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Analysis of Rainbow Trout Recruitment in the Henry's Fork

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Abstract

We present a model relating the mean December through February stream flow downstream of the Buffalo River to the recruitment of rainbow trout two years later. Additionally, we present ongoing work to create a predictive model of stream flow: a model of buffalo river stream flow with respect to time, and a model of Island Park inflow with respect to time.

Keywords Rainbow trout recruitment, Henry's Fork, Streamflow

1. Introduction

The Henry's Fork Foundation is concerned with modelling the recruitment of rainbow trout within the Henry's Fork with respect to time. As found in research conducted by the Idaho Department of Fish and Game, the recruitment of Rainbow Trout within Henry's Fork is related to the mean winter stream flow downstream of the Buffalo River, especially over the months of December to February [3]. That stream flow is the sum of the outflow from the Island Park Reservoir and the outflow from the Buffalo River.

We consider several objectives. First, create a model relating the recruitment of rainbow trout to mean stream flow downstream of the Buffalo River over the months of December to February. Second, create a predictive model of the outflows from the Island Park Reservoir and the Buffalo River. Implicit to the second objective is a third and fourth objective of creating a management function that sets the outflow of the Island Park Reservoir given specific constraints, including the inflow to the Island Park Reservoir.

We consider the first objective to be satisfied, and present a model relating the recruitment of rainbow trout to the mean stream flow downstream of the Buffalo River over the months of December to February. The second objective is partially satisfied, in that we present a model of the Buffalo River outflow which may be satisfactory. However, the third and fourth objectives have not yet been achieved, and so we cannot yet present a model for Island Park Reservoir outflow. Instead, we present findings pertinent to the fulfillment of those objectives.

2. Data analysis

Dr. Van Kirk supplied hydrologic, population, and recruitment datasets, as well as documentation. Our work has leaned heavily on insights provided by Dr. Van Kirk of the Henry's Fork Foundation and found by the Idaho Department of Fish and Game [3]. Our understanding of the system being modeled has depended upon [1] and [2].

The primary data set used in construction of the recruitment model was the file HF Recruitment data.xlsx. The dataset ranges across years 1994 to 2018 for stream flow and 1995 to 2019 for recruitment. The few cases of missing data in that file were filled by linear interpolation between the preceding and following data entries.

The primary data sets used in determining Buffalo River outflow were Buffalo.Old.WY.csv -used for 1936-2006 outflow data, and Buffalo.WY.csv -used for 2007-2019 outflow data.

The primary data sets used in determining the inflow to the Island Park reservoir were HL.Reg.WY.csv -which contains data on the outflow from Henry's Lake, and HLtoIP.NET.WY.csv -which contains data on the other sources of net inflow to the Island Park reservoir.

The Datasets were imported into Jupyter notebooks and were analyzed using the Python language with the Python libraries: Pandas and Numpy [5, 6]. The ranges of data used in constructing models were selected based upon the completeness of the input variable data sets-the input datasets of a model are limited to the range of the least complete input variable.

3. Variables

The recruitment of rainbow trout at time t is denoted by Y_t. and the mean stream flow downstream of the Buffalo River over the months of December through February is denoted X_t and is the sum of the corresponding mean outflows from the of the Island Park reservoir denoted $IP_{out}(t)$, and from the Buffalo River-denoted $BR_{out}(t)$. Here, the variable t represents years since 1939.

4. Recruitment Model

The model relating streamflow downstream of Buffalo River to the recruitment of Rainbow trout was found to be as follows (for X_t as streamflow, and Y_{t+2} as recruitment two years later).

$$e^{e^{1.0831} X_t^{0.14012}} = Y_{t+2}$$

This equation is come to by assuming a power model-done at the suggestion of Dr. Van Kirk of the Henry's Fork Foundation, and performing linear regression on log log X_t. The linear regression on log-log data gave the following equations with $a \approx 1.0831$ and $b \approx 0.14012$

$$a + bln(X_t) = ln\big(ln(Y_{t+2})\big)$$

$$\equiv e^a X_t^b = ln(Y_{t+2})$$

$$\equiv e^{e^a X_t^b} = Y_{t+2}$$

Figure 1: Recruitment by year since 1995, predicted and actual

Calculation of R^2 results in $R^2 \approx 0.432$. Given the complexity inherent to ecological systems, this value may be considered acceptable.

5. Buffalo River Analysis

The mean streamflow over December through February downstream of the Buffalo River is the sum of the corresponding mean outflow from the Island Park reservoir - $IP_{out}(t)$, and the mean outflow from the Buffalo River - $BR_{out}(t)$. Given that $IP_{out}(t)$ is the result of a management policy based on the content of the reservoir and the predicted total inflow, we concern ourselves with describing $BR_{out}(t)$.

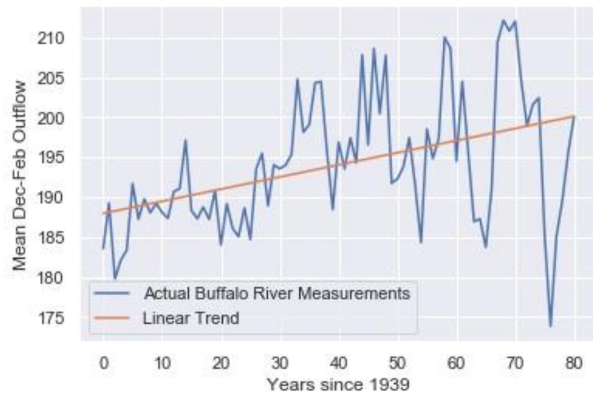

Figure 2: Dec-Feb mean December through February outflow across years since 1939, predicted and actual

We let $BR_{out}(t)$ represent mean December through February outflow from the Buffalo River across years since 1939. By linear regression and maximum likelihood estimation, we find that $BR_{out}(t)$ is approximately given by the following equation where t represents years since 1939.

$$BR_{out}(t) = 187.9 + 0.152t + \sqrt{(3.270 + 0.0899t)}N(0,1)$$

Notice that the residuals are distributed with variance increasing with respect to time. Though there appears to be a degree of seasonality in the data, attempted estimation by spectral analysis and parameter estimation yielded no results of significant magnitude.

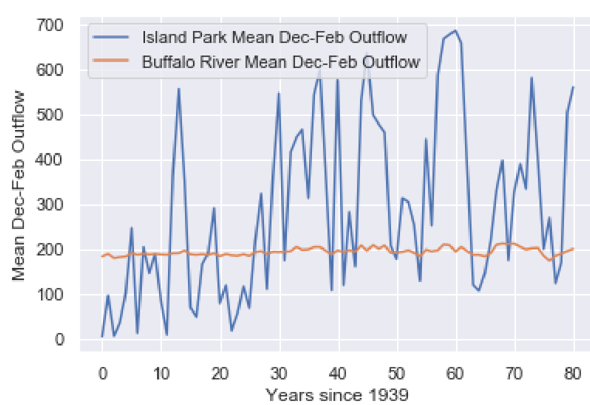

Figure 3: Island Park and Buffalo River mean December through February outflow across years since 1939

From Figure 3 we see that the variation of $BR_{out}(t)$ may be considered minor relative to the variation of $IP_{out}(t)$. Therefore, we consider the linear model of $BR_{out}(t)$ to be sufficient to predict future outflow.

6. Island Park Reservoir Inflow Analysis

As the outflow from the Island Park Reservoir is determined by the existing management policy on the total inflow to the Island Park Reservoir-especially over October to March, it is necessary to consider the inflow to the Island Park Reservoir. Therefore, we create a model to predict the total inflow to the Island Park Reservoir-which we represent by $IP_{in}(t)$ from October to March.

Considering the inflow given in HL.Reg.WY.csv and HLtoIP.NET.WY.csv and as a measured average across the day, we convert mean cubic feet per second to total acre-feet by the ratio $86400/43560 \approx 1.98$. By multiplying the sum of each corresponding entry in HL.Reg.WY.csv with HLtoIP.NET.WY.csv by $86400/43560 \approx 1.98$, we obtain the total inflow associated with each day.

We find that $IP_{in}(t)$ is generally linear with respect to time from October to March. This is demonstrated in Figure 4 by the high R^2 values associated with linear modeling of cumulative inflow. Therefore we consider that $IP_{in}(t)$ is approximately $182IP_{\Delta in}(t)$, where 182 represents the total number of days in October through March. We depict the values of $IP_{\Delta in}(t)$ in Figure 4.

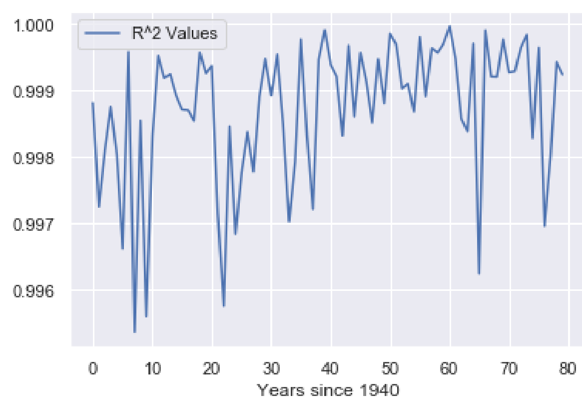

Figure 4: R^2 values of linear regression on cumulative Oct-Mar inflow

Figure 5: Slopes of linear regression on cumulative Oct-Mar inflow

We consider that a static model of the slope of the inflow curve: $IP_{\Delta in}$ with respect to year since 1940 would consist of a linear component $LC(t)$, a seasonal component $SC(t)$, and an error term $E(t)$ where t represents the number of years since 1940. The component terms have been found to be:

$$IP_{\Delta in}(t) = \left(LC(t) + SC(t) + E(t)\right)$$

$$LC(t) = 917.586 + 0.644t$$

$$SC(t) = -111.471 + 228.324\, sin^2\left(\frac{\pi}{13}t\right)$$

$$E(t) \;=\; N(0, 132.271 + 0.796t)$$

So the total inflow would be predicted by 182 - the number of days in October through March - multiplied by the slope of the inflow curve with respect to year. So, the total inflow with respect to year is given by:

$$IP_{\Delta in}(t) \;\approx 146712 + 117.21t + 41554\, sin^2\left(\frac{\pi}{13}t\right) \;+\; 182N(0, 132.27 + 0.796t)$$

Notice that the above equation has variance that increases linearly with t.

Ignoring the previous error term $E(t)$, and that inflow is assumed to be linear, $182IP_{\Delta in}(t) \approx IP_{in}(t)$, the residuals $E(t) = IP_{in}(t) - 182IP_{\Delta in}(t)$ are found to be distributed as $N(\mu,\sigma)$ with mean $\mu = -1578.461620$ acre-feet and standard deviation $\sigma = 29632.883112$ acre-feet.

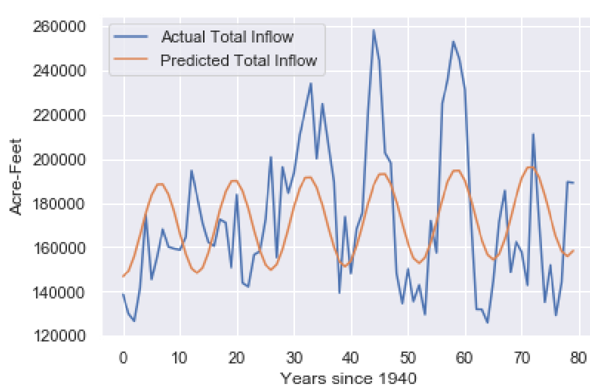

Figure 6: Static Model Predictions and Actual Total Oct-Mar Inflow

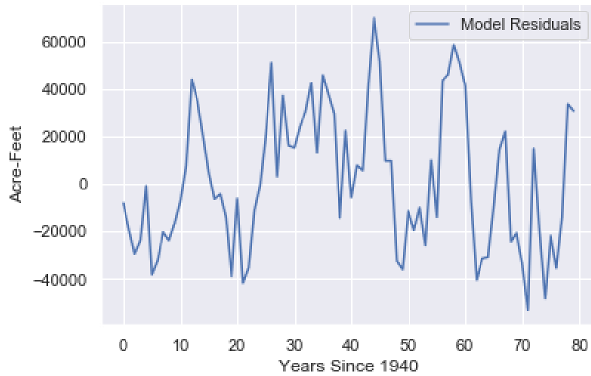

Figure 7: Residuals of Static Model

The graph of the residuals left by the static model suggest that there is additional structure not described by the static model. As is, the coefficient of determination for the static model has been found to be $R^2 \approx 0.212$

7. Optimization of Recruitment

As a precursor to the third and fourth objectives, we explored the relationship between recruitment and initial volume of the Island Park Reservoir, as well as the relationship between recruitment and reservoir outflow, and Buffalo River downstream streamflow, over the months from December through February, in an attempt to determine the ideal conditions for the maximization of recruitment. In particular, using the datasets provided by Dr. Van Kirk, we created several different scatter plots to examine the different relationships on the basis of filling strategy for the reservoir.

According to the Island Park Drought Management Plan, the Island Park Reservoir is known to have followed two different overflow (filling) strategies: uniform and non-uniform, for different time periods. From 1978 to 2005, the reservoir was consistently filled uniformly between October 1st and April 1st. Since 2006, however, the strategy has been adjusted to where the reservoir would be filled disproportionately more in October and November, and less in December through March. Fisheries advocates affiliated with Island Park surmise that the recruitment of rainbow trout can be optimized when the reservoir content reaches a certain amount.

First, we consider the relationship between the contents of the Island Park Reservoir on October 1st of the previous year from 1994 to 2005 and recruitment during the spring of the corresponding recruitment year from 1995 to 2006, before the adoption of the non-uniform filling strategy.

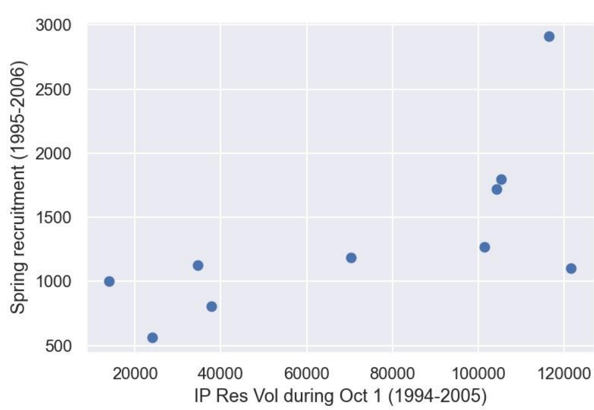

Figure 8: IP Reservoir volume during Oct 1 from 1994-2005 vs. Spring Recruitment from 1995-2006

As can be seen in Figure 8, we find that recruitment tends to slowly increase if the initial volume of the reservoir is increasingly filled. Roughly the same linear trend is observed when we relate recruitment to December through February outflow of the reservoir and the downstream streamflow of the Buffalo River across years from 1995 to 2006. The same can be said about the trend in the case of recruitment vs. the final volume of the Island Park reservoir on April 1st of the recruitment year from 1995 to 2005, in accordance with the adoption of the uniform filling strategy. In each of the plots, all data points appear to be interspersed and there is a discernable outlier with a recruitment value of almost 3000 specimens. This outlier seems to disrupt the general trend in the Buffalo River scatterplot.

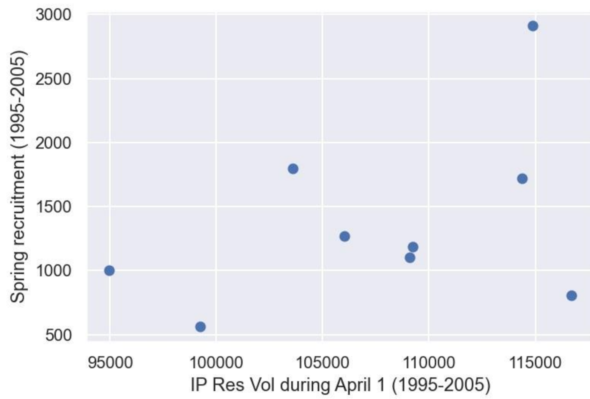

Figure 9: IP Reservoir volume during April 1 from 1995-2005 vs. Spring Recruitment from 1995-2005

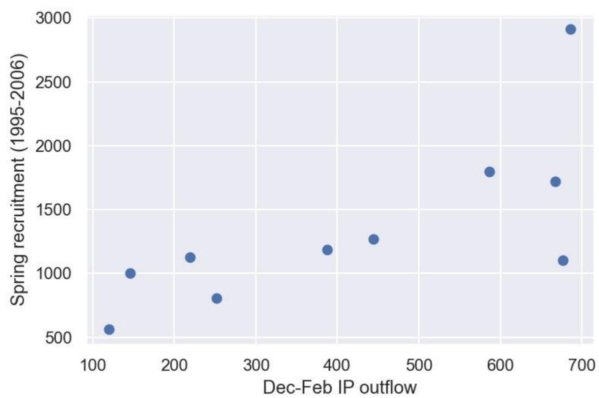

Figure 10: Dec-Feb IP Reservoir volume outflow vs. Spring Recruitment from 1995-2006

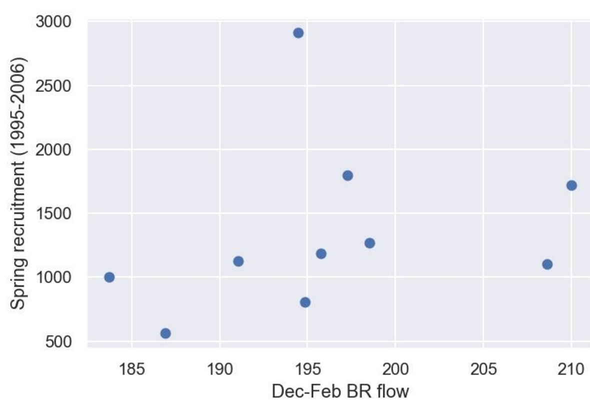

Figure 11: Dec-Feb Buffalo River flow vs. Spring Recruitment from 1995-2006

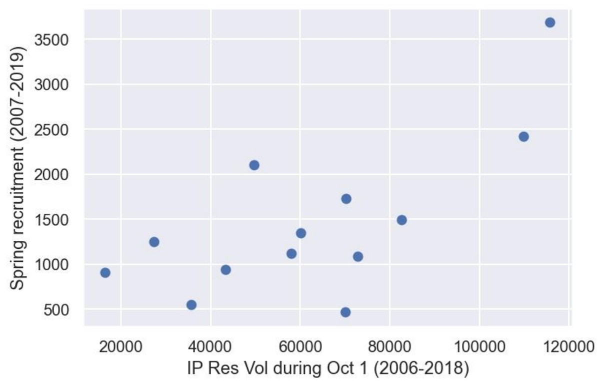

Figure 12: IP Reservoir volume during Oct 1 from 2006-2018 vs. Spring Recruitment from 2007-2019

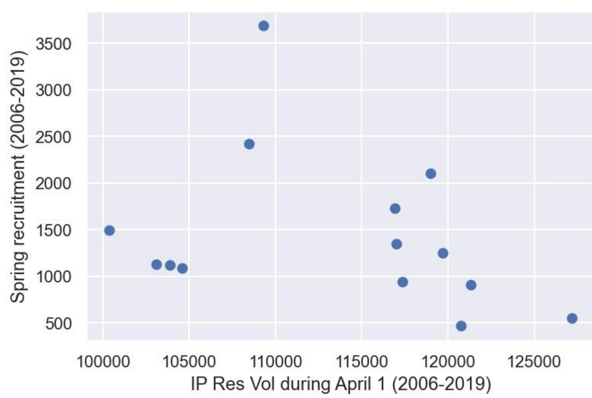

Figure 13: IP Reservoir volume during April 1 from 2006-2019 vs. Spring Recruitment from 2006-2019

When the reservoir is filled with disproportionately more water in October of the previous year from 2006 to 2018, recruitment tends to increase the following year from 2007 to 2019, as can be seen in Figure 12. Recruitment also tends to increase if reservoir outflow and Buffalo River streamflow, from December of the previous year to February of the recruitment year, are increased. In April of the recruitment year, however, the distribution of data points appears somewhat skewed and does not follow any particular trend. In addition, in each plot, some data points appear more clustered around each other than in the case of the uniform filling strategy.

In either case of the filling strategy, however, it is unclear whether one is more effective than the other in terms of maximizing recruitment. More work would need to be done in order to arrive at a meaningful conclusion, such as applying linear regression to measure the relationship between these variables or perhaps creating an optimization algorithm given constraints provided by Island Park Management.

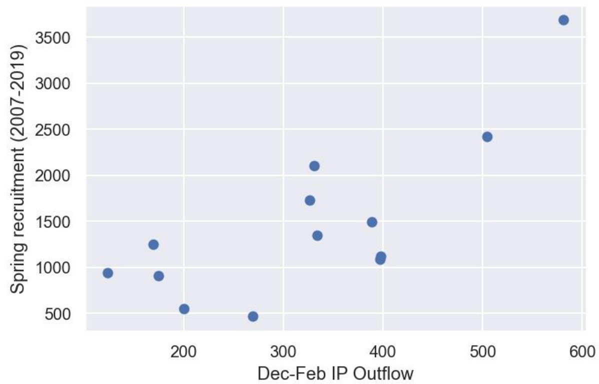

Figure 14: Dec-Feb IP Reservoir volume outflow vs. Spring Recruitment from 2007-2019

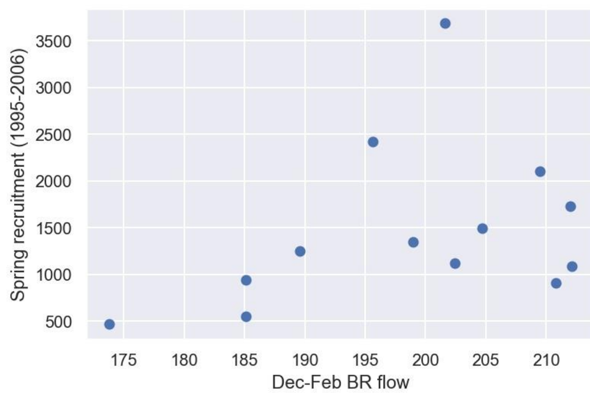

Figure 15: Dec-Feb Buffalo River flow vs. Spring Recruitment from 2007-2019

Knowing the extent of these relationships will prove useful when we construct a management model that accounts for the inflow and outflow of the Island Park Reservoir, given constraints based on management policies of Island Park.

8. Conclusion and Future Plan

We have presented a model relating mean December through February stream flow downstream from the Buffalo River - X_t, to the recruitment of rainbow trout in the Henry's Fork two years later - Y_{t+2}. Use of that relationship in forecast requires a predictive model of X_t. Given that $X_t = BR_{out}(t) + IP_{out}(t)$ and $BR_{out}(t)$ has been described, future work should be directed at determining $IP_{out}(t)$.

In order to determine $IP_{out}(t)$, a predictive model of $IP_{in}(t)$ should first be found and then incorporated into the definition of a management policy for the reservoir which maximizes $IP_{out}(t)$ while respecting requirements on the volume of the Island Park reservoir. We have produced a model for $IP_{in}(t)$, however, its residuals exhibit large variance and possible additional structure. Further analysis of $IP_{in}(t)$ is necessary to creating a useful model.

9. Acknowledgements

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10. References

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