at recapture) was used to estimate mean error. Our approach differed from that of Gutreuter and Krzoska (1994) because investigators in that study were aware of each other's measurements. Similar to Page et al. (2004), we eliminated error outliers greater than three standard deviations from the mean for each species. Fish were separated by species and grouped into 100-mm size intervals ranging between 100 and 300 mm TL, and a group for those greater than 300 mm TL was established. We did not include species and size groups with a sample size less than 30. We plotted error frequency by 1-mm increments.

Juvenile Chub Evaluation

To evaluate error for juvenile Humpback Chub that did not receive tags, we used a blind experimental design in which fish less than 100 mm TL were measured by two separate investigators. Fish were captured using hoop nets placed in the Little Colorado River during Arizona Game and Fish Department and U.S. Fish and Wildlife Service monitoring efforts in May–June 2012. Investigators were instructed to measure fish and record data with the same techniques they normally used during routine sampling. They were not aware of each other's measurements throughout the experiment.

Digit Preference

We evaluated digit preference (Beaman and Grenier 1998), otherwise known as "digit bias" (Sette 1941) or "response heaping" (Vaske and Beaman 2006), as a potential source of error. We plotted the frequency distribution of the last digit from all TL measurements available in the database and tested for significant differences using a chi-square goodness-of-fit test (significance level $\alpha = 0.001$) to evaluate the hypothesis that each digit was assigned with equal probability (Zar 2010). Additionally, we separated measurements into 10-mm length groups (i.e., 10–690 mm) and conducted a chi-square goodness-of-fit test for significance (same as above) for each length group independently.

Growth Rate Variability

We estimated absolute growth rate (millimeters per day) for Humpback Chub over a 23-year time series (1989–2011). The equation from Busacker et al. (1990) used to estimate absolute growth rate for individual fish is shown below:

$$\text{Absolute growth rate} = Y_2 - Y_1 / t_2 - t_1 \qquad (1)$$

where $Y_2 - Y_1$ is the difference in length between capture occasions, and $t_2 - t_1$ is the difference in time between capture occasions (i.e., days at liberty). The resulting data were plotted against days at liberty to highlight the variability in growth. Additionally, we plotted absolute growth rate as a function of fish length at initial capture for two groups: (1) fish with <30 days at liberty and (2) fish with ≥30 days at liberty.

RESULTS

A total of 8,909 fish were recaptured within 3 days of a previous capture event, which enabled us to obtain empirically based species- and size-specific error estimates. The frequency histogram showed that data were evenly distributed around zero

Photo 1. Photograph of an adult Humpback Chub collected during Little Colorado River monitoring. Length measurements were taken from a conventional wooden board with a measuring tape adhered to the top surface. Photo credit: Arizona Game and Fish Department.

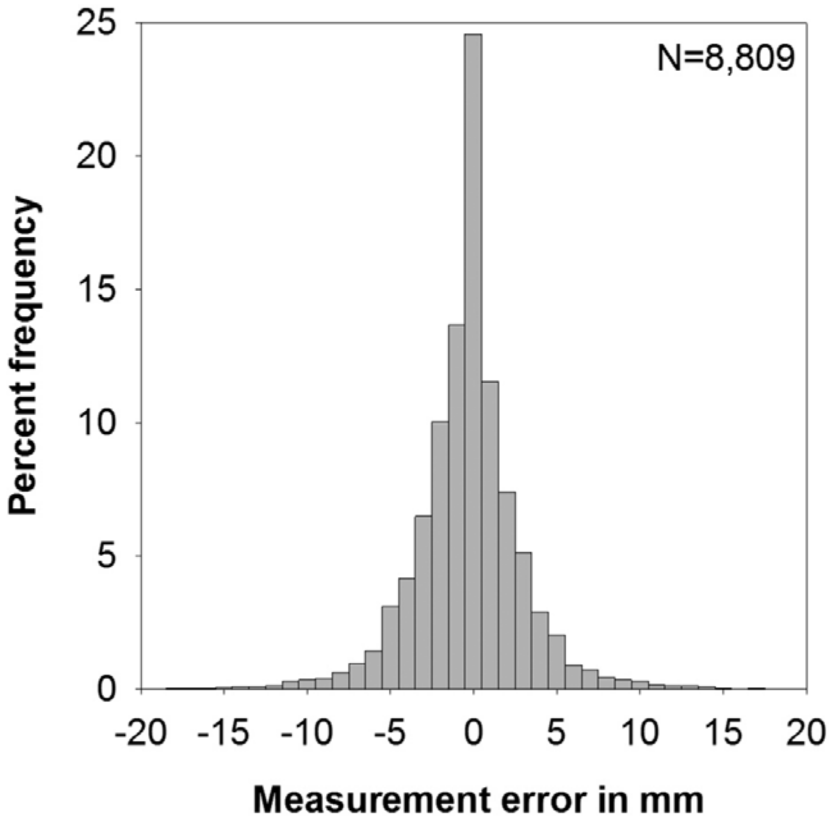

Figure 1. Length measurement error (total length in millimeters) frequency histogram in 1-mm increments. Negative numbers occurred due to shorter measurements taken during recapture event. Large outliers are not shown because the x-axis was bounded at −20 to 20.

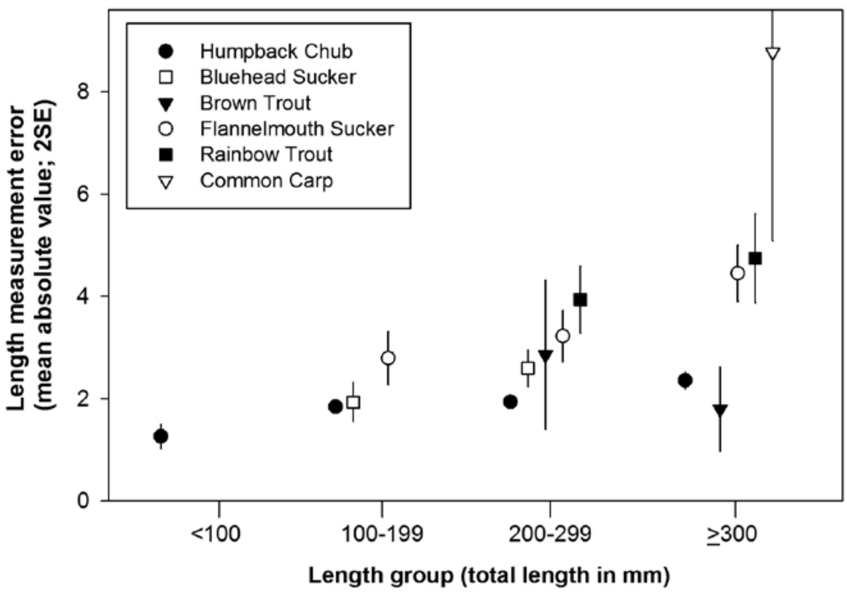

Figure 2. Mean ± 2 standard error length measurement error (absolute value; total length in millimeters) separated by fish species and size group. Humpback Chub (black circles), Bluehead Sucker (white squares), Brown Trout (black triangles), Flannelmouth Sucker (white circles), Rainbow Trout (black squares), and Common Carp (white triangles) were separated into four size groups (<100, 100–199, 200–299, and ≥300). Not all fish species met the sample size requirements (N > 30) for each size class.

with no error occurring 25% of the time (Figure 1). One hundred and twenty-two juvenile Humpback Chub were evaluated during the blind study. Humpback Chub error estimates from Figure 2 reflect those derived from the database, as well as those from the juvenile chub evaluation. Humpback Chub, Bluehead Sucker, and Brown Trout had the smallest mean error (Figure 2). Large Common Carp had the largest mean error (Figure 2). Several species showed increased pattern of error with size (Figure 2).

Empirical growth estimates from Humpback Chub showed that variability associated with error was reduced substantially

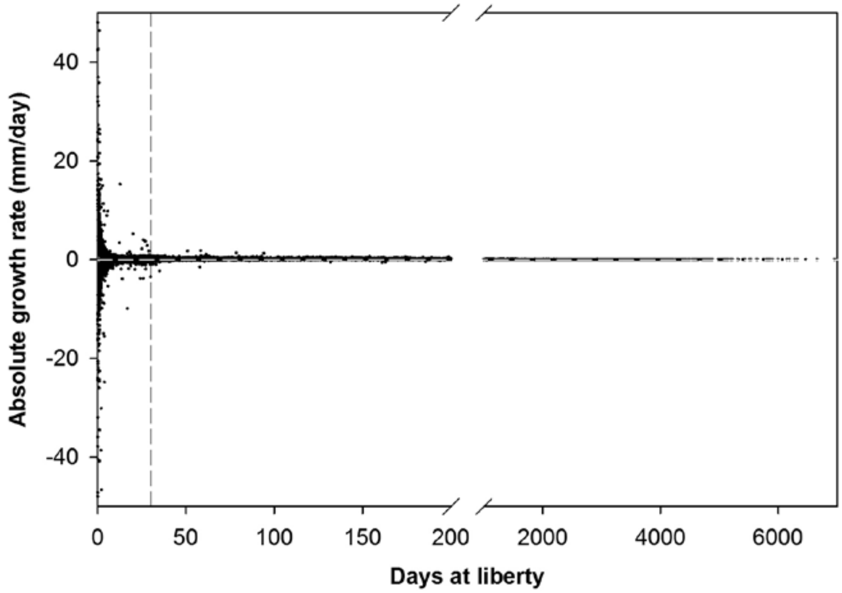

Figure 3. Empirically estimated mean absolute growth rate (millimeters per day) for Humpback Chub during long-term monitoring activities from 1989 to 2011 as a function of days at liberty. The horizontal white dashed line was set to zero for reference. The vertical black dashed line was set to 30, indicating the suggested number of days adequate for growth rate estimation.

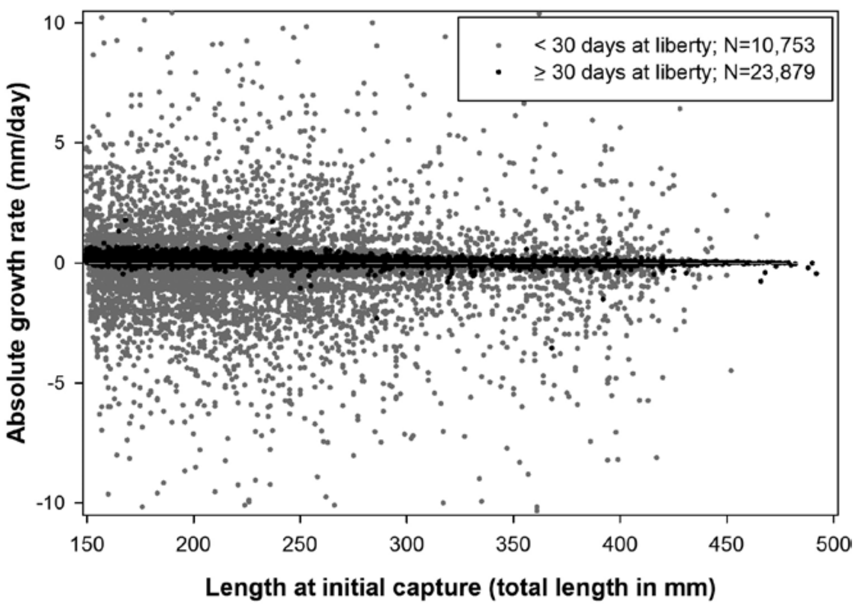

Figure 4. Empirically estimated mean absolute growth rate (millimeters per day) for Humpback Chub during long-term monitoring activities from 1989 to 2011 as a function of fish length at initial capture (total length in millimeters). Gray circles indicate data derived from growth rates attained with <30 days at liberty. Black circles indicate data derived from growth rates attained with ≥30 days at liberty.

over longer durations between capture events (Figures 3 and 4). The daily mean ± 2 standard error absolute growth rate for Humpback Chub recapture histories was lower (and negative) when using all data (−0.04 ± 0.25 mm/day; N = 34,632) compared to removing data for fish less than 30 days between captures (0.07 ± 0.01 mm/day; N = 23,879; Figure 4).

We identified a digit preference in the data set for numbers ending with zero or five (Figure 5; χ^2 = 28,098; df = 9; P < 0.001). This digit preference was evident across all length groups (χ^2 > critical value for all tests; df = 9; P < 0.001); however, preference was exacerbated with larger fish size (Figure 6).

Error Factors

Empirical error estimates varied among fish species and generally increased with fish size. Sources of error can be explained using an extension of the concepts introduced in Anderson and Neumann (1996). Error factors can be split into three categories: (1) human induced, (2) situation induced, and (3) specimen induced (Table 1). Most human-induced factors can be minimized if they are recognized and corrected (Phelps et al. 2012). For example, if incorrect fish snout placement on the measuring board is common for an investigator, this behavior could be altered to correct the bias. It could simply be an equipment problem where a gap is present between the board and the

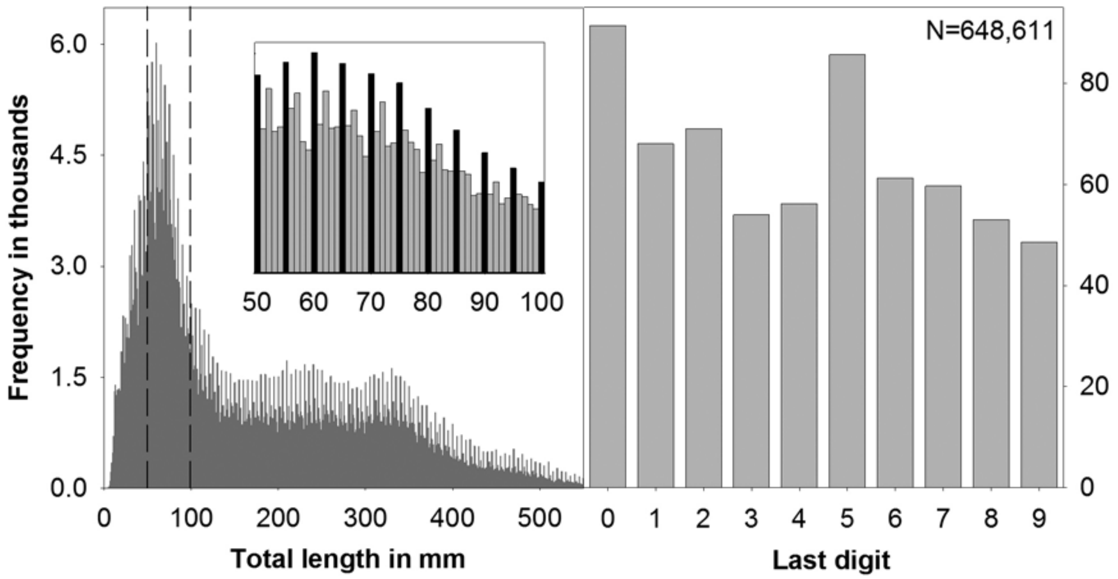

Figure 5. Total length measurements from a long-term fish monitoring database from various Colorado River and Little Colorado River studies conducted since the late 1970s. The dashed lines indicate the zoomed area (50–100 mm). The black bars (left plot) and gray bars (right plot) indicate a digit preference of numbers ending in zero and five.

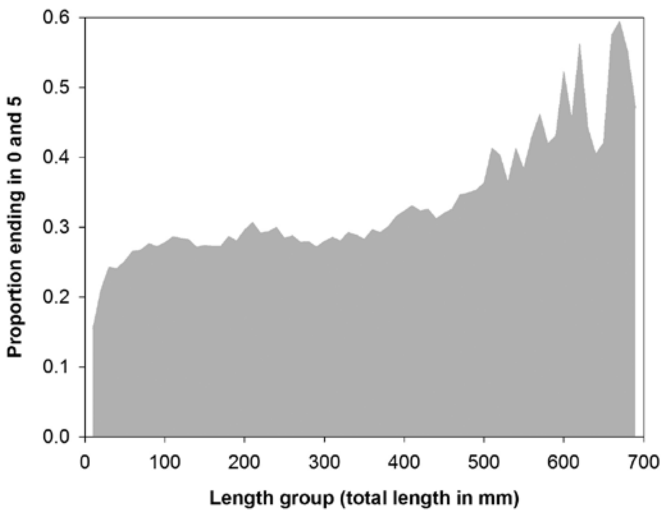

Figure 6. Investigators showed a proportionally higher digit preference for numbers ending in zero or five for larger fish. The proportion is shown for measurements ending in zero and five for each 10-mm length group (i.e., 10–690 mm).

start of the ruler. The pace of measurements likely influences precision, because a faster pace may yield higher error rates.

Digit preference is defined as consciously or inadvertently choosing certain patterns when reporting numerical values. Investigators showed a proportionally higher digit preference for numbers ending in zero or five, which was exacerbated with larger sized fish. Similarly, hunters and fishers tend to prefer numbers ending with a zero or five when reporting harvest (Vaske and Beaman 2006; Bailey 2007). Our inherent subconscious preference toward numbers ending with zero and five could influence error. According to Vaske and Beaman (2006), systematic digit preference can distort results. Digit preference (bias) has also been well established in the medical literature (e.g., blood pressure measurements; Wen et al. 1993; Thavarajah et al. 2003).

Situation induced factors are often uncontrollable (e.g., weather conditions), with the exception of a laboratory setting, which may facilitate fewer errors. Certain sampling situations make it more difficult to take precise measurements. For example, Harvey et al. (2002) found low precision (i.e., high standard deviation) in measurements obtained by experienced scientific divers. Field conditions vary widely across projects. Some projects are conducted during daylight hours on shore as opposed to nighttime work aboard boats. We found higher error in Rainbow Trout measurements than Humpback Chub measurements possibly because Rainbow Trout were sampled at night and processed aboard boats. Humpback Chub were primarily sampled during the day and processed on shore.

Fisheries professionals probably focus on relative error (error divided by length) rather than absolute error. One might assume (perhaps correctly) that the impact of a 5-mm error on a 300-mm fish differs from the same error on a 30-mm fish. Thus, measurement performance may be more related to minimizing relative rather than absolute error. Therefore, fish size is likely an important factor, because larger fish showed lower precision and higher digit preference for zero and five. We found that Common Carp, which are generally much larger than other fish in the Grand Canyon, had the largest error. Phelps et al. (2012) found a substantial amount of error in large Shovelnose Sturgeon (*Scaphirhynchus platorynchus*).

Morphological attributes and behavior vary across species. For example, snout morphology and size and placement of mouthparts could influence error. Flannelmouth Suckers have a blunt rounded snout and subterminal mouthparts. Without proper care when measuring Flannelmouth Suckers it is easy to apply too much pressure, causing the snout to turn downwards and, therefore, the body would not extend properly, causing an inaccurate measurement. Some fish species may exhibit stressed behavior while on the measuring board, whereas others may

Table 1. List of length measurement error factors and potential sources of bias.

Factor	Considerations
Human induced	Communication error between processor and data recorder Correct placement on measuring board Digit preference (bias) Equipment condition Misinterpretation Pace of measurements Skill level Vision problems
Situation induced	Setting (e.g., aboard research vessel, on shore, or in the laboratory) Time of day Weather conditions Visibility during diving surveys Distance of fish during diving surveys
Specimen induced	Disposition (e.g., live, preserved, frozen, or under anesthesia) Size Morphological attributes Behavior Movement during diving surveys

be calmer. Luiselli (2005) found that snake size and behavior influenced length measurements.

Generally, fish show unidirectional growth trajectories; however, Huusko et al. (2011) found that body length reduction can occur naturally in juvenile salmonids because of harsh winter conditions in small streams. Mabee et al. (1998) showed that clearing and staining of sacrificed specimens can cause 3%–5% shrinkage, and others have found length reduction postpreservation (Engel 1974) and without preservation or freezing (Morison et al. 2003). Therefore, it is important to consider fish disposition, especially if a live measurement at marking is compared to measurement postmortem (preserved or not). Fish body parts, especially caudal fins, can become damaged or disfigured between capture occasions. Biologists have observed caudal fin damage on Humpback Chub in the Little Colorado River, which would contribute to shorter measurement at recapture (D. Stone, U.S. Fish and Wildlife Service, personal communication).

Management Implications

Error effects on growth estimates were largest for fish recaptured after a short time, and those effects could bias von Bertalanffy parameters if growth estimates are used directly for parameter estimation. Therefore, time between capture and recapture events should be considered when assessing growth rates. A longer duration between capture and recapture events will lessen the potential for bias in growth rate estimates. Mean absolute growth rate from all Humpback Chub data was negative, indicating that dispersion associated with low days at liberty caused imprecise and erroneous estimates. In equation (1), when $t_2 - t_1$ is only a few days, error has a large impact on the numerator and the overall quotient is substantively influenced by the small denominator. Therefore, small errors in length could have a large effect on growth estimates. A negative growth rate value or one that is exorbitantly high will be a clear indication of error. The difficulty lies in understanding which positive growth rates are erroneous aside from extremely high values. In this study, the proportion of positive and negative errors was nearly equivalent, and thus only removing negatively biased numbers could positively bias mean estimates.

Although error was low in this study, large errors and systematic biases could influence interpretation of length data (Wetherall et al. 1987). The statistical methods required to analyze data will ultimately dictate the level of accuracy and precision needed. Harvey et al. (2002) explained a scenario in which small errors in fish lengths could produce inaccurate weight estimates. There are many other examples showing that other types of measurement errors can influence results, such as stock–recruit relationships (spawner biomass estimation error; Walters and Ludwig 1981), bioenergetics models (relative growth rate error; Bajer et al. 2004), age-structured calculations from otolith aging (aging error; Coggins and Quinn 1998; Campana 2001), and others (Zschokke and Ludin 2001; Hansen et al. 2005).

The error phenomenon described above has important management implications if growth rates are used to develop management goals. For example, Glen Canyon Dam Adaptive Management Program managers have considered options (e.g., temperature control device and flow treatments) to increase water temperatures to facilitate an increase in native fish growth rates (Grand Canyon Monitoring and Research Center 2007; Ralston 2011). As such, Coggins and Pine (2010) developed a temperature-dependent growth model for Humpback Chub in the Colorado River and guarded against the error phenomenon by removing fish observed within 30 days of initial capture. In future growth studies that use a mark–recapture framework, we suggest routinely plotting growth rate against days at liberty to identify bias associated with error. It is essential for fisheries professionals to be cognizant of error factors, especially those that contribute to systematic error.

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