Freshwater Biology

The potential tradeoff between artisanal fisheries production and hydroelectricity generation on the Kafue River, Zambia

Journal:	*Freshwater Biology*
Manuscript ID:	Draft
Manuscript Type:	Applied Issue
Date Submitted by the Author:	n/a
Complete List of Authors:	Deines, Andrew; University of Notre Dame, Biological Sciences Bee, C.; University of Notre Dame, Economics and Econometrics Jensen, Richard; University of Notre Dame, Economics and Econometrics Lodge, David; University of Notre Dame, Biology
Keywords:	Fisheries < Applied Issues, Modelling / statistics < Process / Approach / Methods, Conservation / biodiversity < Applied Issues, River regulation / engineering < Applied Issues, Floodplains < Habitat

SCHOLARONE™
Manuscripts

Summary

1) Freshwater resource managers are increasingly obligated to consider the impacts on ecosystem services of large river engineering projects. We evaluated the effect of altered water regime from the operation of a large dam on the production of the downstream tropical floodplain fishery of the Kafue River, Zambia. We compared the benefits of increased hydropower relative to potentially lost fishery production.
2) We compiled a long-term data set consisting of experimental gillnet catches, artisanal harvesting effort and monthly river flows for 25 years prior to and 29 years after the 1977 completion of the upstream Itezhi-tezhi dam. As a metric of the flood regime we calculated a canonical correlation score for each hydrological year before and after dam closure. For the period following dam construction, we used the Muskingum method of flood routing to estimate "no-dam" flows through the fishery area and downstream hydroelectric turbines in the Kafue Gorge dam.
3) We compared 16 alternative models of catch per unit effort with and without an effect of water regime on fish population growth rate. Using the two best fitting models, we estimated the total observed fishery harvest and simulated "no-dam" fisheries harvest and found no significant effect of altered water regime on fishery production.
4) We estimate that the large up-stream dam increases downstream hydropower production by about \$17 million USD per annum. The non-significant reduction in fishery production caused by the altered water regime amounts to about \$2.3 million annually, while the total estimated value of harvest ranges from \$1.3 million to \$56 million annually.
5) Large observed declines in fish abundance over the 54 yr study period are correlated with similarly large increases in total effort in this mostly open-access artisanal fishery.
6) These results contrast with other examples of the effects of flow alteration on fish, probably because levels of fisheries exploitation on the Kafue River are very high relative to better studied regions on other continents; our focus on the whole fish community; and the unprecedented length of the time series we considered. If the management goal is to sustain fishery production, investments in altering flow regime are likely to be less effective than investments to decrease fishing effort.

Copy for Review

Introduction

Maximizing the production of ecosystem services is a desirable outcome for resource management, particularly when increasing the provision of one service decreases the provision of another. In these instances, it is important to estimate the value of ecosystem services--and the tradeoffs between potentially competing services--to efficiently use resources. We estimate two major ecosystem services provided by the Kafue River, Zambia, hydroelectricity generation and fisheries production, and discuss management implications of the potential tradeoff between them.

Globally, there is increasing scientific and policy interest in “environmental flows,” i.e., flows that more closely mimic natural hydrologic patterns, as a tool to sustain ecosystem services and human well-being and better balance potential tradeoffs in flow alteration and other ecosystem services. This interest derives from the fact that large, impounded rivers around the world are facing competing uses of water resources as seasonal flood regimes are altered for hydropower or irrigation by storing water from high-flow seasons for use in dryer periods. Changes in water flow can impact river biodiversity by altering the physical channel structure, disrupting organisms’ life history patterns, severing connectivity, and by encouraging species invasions (Dudgeon *et al,*. 2005). These water regime changes also impact fisheries production and related ecological services (Welcomme, 2008; Poff & Zimmerman, 2010).

The task of assessing tradeoffs in ecosystem services as a result of flow alteration is especially relevant in Africa where there are 20 large dams now under construction or advanced planning, 42 undergoing expansions or rehabilitation, and 83 proposed new dams (International Rivers Africa Program, 2010). Little knowledge exists for similar rivers on the effect of changes in flow regime on biotic ecosystem services. Most work on environmental flows has occurred in the Northern hemisphere in mostly small streams and rivers, has focused on particular species (such as salmon, e.g. Service, 2011) or been conducted in the absence of significant fisheries. The need for ecological information has led to the development of the comprehensive Integrated Basin Flow Assessment (IBFA) approach over the last 15 years to integrate expert ecological

Copy for Review

knowledge and social-economic factors to inform river management (King & Brown, 2010). It is too soon to see the effectiveness of IBFA implementation; thus the responses of ecosystems, particularly fisheries, to changes in hydrologic regime remain largely unstudied in Africa (Poff & Zimmerman, 2010). The Kafue River, Zambia therefore presents an opportunity to examine the importance of water regime in a highly relevant social, economic and environmental context: heavily exploited artisanal fisheries.

Pre-dam fisheries studies conducted on the Kafue in the mid-1970s found annual fisheries harvest to be significantly correlated to flood regime (Chapman *et al.,* 1971; Lagler, Kapetsky & Stewart, 1971; Dudley, 1974; Kapetsky & Illies, 1974; Welcomme, 1975a; Muncy, 1977). These relationships between hydrological regime and fishery yield are complicated, however, because these studies focused on total harvest which overlooks the reciprocal relationships between fish abundance and fishery effort. No studies have evaluated the impact of change in water regime on Kafue fisheries since dam construction was completed, though negative impacts on fisheries are often assumed (Chipungu, 1981; Schelle & Pittock, 2005). Changes in other ecosystem properties such as decreased extent of wetland habitat (Munyati, 2000; Mumba & Thompson, 2005) and water chemistry (Obrdlik, Mumeka & Kasonde, 1989) have also been reported. In response to these observations environmental flows have been advocated by some stakeholders (Schelle & Pittock, 2005).

We hypothesized that the upstream construction of Itezhi-tezhi (ITT) dam altered the Kafue River water regime and therefore reduced downstream fish abundance. To determine the relationship between water regime and fishery production, we compiled experimental catch per unit effort, artisanal effort, total harvest, and monthly-mean discharge hydrographs from the Kafue River for the years 1954-2010 and developed state-space population growth models to test the effects of flood regime on multi-species fish community population growth rate. Using flow data from above ITT reservoir we simulated the water regime on the Kafue River for the post-ITT dam period as if ITT dam had not been constructed. Using this “no-dam” simulated flow we used the best fitting population growth models to estimate fisheries production and hydroelectric

Copy for Review

generating capacity downstream of ITT. Finally, we compared the revenue derived from these ecosystem services with and with-out water regulation by ITT dam.

Methods

Site description

The Kafue Flats are a large, flat floodplain of the Kafue River in Zambia (Fig. 1). Historically, after the onset of the rainy season in November, flood waters began to rise from a dry season low of about $30 m^3 s^{-1}$, and peaked in April or May at more than $1500 m^3 s^{-1}$. More than 6,000 square kilometers were underwater during typical flood stage; for comparison this is an area more than 10X the area of Lake Constanz (Germany, Austria, Switzerland) and roughly one third the size of Lake Ontario of the Laurentian Great Lakes. The fishery has remained primarily artisanal. Fishers typically use dugout canoes or fiberglass "banana boats" and multifilament gillnets. Though illegal, large (>100m) hand drawn seines of <1mm mesh are also common, as are monofilament gillnets, and gillnets of mesh less than 50mm mesh. Fish-driving is also commonly practiced, by beating the water to drive fish into these gillnets.

The main fishery area is bracketed by two dams (Fig. 1). The downstream Kafue Gorge dam (KG), completed in 1972, was originally installed with 600 megawatt (MW) of generating capacity, but was later expanded to 900 MW (Smardon, 2009). The estimated maximum capacity of the reservoir at KG is 800 million m^3 (Knaap, 1994), thus without water regulation during the dry season, the dam would only have enough water available for 207 MW of power output. To increase hydropower capacity, the ITT dam was built at the upstream end of the Kafue Flats in 1977. With a much larger reservoir holding 4,950 million m^3, ITT provides steady flow downstream during the dry season, reducing the risk of insufficient water for maximum power generation at KG (Smardon, 2009).

Data compilation

Experimental gillnet fisheries data (Fig. 2A) were compiled from published literature and unpublished data from the Zambian Department of Fisheries (DoF) for the years 1954-2010, and are assumed to be an index of total fish abundance as catch per unit effort (CPUE) calculated in

Copy for Review

mass per meter of net per night (Williams, 1960; CSO, 1970; Kapetsky 1974; CSO, 1978, 1984, see Supporting Information). In this analysis we included only those mesh sizes and sampling locations (Table S1) and taxa (Table S2) as those reported in the pre-dam data to produce a data string that is comparable across all years. Fishing effort data on the Kafue was available as the number of gillnets and the number of boats (Fig. 2B) (Mortimer, 1965; Kapetsky & Illies, 1974; CSO, 1978; Muyanga & Chipungu, 1978; Chipungu, 1981; CSO, 1984; Lupikisha, 1992; DoF, 1993; Lupikisha, 1993; DoF & CSO, 2007). Total harvest (metric tons) (Fig. 2C) estimates were as reported for 1954-1996 by Nyimbili (2006). Comparable total harvest data after 1996 are not available.

Monthly mean discharge (m^3s^{-1}) at the ITT dam was obtained from the Food and Agriculture Organization (1968) for the years 1953 through 1963, the Zambian Ministry of Energy and Water Development for 1960 through 1991, and Nyimbili (2006) from 1980 through 2005 (Fig. 2D). Using the before and after damming mean monthly hydrographs we preformed canonical correlation analysis (CCA) with the CCA package in R (vers 2.14.0; R Development Core Team, 2011) and used the resulting correlation score in each year as a flood regime metric that maximizes the differences between the before and after hydrographs relative to the variation within each before-after grouping.

Modeling the impact of flood regime on fishery production

We used a multivariate auto-regressive state-space (MARSS) model to fit time series of experimental CPUE, fisheries effort and water regime data to population growth models using maximum likelihood estimation. This state-space approach allowed the simultaneous estimation of the unobserved state process of fish abundance (CPUE) and fisheries effort (meters of gillnet) with observation error and including the effect of water level as a covariate to the CPUE process.

The MARSS model assumes Gompertz population growth expressed as a linear model by taking the natural log of CPUE and effort. In multivariate state-space, state and observation processes are arranged into a system of equations in matrix form including covariates (Holmes & Ward, 2011).

Copy for Review

$$\begin{bmatrix}\mathbf{x}^{(v)}\\ \mathbf{x}^{(cv)}\end{bmatrix}_t = \begin{bmatrix}\mathbf{B}^{(v)} & \mathbf{B}^{(cv)}\\ 0 & 1\end{bmatrix}\begin{bmatrix}\mathbf{x}^{(v)}\\ \mathbf{x}^{(cv)}\end{bmatrix}_{t-1} + \begin{bmatrix}\mathbf{u}^{(v)}\\ \mathbf{u}^{(cv)}\end{bmatrix} + \mathbf{w}_t, \mathbf{w}_t \sim \mathrm{MVN}\left(0, \begin{bmatrix}\mathbf{Q}^{(v)} & 0\\ 0 & \mathbf{Q}^{(cv)}\end{bmatrix}\right) \quad \text{(1a)}$$

$$\begin{bmatrix}\mathbf{y}^{(v)}\\ \mathbf{y}^{(cv)}\end{bmatrix}_t = \begin{bmatrix}\mathbf{Z}^{(v)} & 0\\ 0 & \mathbf{Z}^{(cv)}\end{bmatrix}\begin{bmatrix}\mathbf{x}^{(v)}\\ \mathbf{x}^{(cv)}\end{bmatrix}_{t} + \begin{bmatrix}\mathbf{a}^{(v)}\\ \mathbf{a}^{(cv)}\end{bmatrix} + \mathbf{v}_t, \mathbf{v}_t \sim \mathrm{MVN}\left(0, \begin{bmatrix}\mathbf{R}^{(v)} & 0\\ 0 & \mathbf{R}^{(cv)}\end{bmatrix}\right) \quad \text{(1b)}$$

Where $\boldsymbol{x}^i$ are state vectors at time *t* defined by a state process equation (Equation 1a) with *i* superscripts representing estimated variates *(v)* CPUE and effort, or the covariates *(cv;* in this case the CCA score representing water regime). $\boldsymbol{B}^i$ are parameter matrices to be estimated. Process error, $\boldsymbol{w}_t$, is modeled as a multivariate normal distribution with mean zero and variance-covariance matrix of process (environmental) stochasticity $\boldsymbol{Q}$. Vectors of observed data $\boldsymbol{y}^i$ are related to the process states through the observation process equation (Equation 1b). $\boldsymbol{Z}$ are identity matrices that associate one or more observations to unobserved state processes, with $\boldsymbol{a}$ parameters that linearly scale multiple observations of the same state, and multivariate normal observation error $\boldsymbol{v}_t$ with $\boldsymbol{R}$ variance-covariance matrixes.

In total we specified 3 state processes for CPUE, effort, and water. Following standard practice we demeaned and standardized all data and used the resulting *z*-scores for estimation. We assumed that processes do not co-vary and fixed CCA score variance at unity to give the process model the flexibility to exactly equal the true covariate values; thus the covariate processes are not modeled but exactly specified (Holmes & Ward, 2011). Initial results indicated process errors less than 1e-15 in all cases, leading to instability in the estimation algorithm. We therefore fixed process error for CPUE and effort at a trivially small value, $1e^{-5}$. We specified two observation vectors for the effort process, gillnet meters and boat counts, where boat counts are linearly scaled to gillnets by estimating the number of gillnet meters per boat in vector $\boldsymbol{a}^{(v)}$. Assuming this scaling is constant over the time period is reasonable given that the common type dugout canoe has changed little over time, and they have probably always worked at capacity.

We created 16 base models that variously included or excluded all combinations of the effect of density dependence for CPUE and effort, of CPUE_{t-1} on effort, and water_{t-1} on CPUE. Models

Copy for Review

were estimated using the MARSS package (vers 2.8; Holmes & Ward, 2011) in R, and ranked by Akaike's Information Criteria (corrected, AICc). For the two best models we estimated the 95% bootstrap confidence intervals (CI) for the parameters and the CPUE and effort states. To perform the bootstrap we resampled the mean CPUE data for each year and parametrically simulated 500 bootstrap replicates of gillnets and boats counts based on the error estimated in each model. Using the original model estimate for initial conditions, these bootstrap data were used to re-estimate parameters and states for each model and estimate the 95% CI for the observations of CPUE, gillnets, and boats.

Sensitivity analysis

The treatment of observation error in state-space models is critical to estimating environmental effects on population dynamics (Linden & Knape, 2009) and the key motivation for sensitivity analysis. Ives *et al* (2003) recommended against directly fitting observation error from data without independent estimates, and suggested instead to fit the model with rough estimates of observation variance and then test the sensitivity of the model to these estimates. We therefore fit models while estimating observation error, fixing observation error with rough estimates, and fixing observation error at unity. We fixed rough estimates of observation error as follows. For CPUE, we used the mean variance from 10000 bootstrap samples of each year with >= 4 sampling periods (= 0.069). Gillnet observation variance derives from the variance observed in gillnets used in several areas over a 12 month period in 1972 (=0.321, CSO, 1978). To roughly estimate observation error in boat counts, we assumed that fishermen and boats where censused with the same error (counts of fishermen roughly coincide with boats counts; data not shown), we therefore conservatively use the maximum variance in any year between multiple counts of boats and/or counts of fishermen, which occurred in 2006 (=0.085). This yielded a total of 48 models for comparison.

We also tested the ability of the MARSS and AICc model selection procedure to select the correct model by re-running the selection for each model replacing the data with the estimated state vectors. That is, for each of the 16 base models the state vectors represented data simulated from a known model with known parameters, and we tested if running model selection on that simulated data would recapture the model from which it was generated.

Copy for Review

Simulating flood regime and hydroelectric generating capacity

The ITT dam is intended to provide a more consistent supply of water during the dry season and thereby keep the turbines at KG dam capable of running at full capacity year-round. We apply the widely used Muskingum method of flood routing, or predicting downstream flows based on known upstream flows (McCarthy, 1938), to predict actual and counterfactual "no-dam" flows at KG based on flows at ITT. Detailed methods are provided in the supporting information and summarized below.

First, we estimated counterfactual "no-dam" discharge for ITT using daily discharge at Hook Bridge monitoring station up-stream from ITT reservoir (Fig. 1, S2) to estimate the inflows into the Muskingum model and discharge at ITT to represent outflows. Similarly, to model hydropower production at the downstream KG dam under both actual and counterfactual flows we used the actual and this estimated counterfactual daily discharge at the ITT dam to represent inflows to the Muskingum model, and flows at KG dam to represent outflows. Additionally, to calculate the "no-dam" scenario water regime CCA metric we multiplied the CCA loadings calculated from the observed ITT hydrograph by this counterfactual mean monthly flow at ITT.

To estimate hydropower production under alternate flow regimes, we took the annual average for each simulated Kafue Gorge hydrograph as an expected difference in flow attributed to the Itezhi-tezhi dam's influence on the Kafue River's flood regime. Reduced discharges into the reservoir at KG dam do not necessarily imply reduced generating capacity as the KG generating station can still operate until the reservoir is emptied, and even then it can use the reduced inflow directly. Therefore we conservatively compute the minimum reduction of power output in the "no-dam" scenario relative to that which uses the full capacity of the reservoir. To estimate the value of this reduction in generation we use the replacement cost of importing the foregone electricity to Zambia, which is estimated at about $31 per MWh (PB Power, 2006)

Harvest Revenue

Copy for Review

Using the actual and "no-dam" CCA water regime metrics and the parameter estimates of the best models, we calculated harvest for each year after the dam up to 2006 for each of 500 bootstrap CPUE replicates by rescaling the state process estimates and taking the product of the CPUE (kg m^{-1} $night^{-1}$), effort (m), and activity rate by fishers (proportion of nights per year spent fishing), for which a range of estimates exist. We multiplied the upper 95% CI of CPUE * effort by an activity rate = 1 (365 days of fishing per year) to retrieve maximum total harvest per year assuming that all nets were deployed every night of the year. For an intermediate estimate of annual harvest, we multiplied the median of the product by the "standard" activity rate reported by the DoF = 0.65 (237.25 days) (DoF, 1993). For a minimum harvest estimate we used activity rate = 0.4 (146 days), the minimum reported in the compiled data (Lupikisha, 1993).

There is no known record of the price of fish in Zambia for any years in the time series analyzed. We can provide only a point estimate of the value of harvest in 2006, the last year of the time series analyzed, based on a survey at 6 markets in Lusaka of the retail price of fresh tilapia (species of the genus *Oreochromis*) in 2008, about 15,000 Kwacha per kg (B. Klco and Deines, unpublished data). We assume that the real price of fish was relatively constant between 2006 and 2008, adjust for inflation, and convert the nominal 2008 price in kwacha into real 2006 dollars and calculate the harvest revenue, D, in US dollars as

$$D_{2006}= H_{2006} * P_{2008} * (CPI_{2006}/CPI_{2008}) * z_{2006} \qquad (2)$$

Where H is the harvest described above and P is the market price of tilapia in 2008, CPI is the consumer price index (Central Statistical Office 2008) and z is the 2006 exchange rate for Zambian Kwacha to USD, equal to $2.9e^{-4}$ (http://www.xe.com, accessed 3-18-12)

Results

The counterfactual "no-dam" flow at ITT estimated from Hook Bridge flows is shown in Figure 3A. The CCA flood regime metric (Fig. 3B) captured 95% of the variance between the pre-and post- dam mean monthly hydrographs, with 67% of the CCA loading assigned to the historical low water months of September and October. Thus, the CCA loadings and the counterfactual

Copy for Review

"no-dam" flows were used to simulate what the CCA metric would have been had the ITT dam not existed (Fig. 3B).

The Impact of Flood Regime on Fishery Production

We excluded from consideration here models that were non-stationary, models that estimated negative intrinsic population growth (u^{CPUE}), and models with difference in AICc (dAICc) from the best model greater than 10 (results for all models are presented in Table S3). The difference in dAICc between the three best models (dAIC=0.06) provides very little support for choosing any over the others, though there is some support from dAICc that these three models are better fits to the data than the other models (dAIC≥2.25) (Table 1). All three models included density dependence (*b1-1*) for CPUE and negative effects of effort on CPUE (*b3*), consistent with biological intuition. Contrary to our expectation, two of the top three models, including the best model, did not include an effect of water regime on CPUE. The best model included a small positive effect of CPUE on effort (*b2*). The second-best model included a small negative impact of water regime on CPUE and implies a strictly linear increase in effort over time. The third model also did not include a water regime effect nor an effect of CPUE on effort, but did include weak density dependence on effort.

The sensitivity analysis showed that all but one model was successfully recaptured, the exception being a non-stationary model that was removed from the analysis. In all remaining models except one the estimated observation error was smaller than our conservative fixed estimates. This excepted model was however removed from consideration because it also estimated negative population growth. Whether observation error was fixed using rough estimates, fixed at large variance (unity), or estimated within the model, the results of model selection were very similar. In all cases, three of the top four models corresponded to the top three models in Table 1, demonstrating reasonable model selection over a wide range of observation variance. The exception to this pattern was model 6 (Table 1), which was estimated as the best model when observation error was fixed at rough estimates or at unity. Model 6 with estimated observation error (as in Table 1), however, still fits better than either the roughly fixed model or fixed at unity model.

For Review

We used model 1 and model 2 to estimate the current- or status quo- fishery harvest, and model 2 to estimate any potential counterfactual value of the fishery harvest using simulated "no-dam" discharge from ITT (Fig. 4). Similarity in model likelihoods suggests there was no significant difference in CPUE estimated between the best two models. The 95% CI around parameters for models 1 and 2 (Table 1) demonstrated no significant effect of CPUE on effort levels or water regime on CPUE. Moreover, the CI on the estimate of CPUE (Fig. 4A) demonstrated no significant difference between the observed CPUE estimated from model 1 and model 2, or between those models and the counterfactual no-dam water regime simulation.

Effort increased exponentially in both model 1 and model 2 (Fig. 4B). In model 1, the effect of CPUE on effort was non-significant, while model 2 did not include any covariant or density dependent effects of effort (Table 1). In both models the intrinsic growth rate of effort was greater than that for the fish population indexed by CPUE (Table 1). This difference in growth rate was only significant in model 2 where the 95% CI of CPUE and effort do not overlap, whereas the CPUE growth rate in model 1 was itself not significant as the 95% CI includes zero, and overlaps with the effort CI (Table 1).

The median total harvest (Fig. 4C) corresponded well, within about an order of magnitude, to the reported DoF data though the total harvest was not directly included in the model. There was no significant difference in harvest between the observed *status quo* models and the no-dam simulation though the no-dam scenario suggests a slightly larger harvest. We estimated that revenue derived from total harvest in 2006 was approximately USD $7 million, while under the "no-dam" scenario it was approximately $9 million, but could range from approximately $1.3 million up to about $56 million per year as result of the large range of the harvest confidence intervals and fishing activity rates. While not statistically different, the difference in median harvest between the status-quo and no-dam scenarios is about 900 metric tons, equivalent to about $2.3 million.

The Effect of Flood Regime on Hydroelectric Generating Capacity

Copy for Review

The analysis of the impact of ITT dam on the value of hydropower generated at KG dam suggests that with ITT dam in place the KG turbines can keep 254 m^3s^{-1} of constant flow during the dry season, which corresponds to 888 MW, since each cubic meter per second generates 3.501 MW (estimated by OLS regression of daily power output on discharge through turbines; R^2=0.961, N=2161, Std. Err.=0.015) (Fig. 5). The installed generating capacity is 900 MW (corresponding to 256 m^3s^{-1}); therefore the KG power generation is on average unconstrained. Without ITT dam the KG turbines could keep only 203 m^3s^{-1} of constant flow during the dry season, corresponding to 713 MW. This implies a total power deficit of (888 – 713) MW * 136 d * 24 hrs*d^{-1} = 571,200 MWh. The cost of importing electricity to Zambia is about $31 per MWh (PB Power, 2006); thus we estimate the total annual replacement cost as about $17.7 million if the ITT dam were not in place.

Discussion

We showed that the construction of the Itezhi-tezhi dam had substantial impacts on the water regime in the Kafue Flats. This hydrological manipulation has allowed gains in hydroelectric generating capacity of about $18 million per year at Kafue Gorge dam, estimated by the replacement cost method (i.e., the cost of purchasing the same amount of electricity from another source at the current price). A more accurate measure of gains would be lost total surplus, which accounts for losses to consumers who must pay higher prices for electricity and to taxpayers who must make up lowered revenues. There is considerable evidence that the Zambian power authority does not price its electricity according to market conditions, however, so it is impossible to estimate lost total surplus by using observed price data (IPA Energy Consulting, 2007). Thus, our estimate is likely an underestimate of the true value of the hydroelectric production benefit of ITT.

Our fishery modeling sensitivity analysis indicated that our modeling methods were able to select appropriate models. The best models, however, did not indicate a significant impact of the dam-altered water regime on the fisheries production of the Kafue River. Our estimates are the first published for the monetary value of this fishery, which is as large as $56 million annually: potentially more than three times as great as the replacement value of hydropower generated as a

Copy for Review

result of the construction of ITT dam. Nevertheless our model selection and simulations suggest that under current fishery practices no tradeoff or at most a small tradeoff of about $2.3 million exists between hydropower and fisheries production.

Total harvest calculated from our model was consistent with the independently reported DoF statistics. Considering that harvest was not included in the model and that the data used in this model were apparently not used in constructing the DoF harvest estimates, the similarity of these independent estimates of the Kafue River fishery lends confidence both to the models presented here and to the long term harvest records reported by the DoF. Differences in the harvest estimates are however apparent particularly in the early years where the model predicts dramatic declines in harvest, while the DoF data suggested increasing harvests. It is likely that during the early years of development of the fishery, the activity rate was unstable as large changes in social structures and populations were underway (Haller & Merten, 2008), particularly in the seasonality of fishing. We find it likely that the activity rates in these early years where much lower than even the low estimate (146 days per year) considered here, which would significantly reduce the estimated total harvest during that time. The generally close agreement of the model and DoF estimates suggests that in future work the reported harvest should explicitly be incorporated into the model estimation.

In apparent contrast to the results reported here, several studies have related total harvest to various aspects of pre-dam water regimes on the Kafue river (Chapman *et al,*. 1971; Lagler *et al.,* 1971; Dudley, 1974; Kapetsky & Illies, 1974; Welcomme, 1975a; Muncy, 1977). Two studies however, examined the effect of changed flood regime on fisheries after the construction of KG dam downstream but before ITT dam was built upstream, and found that there was no detectable influence on the growth rate of two important tilapia species (Dudley, 1979), or on CPUE for most species (Dudley & Scully, 1980). The latter results are consistent with our results for the entire fishery.

It would be incorrect to interpret our results as indicating that there is no relationship between hydrology and fishery production on the Kafue River. Rather our results are more specific,

Copy for Review

indicating only that there is no relationship between fish abundance and the hydrological changes most influenced by the dam, as indexed by the CCA. The ability of the CCA to clearly isolate the effect of the dam on water regime is a novel and critical strength of our analysis. Selection of appropriate biologically relevant water metrics for comparing average yearly CPUE to the monthly mean flows is a multivariate reduction problem seeking a complex balance between accounting for as much hydrologic variation as possible while minimizing co-variance between indices (Olden *et al*., 2003). Hundreds of metrics have been published for this purpose (Poff *et al*,. 2010). The task of selecting metrics was simplified in this case because we only needed to find the differences in the hydrograph along one dimension, before and after the ITT dam, rather than search for metrics with biological relevance. This CCA approach could be applied predictively to the many regions where dams are being constructed or are proposed given expectations about future dam-induced alteration of flows.

The results of this study also apparently contrast with previous studies of the effects of damming on fish in many streams and rivers around the world (Poff & Zimmerman, 2010). We suggest several reasons that these conflicting results may arise. First, we considered the whole fish community in both experimental gillnets and total harvest while previous work has dealt with particular specialist or sensitive taxa (Poff & Zimmerman, 2010). It is possible that by considering the total fish community, negative impacts on sensitive species may be obscured by positive effects on other species, and *vice-versa*, due to the portfolio effect (Hooper *et al.,* 2005). In particular, the Nile tilapia *Oreochromis niloticus* was introduced to the Kafue River in the 1980s (Schwanck, 1995) and our gillnetting efforts in 2008 and 2010 reveal that this species is now as common as the native *O. andersonii* and is distributed throughout the Kafue River between ITT and KG. A species-specific analysis to hydrological change in the Kafue River would be a logical next step.

Second, the long time period covered by the data set we used, both before and after flow alteration, is exceptionally long and highly resolved. The relevant fish-related papers reviewed in Poff & Zimmerman (2010) contain a maximum of 10 years of pre-dam data and 45 years of post-dam data, though the average and median post-dam data set is only 6 and 2 years

Copy for Review

respectively (n= 33). We provide 25 years of pre-dam observations, and 29 years of post dam observations. It seems plausible that long-term compensatory changes in the fishery could swamp short-term effects of damming detected in other studies.

Third, many problems that are well known to exist with the quality of long-term inland fisheries data may apply less strongly to the Kafue River data. In many other systems, fish collection gears and protocols have been more inconsistent over time (De Graaf *et al.,* 2012) than in the Kafue Flats fishery. On the other hand, we know catches with seine nets and other prohibited methods in the Kafue were underreported and therefore poorly represented in the model. Overall, however, the consistency of the independent CPUE, effort, and total harvest observations over the length of the data and compiled across multiple studies leads us to believe that the Kafue has fared very well in comparison to other systems in terms of the quality of data collection. Indeed, the Kafue was considered the best-documented African floodplain fishery before damming (Welcomme, 1975b).

Finally, we reconcile the differences in the Kafue River and other studies of the relationship between hydrology and fish abundance as the result of harvesting effort in the Kafue River over the period of study that is likely more intense (and increasing) than in most if not all other studied ecosystems. The impact of harvest on fish abundance probably overwhelms the effect from hydrological manipulation. The z-scored data used in the population modeling allows direct comparison of the relative magnitudes of the effects (and uncertainty) of effort and CCA scores (Table 1). In models 1 and 2, the effects of fishing were not significantly different. In model 2, the best model that included an effect of water regime, the effect of water regime on fish abundance was an order of magnitude lower than the effect of effort. Moreover, the growth rate of fishing effort is significantly larger than the growth rate of the fish. Meanwhile, the observation error variance for both gillnets and boats in models 1 and 2 is about twice that for CPUE and an order of magnitude larger than the effect of water regime, indicating the relatively small effects of water regime are easily lost in the noise that surrounds effort in the system. It remains possible that under a fishery regime with less intense effort, restored environmental flows could have a positive impact on fishery production.

Copy for Review

Conclusion

Dam construction does not seem to have had significant impacts on the Kafue Flats fishery. The overall trends in CPUE, effort, and harvest in the Kafue fishery are largely consistent with overfishing, particularly the concept of fishing-down in open access fisheries (Allan *et al.,* 2005). Our data and analysis of the effort on the Kafue River demonstrate that fishing effort has been continually and exponentially increasing over time mostly independent from the abundance of the fish and fishers already present, suggesting little internal control over effort, and the primacy of the effect of increased fishing effort on the observed declining fish abundance. These results do not, however, rule out an interaction between fishing effort and hydrologic regime such that a reduction in fishing effort leading to increased fish abundance could prompt a response to changes in hydrology, or magnify a currently unobserved response into the realm of detectability. The implication of these results is that effort reduction, rather than restoration of the natural flood regime of the Kafue, may be a more effective way to increase fisheries output in the short term, and thereby improve the livelihoods of fishermen.

However, in Zambia, national policy safeguards the right to fish for all Zambians, limiting the power of both the state and traditional institutions to regulate access and effort in the Kafue fishery (Haller & Merten, 2008). Currently, closed fishing seasons, closed areas and gear restrictions are the main regulatory instruments used by the DoF. Devolution of management to local levels and more participatory management schemes have also had varying levels of success, at least in terms of stakeholder acceptance in Lake Kariba and in the Mweru-Luapula complex in northern Zambia (Kapasa, 2004, AMD Pers. Obs.). The increasing levels of effort reported here demonstrate external forces are major drivers of the Kafue fishery in terms of effort, fish abundance and ultimately harvest; future management scenarios will need to explore and accommodate these broader issues. Here we have provided a foundation for future, more comprehensive analyses of alternative management scenarios by estimating linkages to the wider economy in terms of the monetary value of the Kafue fishery and hydropower production. We have not considered other river-related ecosystem services that were reduced by the dam-altered hydrograph, such as the provisioning of pasturing for livestock and habitat for wildlife on the

Copy for Review

floodplain. Given the foundation provided here, changes in management practices in future could probably increase total ecosystem services from the Kafue River.

Acknowledgements

P. Ngalande, L. Njobvu Chilufya, R. Nkhata, I. Bbole, and many others from the Zambian Department of Fisheries contributed data and other assistance. C. Katongo, H.G. Mudenda, B. Klco, J. Deines, and the World Fish Center assisted with much on the ground support. The Zambian Department of Water Affairs and J. Kolding contributed data and J. McLachlan made helpful suggestions on the fisheries model. M. Whitman and the Lodge Lab provided comments on earlier versions of the manuscript. Funding was provided by NSF awards #0504495 and #1046682, and The Kellogg Institute at the University of Notre Dame.

Copy for Review

References

Allan J.D., Abell R., Hogan Z., Revenga C., Taylor B.W., Robin L. Welcomme, *et al.* (2005) Overfishing of Inland Waters. *Bioscience* **55**, 1041-1051.

CSO (1970) Fisheries Statistics (Natural water) 1969.

CSO (1978) Fisheries Statistics 1972 (Natural Waters) : Volume I. **1**.

CSO (1984) Fisheries Statistics 1973 (Natural Waters): Volume 1. **1**.

Central Statistical Office (2008) *Consumer Price Index (CPI) – September 2008*. Lusaka.

Chapman D.W., Miller W.H., Dudley R.G. & Scully R.J. (1971) Ecology of Fishes in the Kafue River. 126.

Chipungu P.M. (1981) The Impact of the Kafue Gorge Dam on the Kafue floodplain fishery (Zambia). 120-129.

DoF (1993) *1993 Fisheries Statistics Report*. Chilanga, Zambia.

DoF & CSO (2007) Report of Kafue Floodplain Frame Survey - 2006. 20.

Dudgeon D., Arthington A.H., Gessner M.O., Kawabata Z.-I., Knowler D.J., Leveque C., *et al.* (2005) Freshwater biodiversity: importance, threats, status and conservation challenge. *Biological Review* **81**, 163-182.

Dudley R.G. (1979) Changes in growth and size distribution of Saroherodon macrochir and Sarotherodon andersoni from the Kafue Floodplain, Zambia, since the construction of the kafue Gorge Dam. *Journal of Fish Biology* **14**, 205-223.

Copy for Review

Dudley R.G. (1974) Growth of Tilapia of the Kafue Floodplain, Zambia: Predicited Effects of the Kafue Gorge Dam. *Transactions of the American Fisheries Society* **1974**, 281-291.

Dudley R.G. & Scully R.J. (1980) Changes in experimental gillnet catches from the Kafue Floodplain, Zambia, since construction of the kafue Gorge Dam. *Journal of Fish Biology* **16**, 521-537.

FAO (1968) *Multipurpose Survey of the Kafue River Basin, Zambia. Vol III Climatology and Hydrology*. United nations Development Program Food and Agriculture Organization of the United Nations, Rome.

De Graaf G., Bartley D., Jorgensen J. & Marmulla G. (2012) The scale of inland fisheries, can we do better? Alternative approaches for assessment. *Fisheries Management and Ecology*, no-no.

Haller T. & Merten S. (2008) "We are Zambians—Don't Tell Us How to Fish!" Institutional Change, Power Relations and Conflicts in the Kafue Flats Fisheries in Zambia. *Hum Ecol* **36**, 699-715.

Holmes E.E. & Ward E.J. (2011) *Analysis of multivariate timeseries using the MARSS package, version 2.8*. Mathematical Biology Program Northwest Fisheries Science Center, Seattle, WA.

Hooper D.U., Chapin F.S., Ewel J.J., Hector A., Inchausti P., Lavorel S., *et al.* (2005) Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. *Ecological Monographs* **75**, 3-35.

IPA Energy Consulting (2007) Revised ZESCO ' s Cost of Service. Capability and Capacity Strengthening of the Energy Regulation Board. *Information Systems*, 398.

International Rivers Africa Program (2010) *Africa Dams Briefing 2010*. Berkeley, USA.

Copy for Review

Ives A., Dennis B., Cottingham K. & Carpenter S.R. (2003) Estimating community stability and ecological interactions from time-series data. *Ecological Monographs* **73**, 301-330.

Kapasa C.K. (2004) From Government Management to Collaborative Management: A Case Study of Co-Management Process and Perceptions of Stakeholders On Key Supportive Institutions of Mweru Luapula Fishery, Northern Zambia. 50.

Kapetsky J.M. (1974) Growth, Mortality, and Production of Five Fish Species of the Kafue River Floodplain, Zambia. *Fisheries*.

Kapetsky J.M. & Illies J. (1974) The Kafue River Floodplain: and example of pre-impoundment potential for fish production. In: *Lake Kariba: A man-made tropical ecosystem in central Africa*. (Eds E.K. Balon & A.G. Coche), pp. 497-523. Dr. W. Junk Publishers, The Hague.

King J. & Brown C. (2010) Integrated basin flow assessments: concepts and method development in Africa and South-east Asia. *Freshwater Biology* **55**, 127-146.

Knaap van der (1994) *Status of fish stocks and fisheries of thirteen medium-sized African reservoirs. CIFA Technical Paper*. FAO, Rome.

Lagler K.F., Kapetsky J.M. & Stewart D.J. (1971) The Fisheries of the kafue Flats, Zambia, in Relation to the Kafue Gorge Dam. 161.

Linden A. & Knape J. (2009) Estimating envrionmental effects on population dynamics: consequences of observation error. *Oikos* **118**, 675-680.

Lupikisha J.M.C. (1993) 1992 Fisheries Statistics.

Lupikisha J.M.C. (1992) Department of Fisheries 1991 Fisheries Statistics. 150.

McCarthy G.T. (1938) The unit hydrograph and flood routing. In: *Conference of the North Atlantic Division, US Corps of Engineers*. US Corps of Engineers, New London, CT.

Copy for Review

Mortimer M.A.E. (1965) *Natural Resources Handbook, The fish and fisheries of Zambia.* Falcon Press Inc., Indola, Zambia.

Mumba M. & Thompson J.R. (2005) Hydrological and ecological impacts of dams on the Kafue Flats floodplain system, southern Zambia. *Physics and Chemistry of the Earth* **30**, 442-447.

Muncy R.J. (1977) An Evaluation of the Zambian Kafue River Floodplain Fishery. *Symposium on River and Floodplain Fisheries in Africa*, 153-164.

Munyati C. (2000) Wetland change detection on the Kafue Flats, Zambia, by classification of a multitemporal remote sensing image dataset. *Int. J. Remote Sensing* **21**, 1787-1806.

Muyanga E.D. & Chipungu P.M. (1978) A short review of the Kafue Flats fishery from 1968 to 1978. In: *National Seminar on Environment and Change, the Consequences of Hydroelectric power Development on the utilization of the Kafue Flats*. p. 9. Kafue Basin Research Committee, Lusaka, Zambia.

Nyimbili B. (2006) An evaluation of fish population changes in the Kafue Flats floodplain fishery of Zambia from 1980 to 2005. *Department of Biology*, 66.

Obrdlik P., Mumeka A. & Kasonde J.M. (1989) Regulated Rivers in Zambia- The Case Study of the Kafue River. *Regulated Rivers: Research & Management* **3**, 371-380.

PB Power (2006) Zambian Energy Regulation Board Capactiy Strengthening. generation Planning. Least Cost generation Plan Report. 53.

POFF N.L., RICHTER B.D., ARTHINGTON A.H., BUNN S.E., NAIMAN R.J., KENDY E., *et al.* (2010) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**, 147-170.

Poff N.L. & Zimmerman J.K.H. (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**, 194-205.

Copy for Review

R Development Core Team (2011) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Schelle P. & Pittock J. (2005) Restoring the Kafue Flats: A partnership approach to environmental flows in Zambia. 10.

Schwanck E.J. (1995) The introduced Oreochromis niloticus is spreading on the kafue floodplain, Zambia. *Hydrobiologia* **315**, 143-147.

Service R.F. (2011) Will Busting Dams Boost Salmon□? *Science* **334**, 888-892.

Smardon R.C. (2009) *Sustaining the World's Wetlands: Setting Policy and Resolving Conflicts*. Springer-Verlag.

Welcomme R. (2008) World prospects for floodplain fisheries. *Ecohydrology & Hydrobiology* **8**, 169-182.

Welcomme R.L. (1975a) *The fisheries ecology of African floodplains. CIFA Tech.Pap., (3)*. FAO, Rome.

Welcomme R.L. (1975b) The fisheries of African floodplains. L'ecologie des peches dans les plaines inondables africanes. *CIFA Tecnical Paper* **3**, 51.

Williams N.V. (1960) A Reveiw of the kafue River Fishery. *Rhodesia Agricultural Journal* **57**, 86-92.

Copy for Review

Supporting Information

Supporting information includes detailed descriptions of data compilation, species lists, and fisheries and hydrological modeling methods and results.

Table S1. Gillnet mesh sizes, months sampled and sampling locations by year.
As excel file "Deines et al Table S1- SupInfo- Mesh sizes and Sampling Locations.xlsx"
Table S2. Fish species reported in each dataset compiled for analysis.
As excel file "Deines et al Table S2- SupInfo- Species Lists.xlsx"
Table S3. Full modeling results.
As excel file "Deines et al Table S3- SupInfo- Full modeling results.xlsx"

Copy for Review

Figure Legends

Fig. 1. Map of the Kafue River, Zambia, in southern Africa (insert) focusing on the area of the Kafue Floodplain fishery (grey hatched) between the upstream Itezhi-tezhi dam and the downstream Kafue Gorge dam and power station. Sampling locations (▲) included in this analysis from west to east: Namwala, Maala, Chunga Lagoon, Nyimba, Mazabuka, and Chinyanya. Water flows west to east in this region.

Fig. 2. Fishery and hydrologic data for the Kafue River fishery, Zambia. (A) Annual experimental gillnet catch per unit effort, (B) annual artisanal effort in meters of gillnet (O), with the last data point slightly offset on the x-axis for visibility and number of boats (●), (C) annual total reported harvest, and (D) mean monthly discharge from Itezhi-tezhi dam. The first vertical dashed line indicates the closure of Kafue Gorge dam (downstream), while the second indicates the closure of Itezhi-tezhi dam (upstream).

Fig. 3. Hydrograph modeling results. (A) Simulated “no-dam” mean monthly discharge in cubic meters per second at ITT and (B) the canonical correlation analysis scores which represent the maximum difference in yearly hydrograph along the dimension of before and after ITT dam construction for the observed hydrograph (●) and the simulated hydrograph (■). The first vertical dashed line indicates the closure of Kafue Gorge dam, while the second indicates the closure of Itezhi-tezhi dam.

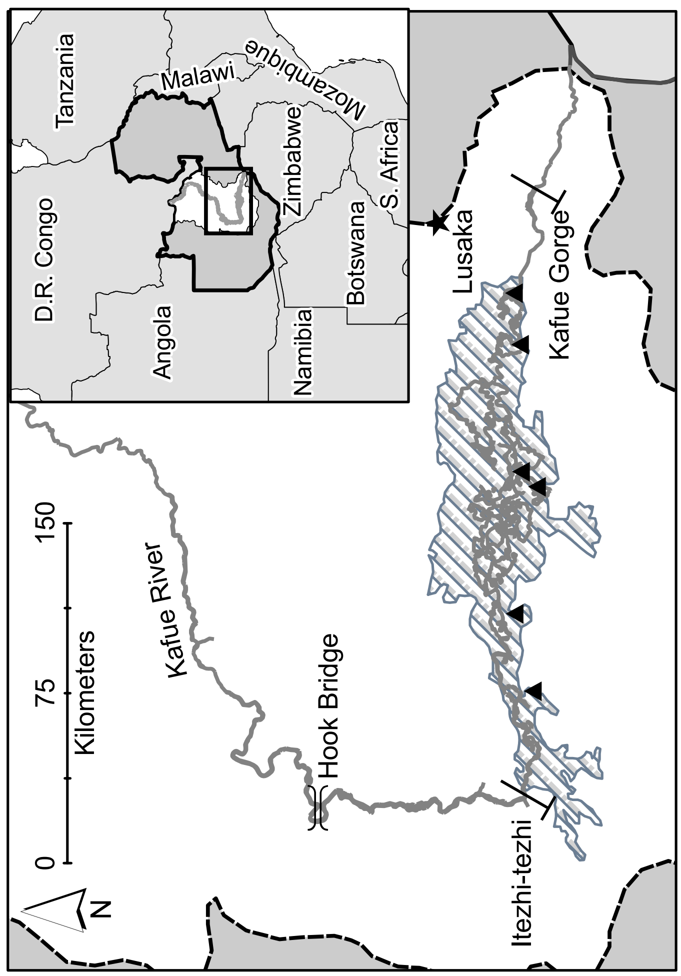
Fig. 4. The first and second best model estimates of the Kafue River (shown in log scale to highlight low abundances and mean observed data). In each panel black symbols are the mean observations, and solid and dashed lines are median model estimates and 95% confidence intervals, respectively. Black and red lines are model 1 and model 2 estimates under the observed water regime, respectively, and blue lines are model 2 estimates under the simulated “no-dam” water regime. (A) CPUE with additional available data shown for the year 2008 and 2010 which were not included in the model. (B) Effort in meters of gillnet (O) and boats (●)

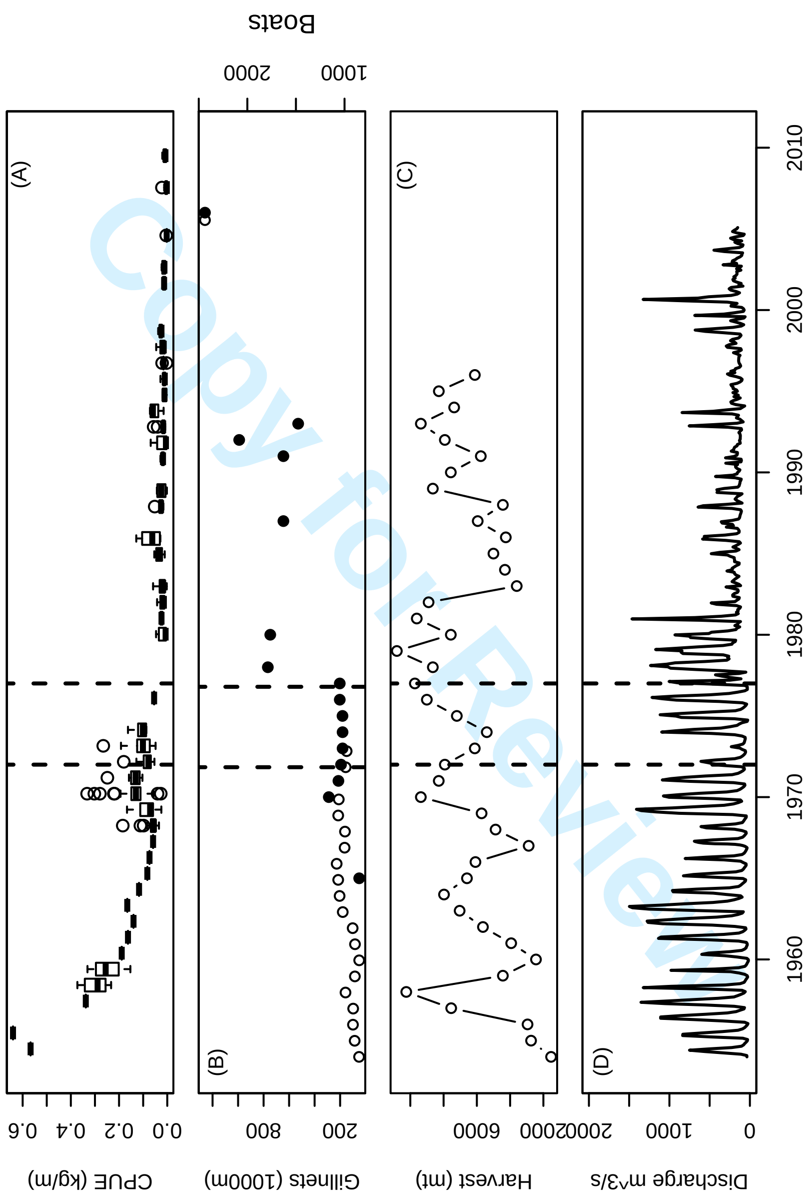
Copy for Review

transformed into gillnets units. (C) The reported and estimated total harvest from the Kafue River.

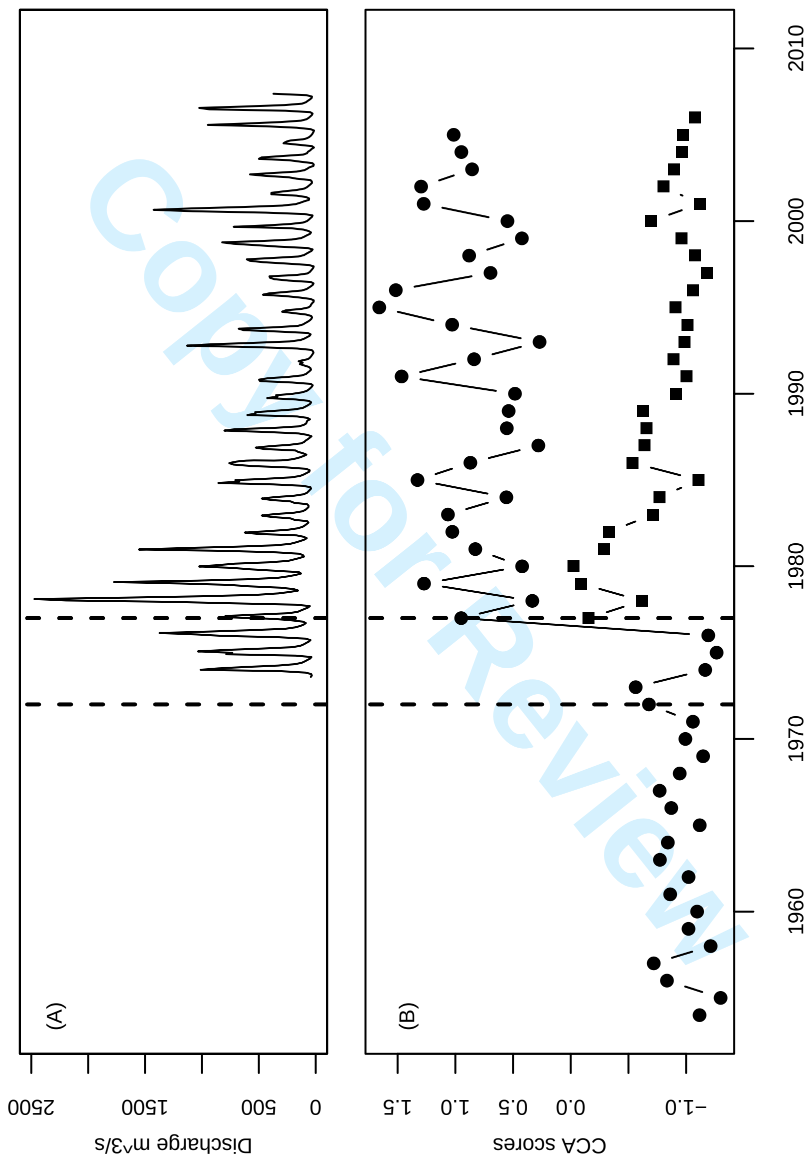
Fig. 5. Averaged simulated seasonal hydrographs at KG with (light grey) and without (black) ITT. Dashed lines represent the dry-season generating capacity in each scenario, corresponding to 254 m^3/s (888 MW) and 203 m^3/s (770 MW) with and without ITT, respectively. Hashed areas represent the differences in turbine flow during the low water season.

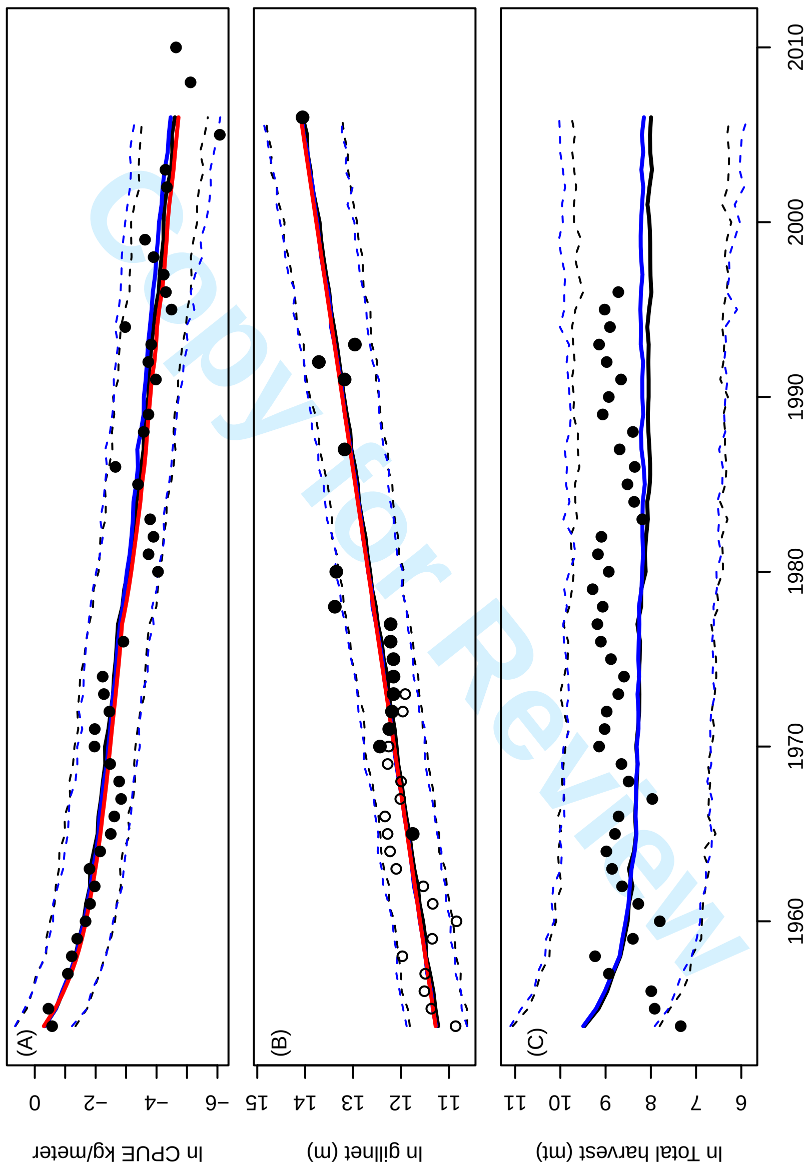
Copy for Review


Tanzania
Malawi
Mozambique
Zimbabwe
S. Africa
D.R. Congo
Angola
Namibia
Botswana
Lusaka
Kafue Gorge
Kafue River
Hook Bridge
Itezhi-tezhi
Kilometers
0
75
150
N

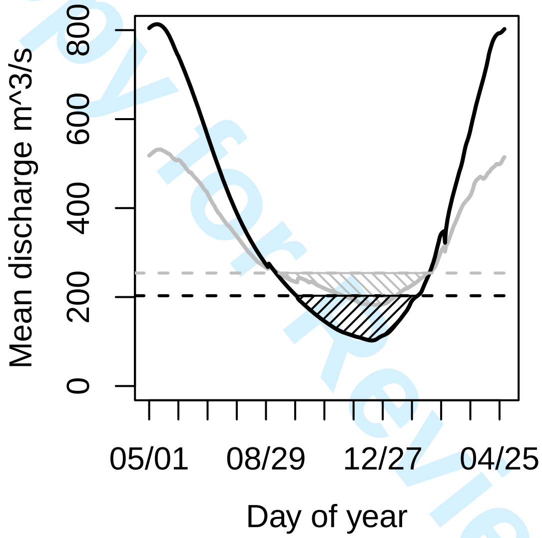


Copy for Review


(A)
(B)
Discharge m^3/s
CCA scores
2500
1500
500
0
1.5
1.0
0.5
0.0
−1.0
1960
1970
1980
1990
2000
2010



Copy for Review



Copy for Review

Table 1 Results of model selection and parameter estimates. Estimates in **bold** indicate parameters that were fixed *a priori* as part of the model specification.

	-LL	*d*AICc	U^{CPUEe}	U^{effort}	CPUE density depend. (*b1-1*)	Effect of CPUE on effort (*b2*)	Effect of effort on CPUE (*b3*)	Effort Density Depend. (*b4-1*)	Effect of Water Regime on CPUE (*b5*)	R^{CPUE}	$R^{gillnet}$	R^{boats}
1	-93.21	0	$7.4e^{-2}$ *$-1.5e^{-4}$–1.7*	$8.0e^{-2}$ *$6.2e^{-2}$–$9.6e^{-2}$*	-0.2* *0.7–0.9*	$5.5e^{-3}$ *$-2.4e^{-2}$–$2.7e^{-2}$*	-0.1* *-0.2– $-7.4e^{-2}$*	***ind***	***ind***	$1.4e^{-1}$ *$1.3e^{-1}$–$2.5e^{-1}$*	$2.2e^{-1}$ *$8.4e^{-2}$–$3.5e^{-1}$*	$2.4e^{-1}$ *$8.8e^{-1}$–$4.3e^{-1}$*
2	-93.24	0.06	$6.3e^{-2}$ *$2.7e^{-2}$–$1.4e^{-1}$*	$7.9e^{-2}$ *$6.4e^{-2}$–$9.3e^{-2}$*	-0.2* *0.6–0.9*	***ind***	-0.1* *-0.2– $-8.8e^{-2}$*	***ind***	$-2.0e^{-2}$ *-0.1–$4.2e^{-2}$*	$1.4e^{-1}$ *$1.3e^{-1}$–$2.4e^{-1}$*	$2.2e^{-1}$ *$9.8e^{-2}$–$3.5e^{-1}$*	$2.4e^{-1}$ *$8.8e^{-2}$–$4.1e^{-1}$*
3	-93.24	0.06	$7.17e^{-2}$	$8.31e^{-2}$	-0.22	***ind***	-0.14	$-3.21e^{-3}$	***ind***	$1.4e^{-1}$	$2.2e^{-1}$	$2.4e^{-1}$
4	-93.12	2.25	$8.00e^{-2}$	$8.04e^{-2}$	-0.26	$7.18e^{-3}$	-0.14	***ind***	$-2.9e^{-2}$	$1.4e^{-1}$	$2.2e^{-1}$	$2.4e^{-1}$
5	-93.17	2.35	$7.58e^{-2}$	$8.41e^{-2}$	-0.25	***ind***	-0.14	$-4.01e^{-3}$	$-2.5e^{-2}$	$1.4e^{-1}$	$2.2e^{-1}$	$2.4e^{-1}$
6	-99.14	2.53	$6.18e^{-2}$	$7.89e^{-2}$	-0.21	***ind***	-0.13	***ind***	***ind***	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$
7	-99.10	4.73	$6.32e^{-2}$	$7.89e^{-2}$	-0.23	***ind***	-0.13	***ind***	$-2.0e^{-2}$	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$
8	-99.12	4.77	$6.93e^{-2}$	$7.94e^{-2}$	-0.22	$3.46e^{-3}$	-0.14	***ind***	***ind***	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$
9	-99.13	4.80	$6.58e^{-2}$	$8.04e^{-2}$	-0.21	***ind***	-0.13	$-1.3e^{-3}$	***ind***	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$
10	-96.97	5.13	1.38	$7.90e^{-2}$	-1.89	***ind***	-1.42	***ind***	***ind***	$1.7e^{-1}$	$2.2e^{-1}$	$2.4e^{-1}$
11	-99.07	6.97	$7.46e^{-2}$	$7.95e^{-2}$	-0.25	$5.00e^{-3}$	-0.14	***ind***	$-2.5e^{-2}$	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$
12	-99.09	7.02	$6.96e^{-2}$	$8.15e^{-2}$	-0.24	***ind***	-0.14	$-2.2e^{-3}$	$-2.2e^{-2}$	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$
13	-100.8	10.35	$2.25e^{-1}$	1.13	-0.37	-1.28	-0.27	$-9.98e^{-1}$	***ind***	$\mathbf{1.9e^{-1}}$	$\mathbf{3.2e^{-1}}$	$\mathbf{8.6e^{-1}}$

***ind*=** independent (not included), *significant, only evaluated for models 1&2.

Copy for Review

Deines et al. Supporting Information

Modeling the impact of flood regime on fishery production

Gillnet catch per unit effort (CPUE) was compiled from the literature and Zambian department of Fisheries (DoF) records for the years 1954-2010. We assumed that the net and mesh sizes for the years before 1980 which were not reported by Williams (1960), CSO (1970, 1978, 1984) and Kapetsky (1974) were the same as those reported in Everett (1974) for the year 1970. CPUE for 1976 (Dudley & Scully, 1980) was converted to kilograms by multiplying fish number by the average weight of each fish species in 1985 (Mung'omba, 1992). For the 1980 to 2006 post-dam era, the DoF recorded experimental gillnet surveys on the Kafue (Nyimbili, 2006). In a standard DoF gillnet fleet, they used top-set 90m^2 (stretched) multifilament gillnets ranging from 25 to 140 mm stretched mesh in 13 mm increments and hung to 50%, for a hanging length of 45 m each. We supplemented these data with collections in 2008 and 2010, following the standard DoF protocol.

We used a multivariate auto-regressive state-space (MARSS) model to fit time series of experimental CPUE, fisheries effort and water regime data to population growth models using maximum likelihood estimation. This state-space approach allowed the simultaneous estimation of the unobserved state process of fish abundance (CPUE) and fisheries effort (meters of gillnet) with observation error and including the effect of water level as a covariate to the CPUE process.

The univariate auto-regressive (1) growth model for a population time series with effort, *E,* and water, *W,* takes the form

$$N_t = N_{t-1} * \exp\left(u + b_1 N_{t-1} + b_2 E_{t-1} + c_1 W_{t-1} + \sigma_t\right) \qquad \text{(S1)}$$

Where N_t is the experimental gillnet catch per unit effort (CPUE $kg*m^{-1}*night^{-1}$) in year *t,* and *b* and *c* are parameters to be estimated, with *u* the intrinsic population growth rate, and σ_t is random, independent, identically normally distributed observation error. Taking the natural log of N_t such that $X_t = ln(N_t)$ yields a linear equation which assumes Gompertz growth,

Copy for Review

$$X_t = u + (b_1 + 1)X_{t-1} + b_2 E_{t-1} + cW_{t-1} + \sigma_t \quad \text{(S2)}$$

In multivariate state-space, the state and observation processes are arranged into a system of equations in matrix form including covariates (Holmes & Ward, 2011).

$$\begin{bmatrix} \mathbf{x}^{(v)} \\ \mathbf{x}^{(cv)} \end{bmatrix}_t = \begin{bmatrix} \mathbf{B}^{(v)} & \mathbf{C} \\ 0 & \mathbf{B}^{(cv)} \end{bmatrix} \begin{bmatrix} \mathbf{x}^{(v)} \\ \mathbf{x}^{(cv)} \end{bmatrix}_{t-1} + \begin{bmatrix} \mathbf{u}^{(v)} \\ \mathbf{u}^{(cv)} \end{bmatrix} + \mathbf{w}_t, \mathbf{w}_t \sim \mathrm{MVN}\left(0, \begin{bmatrix} \mathbf{Q}^{(v)} & 0 \\ 0 & \mathbf{Q}^{(cv)} \end{bmatrix}\right) \quad \text{(S3a)}$$

$$\begin{bmatrix} \mathbf{y}^{(v)} \\ \mathbf{y}^{(cv)} \end{bmatrix}_t = \begin{bmatrix} \mathbf{Z}^{(v)} & 0 \\ 0 & \mathbf{Z}^{(cv)} \end{bmatrix} \begin{bmatrix} \mathbf{x}^{(v)} \\ \mathbf{x}^{(cv)} \end{bmatrix}_t + \begin{bmatrix} \mathbf{a}^{(v)} \\ \mathbf{a}^{(cv)} \end{bmatrix} + \mathbf{v}_t, \mathbf{v}_t \sim \mathrm{MVN}\left(0, \begin{bmatrix} \mathbf{R}^{(v)} & 0 \\ 0 & \mathbf{R}^{(cv)} \end{bmatrix}\right) \quad \text{(S3b)}$$

Where $\boldsymbol{x}^i$ are state vectors at time t defined by a state process equation (Equation S3a) with i superscripts representing estimated variates *(v)* CPUE and effort, or the covariates *(cv;*in this case the CCA score representing water regime). $\boldsymbol{B}^i$ are matrices which correspond to parameters b in the univariate case, while $\boldsymbol{C}$ corresponds to covariate parameters c and $\boldsymbol{u}^i$ are growth rates. Process error, $\boldsymbol{w}_t$, is modeled as a multivariate normal distribution with variance-covariance matrix of process (environmental) stochasticity $\boldsymbol{Q}$. Vectors of observed data $\boldsymbol{y}^i$ are related to the process states through the observation process equation (Equation S3b). $\boldsymbol{Z}$ are identity matrices which associate one or more observations to unobserved state processes, with $\boldsymbol{a}$ parameters which scale multiple observations of the same state and multivariate normal observation error $\boldsymbol{v}_t$ with $\boldsymbol{R}$ variance-covariance matrixes.

In total we specified 3 state processes for CPUE, effort, and water (Equation S4). We demeaned and standardized all data and used the resulting z-scores for estimation.

$$\begin{bmatrix} x^{cpue} \\ x^{effort} \\ x^{water} \end{bmatrix}_t = \begin{bmatrix} b1 & b3 & b5 \\ b2 & b4 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{X}_{t-1} + \begin{bmatrix} u^{cpue} \\ u^{effort} \\ 0 \end{bmatrix} + \mathrm{MVN}\begin{pmatrix} & \mathrm{q1} & 0 & 0 \\ 0, & 0 & \mathrm{q2} & 0 \\ & 0 & 0 & 1 \end{pmatrix}_t \quad \text{(S4a)}$$

$$\begin{bmatrix} y^{cpue} \\ y^{gill} \\ y^{boats} \\ y^{water} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{X}_t + \begin{bmatrix} 0 \\ 0 \\ a^{boats} \\ 0 \end{bmatrix} + \mathrm{MVN}\begin{pmatrix} 0, & \begin{matrix} r^{cpue} & 0 & 0 & 0 \\ 0 & r^{gill} & 0 & 0 \\ 0 & 0 & r^{boats} & 0 \\ 0 & 0 & 0 & 1\mathrm{e}-5 \end{matrix} \end{pmatrix}_t \tag{S4b}$$

b_1=CPUE density dependence, b_2= effect of CPUE on fishing effort, b_3= effect of harvest on CPUE, b_4= density dependence of effort, b_5= effect of water regime on CPUE, and dashes represent

The process errors, $\boldsymbol{w_t}$ were modeled as a multivariate normal distribution with mean 0 and variance-covariance matrix $\boldsymbol{Q}$. We assumed that processes do not co-vary and fixed CCA score variance at unity to give the process model the flexibility to exactly equal the true covariate values; thus the covariates processes are not modeled but exactly specified (Holmes & Ward, 2011). Initial results indicated estimated process errors less than 1e-15 in all cases, leading to instability in the estimation algorithm. We therefore fixed process error for CPUE and effort at a trivially small value, $1e^{-5}$. Observation processes, $\boldsymbol{y}$, consist of the observed data with measurement error (Equations S3b and S4b). We specified two observation vectors for the effort process, gillnet meters and boat counts, where boats counts are linearly scaled to gillnets by estimating the number of gillnets meters per boat, a^{boats} in Equation S4b. Assuming this scaling factor is constant over the time period is reasonable given that the common type dugout canoe has changed little over time, and they have probably always worked at capacity.

Estimating the Impact of Flood Regime on Hydroelectric Generating Capacity

We measure the impact of the Itezhi-tezhi Dam on hydroelectric generating capacity at the Kafue Gorge generating station. In order to measure the impact of the Itezhi-tezhi Dam on hydroelectric generating capacity, we apply the widely used Muskingum method of flood routing, or predicting downstream flows based on known upstream flows (McCarthy, 1938) (Flood routing is also sometimes known as channel routing). Other studies have extensively modeled the hydrological system of the Kafue Flats and developed sophisticated systems for informing dam operation in real-time response to contemporaneous rainfall information (Fromelt, 2009; Meier, 2010a b). This simpler method has the advantages of flexibility and

For Review Only

transparency, at the cost of some statistical efficiency. We also calibrate our model using longer time series of daily discharge measurements than has previous work.

To determine the depth and velocity of the flood wave at any point in time, we use two ordinary differential equations. The first equation is

$$\mathrm{d}V(t)/\mathrm{d}t = I(t) - O(t) \tag{S5}$$

where $V(t)$ is the volume of water stored in the given reach (river segment) at time t, $I(t)$ is the flow into the reach, and $O(t)$ is the flow out of the reach. This equation governs conservation of mass. For our modeling purposes, we ignore losses to evaporation and seepage to groundwater, although some authors suggest that these losses can be substantial (Anon, 2007). We also ignore contributions from runoff between the two dams, since such runoff is marginal in comparison to the Kafue‘s discharge and in any case unlikely to be substantially affected by the river‘s flood regime. We use daily discharge data at the Itezhi-tezhi Dam (Figure 2) to represent inflows into the reach, and discharge at Kafue Gorge Dam represents outflows (Figure S1). The latter measure is influenced by flow through the turbines, but for much of the year water must be spilled at the Kafue Gorge Dam due to excess supply, such that during these spillage events, discharge through Kafue Gorge closely approximates the counterfactual, natural flow.

The second differential equation governs conservation of momentum. This equation necessarily varies from stream to stream, depending on the shape of the terrain. In order to close the equation, it must define V. In the simple case of straight riverbed with polygonal, parallel cross-sections and linear edges, the riverbed can be modeled as a frusta, with the following equation for volume:

$$V = h\left(\frac{A_1 + A_2 + \sqrt{A_1 A_2}}{3}\right) \tag{S6}$$

Copy for Review

where h is the height of the frusta and $A1$, $A2$ are the areas of the cross-sections at either end. As $A1$ and $A2$ are to remain unchanged parameters, the volume can also be modeled as equivalent to a prism whose base is weighted average of the cross-sections:

$$V = h\,[X\,A1 + (1 - X)\,A2], \tag{S7}$$

where $0 < X < 1$. Since $A2$ is typically greater than $A1$, X must be less than one-half. If we assume that the flow is proportional to the area of its cross section, then Equation (S7) becomes

$$V = K\,[X\,I + (1 - X)\,O], \tag{S8}$$

where K is a constant. Given these assumptions, K can be interpreted as the time it takes for a wave to travel from one end of the reach to the other, and reflects the rate of decrease of the height of a wave as it travels through the reach. During a flood, the volume stored in the reach necessarily increases. The Muskingum method assumes that this volume is a weighted linear function of both the inflow rate and the outflow rate. X varies their respective weights, and K scales them to the volume of the reach. Substituting (equation S8) into (equation S5) yields the differential equation

$$O + K(1 - X)\frac{dO}{dt} = I - KX\frac{dI}{dt} \tag{S9}$$

This continuous equation is then discretized so that it can be estimated empirically, with small time step $\Delta t \equiv t2 - t1$:

$$\frac{O_1 + O_2}{2} + K(1 - X)\left(\frac{O_2 - O_1}{\Delta t}\right) = \frac{I_1 + I_2}{2} - KX\left(\frac{I_2 - I_1}{\Delta t}\right) \tag{S10}$$

Given an initial value of outflow $O1$, we would like to be able to predict subsequent outflows using only new inflow measurements. As such, we solve for $O2$ in terms of $O1$, $I1$, and $I2$:

Copy for Review

$$\frac{1}{2}O_2 + \left(\frac{K(1-X)O_2}{\Delta t}\right) = -\frac{1}{2}O_1 + \left(\frac{K(1-X)O_1}{\Delta t}\right) + \frac{I_1 + I_2}{2} - KX\left(\frac{I_2 - I_1}{\Delta t}\right) \quad \text{(S11)}$$

$$O_2 = \frac{1}{\frac{1}{2} + \left(\frac{K(1-X)}{\Delta t}\right)}\left[\left(-\frac{1}{2} + \frac{K(1-X)}{\Delta t}\right)O_1 + \left(\frac{1}{2} - \frac{KX}{\Delta t}\right)I_2 + \left(\frac{1}{2} + \frac{KX}{\Delta t}\right)I_1\right] \quad \text{(S12)}$$

We then calibrate the model. K, the travel time of the flood wave, is calculated to be 54 days, the lag which yields the maximum correlation between the discharges at Itezhi-tezhi and Kafue Gorge. X is taken to be 0.2, a typical value for most rivers (Hornberger, 1998). This calibration yields predictions that fit the wet seasons well, but which do not over fit the turbine flows. Figure S2 shows the flows simulated using the estimated values of K and X. We take these predictions to be estimates of the discharge entering the Kafue Gorge reservoir.

We then similarly estimate counterfactual discharge for Itezhi-tezhi, using discharge at the Hook Bridge monitoring station (Figure S2) to estimate the inflows into the reservoir at Itezhi-tezhi. Since Hook Bridge is just upstream from the Itezhi-tezhi Reservoir, the pre-dam time series of the daily discharges at Itezhi-tezhi and Hook Bridge are highly correlated, especially during the wet season. We put this counterfactual Itezhi-tezhi discharge through the simulation described above, constructing a counter factual “no-dam” scenario of what the Kafue Gorge reservoir inflows would be if the Itezhi tezhi did not exist. We take the annual average for each simulated Kafue Gorge hydrograph as an expected difference in flow attributed to the Itezhi-tezhi Dam‘s influence on the Kafue River‘s flood regime (Figure 5).

The KG generating station can operate until the reservoir is emptied, and even then it can use the reduced inflow directly, thus, reduced discharges into the reservoir at KG do not necessarily imply reduced generating capacity. We compute the minimum reduction of power output as that which uses the full capacity of the reservoir, solving the following constrained optimization problem:

Copy for Review

$$max\ G\ such\ that \int_{t_a}^{t_b} G - I(t)\, dt = 800{,}000{,}000\ m^3 \quad (S13)$$

where G is the outflow through the turbines (m^3d^{-1}), $I(t)$ is discharge entering the KG reservoir (m^3d^{-1}), and time t is measured in days. The value t_a represents the date when the reservoir begins to drain, and t_b is the date at which the reservoir is completely empty and begins to refill.

References

Anon (2007) Strategy for Flood Management for Kafue River Basin, Zambia. 158.

CSO (1970) Fisheries Statistics (Natural water) 1969.

CSO (1978) Fisheries Statistics 1972 (Natural Waters): Volume I. **1**.

CSO (1984) Fisheries Statistics 1973 (Natural Waters): Volume 1. **1**.

Dudley R.G. & Scully R.J. (1980) Changes in experimental gillnet catches from the Kafue Floodplain, Zambia, since construction of the kafue Gorge Dam. *Journal of Fish Biology* **16**, 521-537.

Everett G.V. (1974) An Analysis of the 1970 commercial fish catch in three areas of the Kafue Flodplain. *The African Journal of Tropical Hydrobiology and Fisheries* **3**, 147-159.

Fromelt A. (2009) *Hydrologicalmodeling of the Kafue watershed using remote sensing data.* ETH.

Holmes E.E. & Ward E.J. (2011) *Analysis of multivariate timeseries using the MARSS package, version 2.8*. Mathematical Biology Program Northwest Fisheries Science Center, Seattle, WA.

Hornberger G.M. (1998) *Elements of Physical Hydrology*. The Johns Hopkins University Press, Balitmore.

Kapetsky J.M. (1974) Growth, Mortality, and Production of Five Fish Species of the Kafue River Floodplain, Zambia. *Fisheries*.

McCarthy G.T. (1938) The unit hydrograph and flood routing. In: *Conference of the North Atlantic Division, US Corps of Engineers*. US Corps of Engineers, New London, CT.

Meier P. (2010a) Remote Sensing Applications in the Kafue River Basin, Zambia. Working Paper.

Copy for Review

Meier P. (2010b) Remote Sensing for Water Resources Management.

Mung'omba J. (1992) *Kafue Flood Plain Gillnet Survey Data and Summary Tables & Figures*. Zambian Department of Fisheries, Chilanga, Zambia.

Nyimbili B. (2006) An evaluation of fish population changes in the Kafue Flats floodplain fishery of Zambia from 1980 to 2005. *Department of Biology*, 66.

Williams N.V. (1960) A Reveiw of the kafue River Fishery. *Rhodesia Agricultural Journal* **57**, 86-92.

Copy for Review

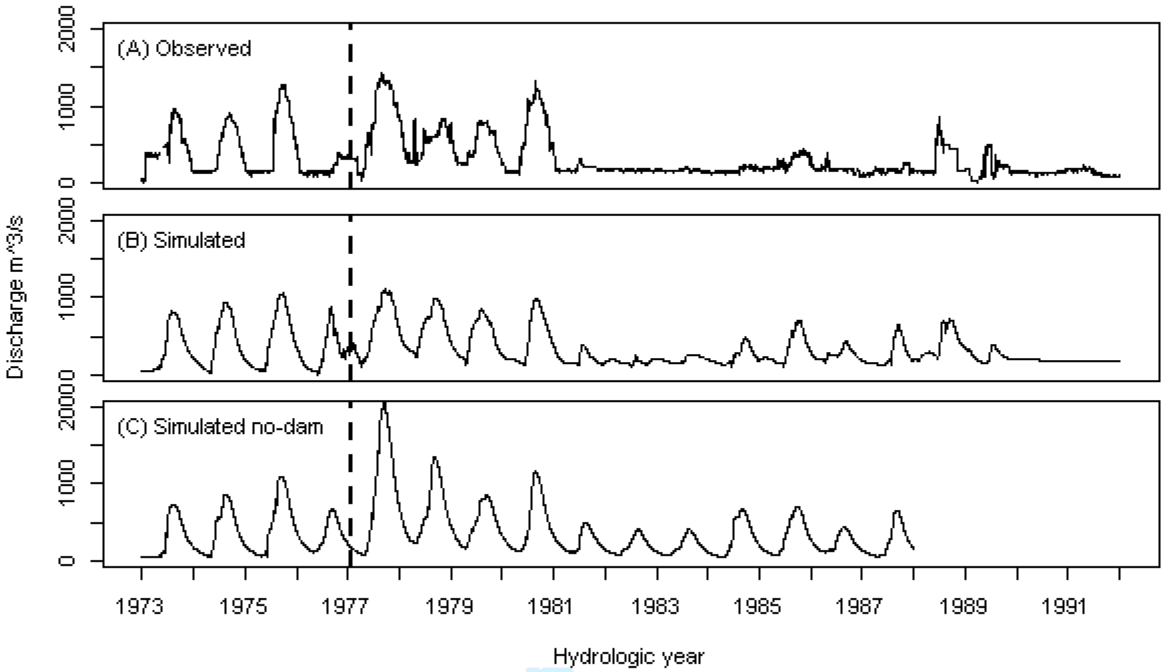


Figure S1. Discharge at KG power generating station (A) observed, (B) Simulated by the Muskingum method based on discharge at ITT, and (C) Simulated counter-factual flow at KG based on simulated ITT counterfactual "no-dam" scenario flows. Dashed vertical line is the year of ITT construction.

For Review

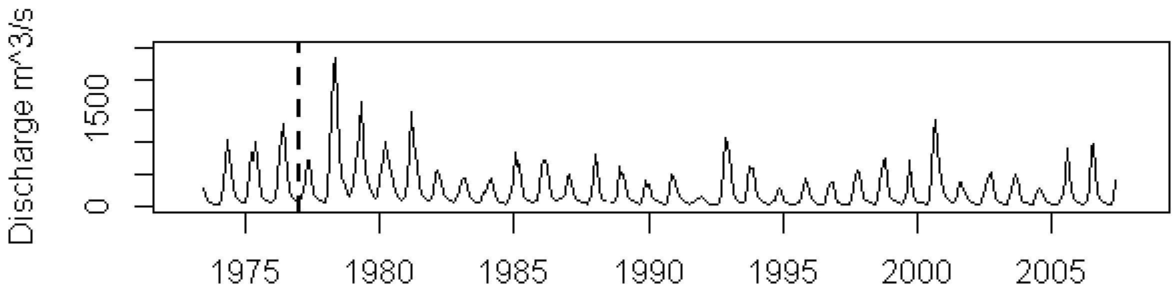


Figure S2. Discharge at Kafue Hook Bridge, upstream of ITT. Dashed vertical line is the year of ITT construction.

Copy for Review

Table S1. Mesh sizes employed by month and location of sampling carried out in each year.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sampling locations	Source	Note
1954	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1955	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1956	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1957	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1958	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	Unspecified	Williams 1960	(2)
1959	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1960	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1961	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1962	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)

Copy for Review

1963	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1964	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1965	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1966	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1967	67, 78, 89, 100, 110												Unspecified	Kapetsky 1974	(1,2)
1968	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	Lusaka District, Mazabuka district, Mumbwa district, Namwala district	DoF 1969 Fisheries Statistics	(2)
1969	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	Lusaka District, Mazabuka district, Mumbwa district, Namwala district	DoF 1969 Fisheries Statistics	(2)
1970	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	Maala, Chunga Lagoon, Chinyanya	Everett 1974	
1971	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110									Maala, Chunga Lagoon, Chinyanya	Everett 1974	

Copy for Review

1972	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	Lusaka District, Mazabuka district, Mumbwa district, Namwala district	1972 fisherie statistics Vol I	(2)
1973			67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	67, 78, 89, 100, 110	Lusaka District, Mazabuka district, Mumbwa district, Namwala district	DoF Fisheries Statistics 1973 Vol 1	(2)
1974															
1975															
1976	59, 74, 90, 106, 121												Chunga Lagoon, Nyimba	Dudley & Scully 1980	
1977															
1978															
1979															
1980		63, 76, 89, 102, 114	63, 76, 89, 102, 114										Chunga Lagoon, Namwala	DoF database	
1981									63, 76, 89, 102, 114				Chunga Lagoon, Nyimba	DoF database	
1982					63, 76, 89, 102, 114				63, 76, 89, 102, 114	63, 76, 89, 102, 114			Chunga Lagoon, Nyimba	DoF database	
1983			63, 76, 89, 102, 114	63, 76, 89, 102, 114		63, 76, 89, 102, 114		63, 76, 89, 102, 114				63, 76, 89, 102, 114	Chunga Lagoon, Namwala, Nyimba	DoF database	
1984															
1985		63, 76, 89, 102, 114	63, 76, 89, 102, 114			63, 76, 89, 102, 114			63, 76, 89, 102, 114				Chunga Lagoon, Namwala	DoF database	
1986			63, 76, 89, 102, 114			63, 76, 89, 102, 114			63, 76, 89, 102, 114				Chunga Lagoon, Nyimba	DoF database	

Copy for Review

1987														
1988				63, 76, 89, 102, 114	63, 76, 89, 102, 114			63, 76, 89, 102, 114		63, 76, 89, 102, 114		63, 76, 89, 102, 114	Chunga Lagoon, Nyimba	DoF database
1989			63, 76, 89, 102, 114	63, 76, 89, 102, 114	63, 76, 89, 102, 114	102, 114	63, 76, 89, 102, 114						Chunga Lagoon, Namwala, Nyimba	DoF database
1990														
1991							63, 76, 89, 102, 114	63, 76, 89, 102, 114				63, 76, 89, 102, 114	Chunga Lagoon, Nyimba	DoF database
1992			63, 76, 89, 102, 114				63, 76, 89, 102, 114	63, 76, 89, 102, 114					Chunga Lagoon, Nyimba	DoF database
1993		63, 76, 89, 102, 114		63, 76, 89, 102, 114		63, 76, 89, 102, 114	63, 76, 89, 102, 114	63, 76, 89, 102, 114		63, 76, 89, 102, 114			Chunga Lagoon, Namwala, Nyimba	DoF database
1994			63, 89, 102, 114	63, 89, 102, 114	63, 89, 102, 114	63, 76, 89, 102, 114		63, 76, 89, 102, 114		63, 76, 89, 102, 114	63, 76, 89, 102, 114		Chunga Lagoon, Namwala, Nyimba	DoF database
1995			63, 89, 102, 114								63, 76, 89		Chunga Lagoon, Namwala	DoF database
1996				63, 76, 89, 102, 114		63, 76, 89, 102, 114			63, 76, 89, 102, 114			63, 76, 89, 102, 114	Chunga Lagoon, Nyimba	DoF database
1997							63, 76, 89, 102, 114			63, 76, 89, 102, 114	63, 76, 89, 102, 114		Chunga Lagoon, Nyimba	DoF database
1998	63, 76, 89, 102, 114		63, 76, 89, 102, 114			63, 76, 89, 102, 114		63, 76, 89, 102, 114					Chunga Lagoon, Nyimba	DoF database

Copy for Review

1999								63, 76, 89, 102, 114	63, 76, 89, 102, 114				Chunga Lagoon, Nyimba	DoF database
2000														
2001														
2002									63, 76, 89, 102, 114				Chunga Lagoon, Nyimba	DoF database
2003					63, 76, 89, 102, 114	63, 76, 89, 102, 114	63, 76, 89, 102, 114	63, 76, 89, 114	63, 76, 89, 114		63, 76, 89, 114		Chunga Lagoon, Nyimba	DoF database
2004														
2005								63, 76, 89, 102, 114	63, 76, 89, 102, 114	63, 76, 89, 102, 114	63, 76, 89, 102, 114		Chunga Lagoon, Namwala, Nyimba	DoF database
2006														
2007														
2008									63, 76, 89, 102, 114	63, 76, 89, 102, 114			Chinyanya, Chunga Lagoon, Kasaka, Mazabuka, Mutukuzhi, Namwala	DoF database
2009														
2010										63, 76, 89, 102, 114	63, 76, 89, 102, 114		Chinyanya, Chunga Lagoon, Mazabuka, Nyimba	DoF database

Notes: (1) Only a total for the year is given, placed in Jan for convience.
(2) Mesh sizes used assumed same as those reported in Everett 1974

Copy for Review

Table S2. Fish species reported in each dataset compiled for analysis. Species synonyms where reconciled using Skelton (2001) and Fishbase.org (Froese and Pauly 2012).

Years	Species	Family	Source	Note
1954-1957 & 1959-1967	unspecified total		Kapetsky 1974	
1958	Oreochromis andersonii	Cichlidae	Williams 1960	
1958	Oreochromis macrochir	Cichlidae	Williams 1960	
1958	Sargochromis codringtonii	Cichlidae	Williams 1960	
1958	Serranochromis angustceps	Cichlidae	Williams 1960	
1958	Serranochromis macrocephalus	Cichlidae	Williams 1960	
1958	Serranochromis robustus	Cichlidae	Williams 1960	
1958	Serranochromis thumbergi	Cichlidae	Williams 1960	
1958	Tilapia rendalli	Cichlidae	Williams 1960	
1958	Tilapia sparrmanii	Cichlidae	Williams 1960	
1958	Clarias gariepinus	Clariidae	Williams 1960	
1958	Clarias ngamensis	Clariidae	Williams 1960	
1958	Labeo cylindricus	Cyprinidae	Williams 1960	
1958	Marcusenius macrolepidotus	Mormyridae	Williams 1960	
1958	Mormyrus spp.	Mormyridae	Williams 1960	
1958	Schilbe intermedius	Schilbeidae	Williams 1960	
1968-1969	Oreochromis andersonii	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1970	Oreochromis macrochir	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1971	Sargochromis carlottae	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1972	Sargochromis codringtonii	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1973	Serranochromis angustceps	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1974	Serranochromis macrocephala	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1975	Serranochromis robustus	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1976	Serranochromis thumbergi	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1977	Tilapia rendalli	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1978	Tilapia sparrmanii	Cichlidae	DoF 1969 Fisheries Statistics	
1968-1979	Clarias gariepinus	Clariidae	DoF 1969 Fisheries Statistics	
1968-1980	Clarias ngamensis	Clariidae	DoF 1969 Fisheries Statistics	
1968-1981	Labeo cylindricus	Cyprinidae	DoF 1969 Fisheries Statistics	
1968-1982	Hepsetus odoe	Hepsetidae	DoF 1969 Fisheries Statistics	
1968-1983	Synodontus spps	Mochokidae	DoF 1969 Fisheries Statistics	
1968-1984	Marcusenius macrolepidotus	Mormyridae	DoF 1969 Fisheries Statistics	
1968-1985	Mormyrus lacerda	Mormyridae	DoF 1969 Fisheries Statistics	
1968-1986	Schilbe intermedius	Schilbeidae	DoF 1969 Fisheries Statistics	
1970-1971	Haplochromis spps	Cichlidae	Everett 1974	
1970-1972	Oreochromis andersonii	Cichlidae	Everett 1975	
1970-1973	Oreochromis macrochir	Cichlidae	Everett 1976	
1970-1974	Serranochromis angustceps	Cichlidae	Everett 1977	
1970-1975	Serranochromis macrocephala	Cichlidae	Everett 1978	
1970-1976	Serranochromis robustus	Cichlidae	Everett 1979	
1970-1977	Serranochromis thumbergi	Cichlidae	Everett 1980	
1970-1978	Tilapia rendalli	Cichlidae	Everett 1981	
1970-1979	Tilapia sparrmanii	Cichlidae	Everett 1982	
1970-1980	Clarias gariepinus	Clariidae	Everett 1983	
1970-1981	Clarias ngamensis	Clariidae	Everett 1984	
1970-1982	Barbus spps.	Cyprinidae	Everett 1985	
1970-1983	Labeo molybdinus	Cyprinidae	Everett 1986	
1970-1984	Hepsetus odoe	Hepsetidae	Everett 1987	
1970-1985	Synodontus spps	Mochokidae	Everett 1988	
1970-1986	Marcusenius macrolepidotus	Mormyridae	Everett 1989	
1970-1987	Mormyrus lacerda	Mormyridae	Everett 1990	
1970-1988	Schilbe intermedius	Schilbeidae	Everett 1991	

Copy for Review

1972	Brycinus grandisquamis	Alestidae	1972 fisheries statistics Vol I	(1)
1972	Brycinus lateralis	Alestidae	1972 fisheries statistics Vol I	(1)
1972	Brycinus peringueyi	Alestidae	1972 fisheries statistics Vol I	(1)
1972	Micralestes acutidens	Alestidae	1972 fisheries statistics Vol I	(1)
1972	Rhabdalestes rhodesiensis	Alestidae	1972 fisheries statistics Vol I	(1)
1972	Ctenopoma multispine	Anabantidae	1972 fisheries statistics Vol I	(1)
1972	Haplochromis adolphifrederici	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Oreochromis andersonii	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Oreochromis macrochir	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Pseudocrenilabrus philander	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Sargochromis carlottae	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Sargochromis codringtonii	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Sargochromis giardi	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Serranochromis macrocephala	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Serranochromis robustus	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Serranochromis thumbergi	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Tilapia rendalli	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Tilapia sparrmanii	Cichlidae	1972 fisheries statistics Vol I	(1)
1972	Citharines	Citharinidae	1972 fisheries statistics Vol I	(1)
1972	Clarias gariepinus	Clariidae	1972 fisheries statistics Vol I	(1)
1972	Clarias ngamensis	Clariidae	1972 fisheries statistics Vol I	(1)
1972	Clarias stappersii	Clariidae	1972 fisheries statistics Vol I	(1)
1972	Clarias theodorae	Clariidae	1972 fisheries statistics Vol I	(1)
1972	Barbus spps.	Cyprinidae	1972 fisheries statistics Vol I	(1)
1972	Barbus spps.	Cyprinidae	1972 fisheries statistics Vol I	(1)
1972	Labeo annectens	Cyprinidae	1972 fisheries statistics Vol I	(1)
1972	Labeo cylindricus	Cyprinidae	1972 fisheries statistics Vol I	(1)
1972	Hepsetus odoe	Hepsetidae	1972 fisheries statistics Vol I	(1)
1972	Mastacembelus frenatus	Mastacembelidae	1972 fisheries statistics Vol I	(1)
1972	Synodontus spps	Mochokidae	1972 fisheries statistics Vol I	(1)
1972	Marcusenius macrolepidotus	Mormyridae	1972 fisheries statistics Vol I	(1)
1972	Mormyrus lacerda	Mormyridae	1972 fisheries statistics Vol I	(1)
1972	Aplocheilichthys spps	Poeciliidae	1972 fisheries statistics Vol I	(1)
1972	Schilbe intermedius	Schilbeidae	1972 fisheries statistics Vol I	(1)
1973	Oreochromis andersonii	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Oreochromis macrochir	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Sargochromis carlottae	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Sargochromis codringtonii	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Serranochromis angustceps	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Serranochromis macrocephalus	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Serranochromis robustus	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Serranochromis thumbergi	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Tilapia rendalli	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Tilapia sparrmanii	Cichlidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Clarias gariepinus	Clariidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Clarias ngamensis	Clariidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Labeo spps	Cyprinidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Hepsetus odoe	Hepsetidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Synodontus spps	Mochokidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Marcusenius macrolepidotus	Mormyridae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	Schilbe intermedius	Schilbeidae	DoF Fisheries Statistics 1973 Vol 1	(2)
1973	other		DoF Fisheries Statistics 1973 Vol 1	(2)
1976	Brycinus lateralis	Alestidae	Dudley & Scully 1980	
1976	Oreochromis andersonii	Cichlidae	Dudley & Scully 1980	
1976	Oreochromis macrochir	Cichlidae	Dudley & Scully 1980	
1976	Sargochromis carlottae	Cichlidae	Dudley & Scully 1980	

Copy for Review

1976	Sargochromis giardi	Cichlidae	Dudley & Scully 1980
1976	Serranochromis angustceps	Cichlidae	Dudley & Scully 1980
1976	Serranochromis macrocephalus	Cichlidae	Dudley & Scully 1980
1976	Serranochromis robustus	Cichlidae	Dudley & Scully 1980
1976	Serranochromis thumbergi	Cichlidae	Dudley & Scully 1980
1976	Tilapia rendalli	Cichlidae	Dudley & Scully 1980
1976	Tilapia sparrmanii	Cichlidae	Dudley & Scully 1980
1976	Clarias gariepinus	Clariidae	Dudley & Scully 1980
1976	Clarias ngamensis	Clariidae	Dudley & Scully 1980
1976	Labeo molybdinus	Cyprinidae	Dudley & Scully 1980
1976	Hepsetus odoe	Hepsetidae	Dudley & Scully 1980
1976	Synodontis spps	Mochokidae	Dudley & Scully 1980
1976	Marcusenius macrolepidotus	Mormyridae	Dudley & Scully 1980
1976	Mormyrus lacerda	Mormyridae	Dudley & Scully 1980
1976	Schilbe intermedius	Schilbeidae	Dudley & Scully 1980
1980-2010	Brycinus imberi	Alestidae	DoF database
1980-2011	Brycinus lateralis	Alestidae	DoF database
1980-2012	Ctenopoma spp	Anabantidae	DoF database
1980-2013	Oreochromis andersonii	Cichlidae	DoF database
1980-2014	Oreochromis macrochir	Cichlidae	DoF database
1980-2015	Oreochromis niloticus	Cichlidae	DoF database
1980-2016	Pseudocrenilabrus philander	Cichlidae	DoF database
1980-2017	Sargochromis carlottae	Cichlidae	DoF database
1980-2018	Sargochromis codringtonii	Cichlidae	DoF database
1980-2019	Sargochromis giardi	Cichlidae	DoF database
1980-2020	Serranochromis angusticeps	Cichlidae	DoF database
1980-2021	Serranochromis macrocephalus	Cichlidae	DoF database
1980-2022	Serranochromis robustus	Cichlidae	DoF database
1980-2023	Serranochromis thumbergi	Cichlidae	DoF database
1980-2024	Tilapia rendalli	Cichlidae	DoF database
1980-2025	Tilapia sparrmanii	Cichlidae	DoF database
1980-2026	Distichodus schenga	Citharinidae	DoF database
1980-2027	Clarias gariepinus	Clariidae	DoF database
1980-2028	Clarias ngamensis	Clariidae	DoF database
1980-2029	Clarias theodorae	Clariidae	DoF database
1980-2030	Barbus spps.	Cyprinidae	DoF database
1980-2031	Labeo cylindricus	Cyprinidae	DoF database
1980-2032	Labeo molybdinus	Cyprinidae	DoF database
1980-2033	Hepsetus odoe	Hepsetidae	DoF database
1980-2034	Mastacembelus frenatus	Mastacembelidae	DoF database
1980-2035	Synodontus spps	Mochokidae	DoF database
1980-2036	Marcusenius macrolepidotus	Mormyridae	DoF database
1980-2037	Mormyrus larceda	Mormyridae	DoF database
1980-2038	Mormyrus longirostris	Mormyridae	DoF database
1980-2039	Mormyrus macrodon	Mormyridae	DoF database
1980-2040	Petrocephalus catastoma	Mormyridae	DoF database
1980-2041	Pollimyrus castelnaui	Mormyridae	DoF database
1980-2042	Schilbe intermedius	Schilbeidae	DoF database

Notes: (1) Reference does not clarify if listed species are those included in the catch, or a total species list for the Kafue River

(2) Species reported only using local names. Translated using Mortimer 1965

Additional references:

Froese, R and D. Pauly. Eds. (2012) FishBase. www.fishbase.org version (04/2012). Accessed 13 June 2012.

Mortimer, M.A.E. (1965) Natural Resources Handbook The Fish and Fisheries of Zambia. Republic of Zambia Ministry of Lands and Natural Resources, Ndola, Zambia.

Copy for Review

Skelton, P. (2001) A Complete Guide to the Freshwater Fishes of Southern Africa. Struik Publishers, Cape Town, South Africa.

Copy for Review

Table S3. Full modeling results. Refer to text and Supplementary Information text for description

Rank	-LL	AICc	dAICc	AICc. wgt	Ucpue	Ueffort	CPUE density dependence (b1-1)	Effect of CPUE on effort (b2)	Effect of effort on CPUE (b3)	Effort Density Dependence (b4-1)	Effect of Water Regime on CPUE (b5)	Rcpue	Rgillnets	Rboats	Notes
1	-93.2	210.66	0.00	0.23	0.07	0.08	-0.22	0.01	-0.14	0.00	0.00	0.14	0.22	0.24	
2	-93.2	210.72	0.06	0.23	0.06	0.08	-0.23	0.00	-0.13	0.00	-0.02	0.14	0.22	0.24	
3	-93.2	210.72	0.06	0.23	0.07	0.08	-0.22	0.00	-0.14	0.00	0.00	0.14	0.22	0.24	
na	-95.8	211.04	0.38	0.19	-0.07	0.08	0.00	0.00	0.01	0.00	0.00	0.16	0.22	0.24	(1)
na	-95.0	211.85	1.19	0.13	-0.03	0.08	0.00	0.00	-0.03	0.00	0.06	0.16	0.22	0.24	(1)
na	-95.3	212.53	1.86	0.09	-0.08	0.09	0.00	0.00	0.01	-0.01	0.00	0.16	0.22	0.24	(1)
na	-95.3	212.54	1.88	0.09	-0.08	0.08	0.00	0.01	0.01	0.00	0.00	0.16	0.22	0.24	(2)
4	-93.1	212.91	2.25	0.08	0.08	0.08	-0.26	0.01	-0.14	0.00	-0.03	0.14	0.22	0.24	
na	-91.9	212.94	2.27	0.07	0.47	1.36	-0.74	-1.64	-0.56	-1.36	-0.03	0.15	0.22	0.19	(2)
5	-93.2	213.01	2.35	0.07	0.08	0.08	-0.25	0.00	-0.14	0.00	-0.02	0.14	0.22	0.24	
6	-99.1	213.20	2.53	0.07	0.06	0.08	-0.21	0.00	-0.13	0.00	0.00	0.19	0.32	0.86	
na	-95.0	214.17	3.51	0.04	-0.03	0.08	0.00	0.00	-0.03	0.00	0.05	0.16	0.22	0.24	(2)
na	-95.0	214.20	3.53	0.04	-0.03	0.08	0.00	0.00	-0.03	0.00	0.05	0.16	0.22	0.24	(2)
na	-101.1	214.86	4.20	0.03	-0.07	0.08	0.00	0.00	0.01	0.00	0.00	0.19	0.32	0.86	(1)
7	-99.1	215.40	4.73	0.02	0.06	0.08	-0.23	0.00	-0.13	0.00	-0.02	0.19	0.32	0.86	
8	-99.1	215.43	4.77	0.02	0.07	0.08	-0.22	0.00	-0.14	0.00	0.00	0.19	0.32	0.86	
9	-99.1	215.46	4.80	0.02	0.07	0.08	-0.21	0.00	-0.13	0.00	0.00	0.19	0.32	0.86	
na	-94.6	215.78	5.11	0.02	-0.03	1.05	0.00	-1.18	-0.03	-0.90	0.04	0.16	0.22	0.22	(2)
10	-97.0	215.79	5.13	0.02	1.38	0.08	-1.89	0.00	-1.42	0.00	0.00	0.17	0.22	0.24	
na	-100.5	215.84	5.17	0.02	-0.03	0.08	0.00	0.00	-0.03	0.00	0.06	0.19	0.32	0.86	(1)
na	-94.9	216.39	5.73	0.01	-0.62	1.75	0.68	-2.04	0.54	-1.59	0.00	0.16	0.21	0.24	(1)
na	-100.8	216.56	5.89	0.01	-0.08	0.08	0.00	0.01	0.01	0.00	0.00	0.19	0.32	0.86	(2)
na	-100.8	216.56	5.90	0.01	-0.08	0.09	0.00	0.00	0.01	-0.01	0.00	0.19	0.32	0.86	(1)
11	-99.1	217.64	6.97	0.01	0.07	0.08	-0.25	0.01	-0.14	0.00	-0.02	0.19	0.32	0.86	
12	-99.1	217.69	7.02	0.01	0.07	0.08	-0.24	0.00	-0.14	0.00	-0.02	0.19	0.32	0.86	
na	-100.5	218.10	7.44	0.01	-0.03	0.08	0.00	0.00	-0.03	0.00	0.06	0.19	0.32	0.86	(2)
na	-100.5	218.11	7.44	0.01	-0.03	0.08	0.00	0.00	-0.03	0.00	0.06	0.19	0.32	0.86	(2)
na	-100.6	218.45	7.79	0.00	-0.07	1.31	0.00	-1.50	0.01	-1.17	0.00	0.19	0.32	0.86	(1)

Copy for Review

na	-98.5	218.81	8.15	0.00	0.48	-0.39	-0.75	0.61	-0.55	0.47	-0.03	0.19	0.32	0.86	(2)
na	-100.5	220.55	9.89	0.00	-0.05	1.16	0.00	-1.31	-0.01	-1.03	0.02	0.19	0.32	0.86	(2)
13	-100.8	221.01	10.35	0.00	0.22	1.13	-0.37	-1.28	-0.27	-1.00	0.00	0.19	0.32	0.86	
na	-120.8	265.80	55.14	0.00	-0.07	-0.01	0.00	0.01	-3.70	-1.84	0.00	0.16	0.95	0.94	(1)
na	-128.5	269.77	59.11	0.00	-0.07	0.08	0.00	0.00	0.01	0.00	0.00	1.00	1.00	1.00	(1)
14	-128.2	271.25	60.59	0.00	0.06	0.08	-0.21	0.00	-0.13	0.00	0.00	1.00	1.00	1.00	
na	-128.4	271.77	61.10	0.00	-0.03	0.08	0.00	0.00	-0.03	0.00	0.06	1.00	1.00	1.00	(1)
na	-128.5	271.84	61.17	0.00	-0.08	0.09	0.00	0.00	0.01	-0.01	0.00	1.00	1.00	1.00	(1)
na	-128.5	271.84	61.17	0.00	-0.08	0.08	0.00	0.01	0.01	0.00	0.00	1.00	1.00	1.00	(2)
15	-128.1	273.47	62.80	0.00	0.08	0.08	-0.23	0.01	-0.14	0.00	0.00	1.00	1.00	1.00	
16	-128.1	273.48	62.82	0.00	0.08	0.09	-0.22	0.00	-0.14	0.00	0.00	1.00	1.00	1.00	
17	-128.2	273.51	62.85	0.00	0.06	0.08	-0.23	0.00	-0.13	0.00	-0.02	1.00	1.00	1.00	
na	-128.4	273.99	63.32	0.00	-0.07	1.32	0.00	-1.53	0.01	-1.16	0.00	1.00	1.00	1.00	(1)
na	-128.4	274.00	63.33	0.00	-0.04	0.09	0.00	0.00	-0.02	-0.01	0.04	1.00	1.00	1.00	(2)
na	-128.4	274.01	63.34	0.00	-0.04	0.08	0.00	0.01	-0.02	0.00	0.04	1.00	1.00	1.00	(2)
18	-128.1	275.74	65.08	0.00	0.08	0.08	-0.27	0.01	-0.15	0.00	-0.03	1.00	1.00	1.00	
19	-128.1	275.77	65.10	0.00	0.08	0.09	-0.26	0.00	-0.14	-0.01	-0.03	1.00	1.00	1.00	
na	-128.3	276.05	65.39	0.00	-0.03	1.03	0.00	-1.15	-0.03	-0.88	0.04	1.00	1.00	1.00	(2)
na	-128.4	276.24	65.58	0.00	-0.58	1.68	0.63	-1.96	0.49	-1.50	0.00	1.00	1.00	1.00	(1)
na	-127.8	277.55	66.88	0.00	0.48	1.36	-0.75	-1.63	-0.57	-1.34	-0.02	1.00	1.00	1.00	(2)

Notes X(1) Excluded from analysis because the intrinsic population growth rate (Ucpue) was estimated as negative

X(2) Excluded from analysis because the B matrix is non-stationary

Copy for Review