Appendix A-5
HEC-ResSim Data Output Post-Processing using R

Overview

The post-process script “scores” the outputs of the HEC-ResSim reservoir model developed in the HH6 task according to the performance indicators developed in the DW4 task. Written in the open-source programming language R (Reference 4), the post-process script accepts continuous daily streamflow and reservoir elevation timeseries outputted from the ResSim model and converts them to daily, monthly, or yearly performance indicator (PI) timeseries for each study reach. Then, the script aggregates the PI results and produces a series of plots to summarize and graphically display the results against the baseline condition or a secondary alternative. Figure 1 shows a simplified example of the script’s basic process for a given reach using a daily timeseries.

Flow Timeseries

Date	Flow
1-May	50
2-May	250
3-May	1000
4-May	800

Performance Indicator

Flow	PI Value
0	0
100	5
250	7
500	10
1000	15

PI Timeseries

Date	PI Value
1-May	2.5
2-May	7
3-May	15
4-May	13

PI	Total Value
Example PI	37.5

Results Plots

Figure 1 - Basic Post-Processing Script Workflow

PI Timeseries

The post-process script’s basic function, as shown in Figure 1, is to convert flow/elevation timeseries to PI timeseries using outputs from the ResSim model and the PI functions developed in the DW4 task. The script does this by linearly interpolating between PI values in the PI tables for each flow or elevation value in a given timeseries. Graphically, this amounts to locating each flow/elevation value on a given PI curve and finding the corresponding PI value, as shown in Figure 2.

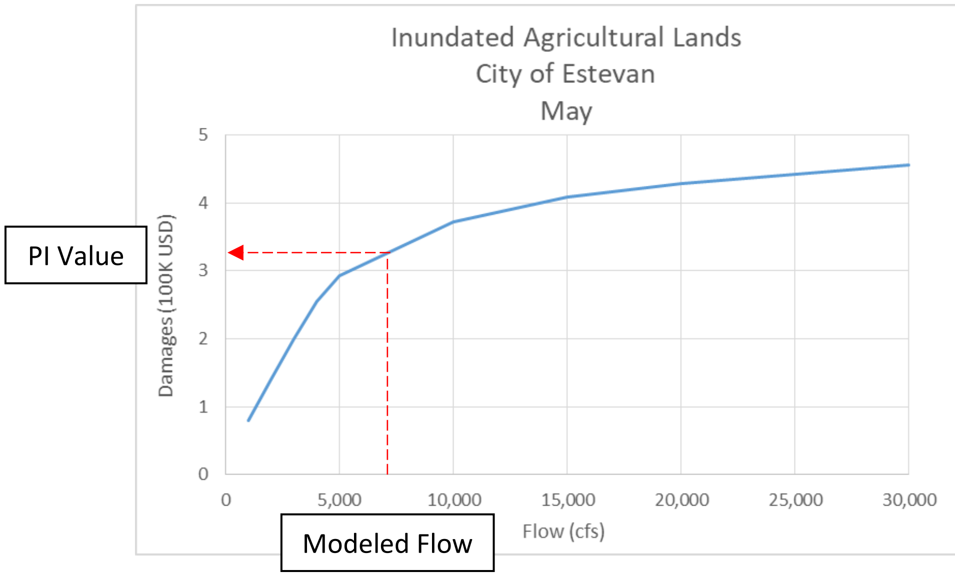


Figure 2 - PI timeseries computation example

The flow/elevation timeseries used depends on the PI being investigated. For example, the Flooded Structures PI uses an annual maximum timeseries, because typically the total structural damages due to flooding in a given year are caused by the maximum flow. Conversely, the Railroad Inundation PI uses a daily timeseries, counting the total number of days the railroad is flooded. Table 1 lists the timeseries used for each PI in the study.

Table 1 - Timeseries durations used to compute Performance Indicator totals

Study Theme	Performance Indicator	Timeseries
Flood Control	Structural Damages	Annual Maximum
Flood Control	Oil Well Inundation	Annual Maximum
Flood Control	Coal Haul Roads	Monthly Average
Flood Control	All other Flood Control PIs	Daily
Agriculture	Agricultural Damages	Daily[1]
Agriculture	Bankfull Exceedances	Daily
Water Supply	Permitted Water Use	Monthly Average[2]
Water Supply	Reservoir Supply Potential	Daily
Environmental	Ground Nesting Bird Habitat	Annual Maximum
Environmental	Fish and Wildlife Habitat (ND)	Monthly Average
Environmental	Fish Habitat	Daily
Environmental	Fish Mortality	Daily
Cultural	Historic Site Inundation	Annual Maximum
Cultural	Crown Land Protection	Daily
Recreation	All Recreational PIs	Daily
Erosion	Channel Erosion	Monthly Average
Water Quality	All Water Quality PIs	5-day Moving Average
Dam Safety	All Dam Safety PIs	Daily

[1] For each year in the simulation, this PI value is set to the maximum agricultural damages computed for that year. To compute the total PI value for the entire simulation, the PI value for each year is summed.

[2] For Rafferty and Grant Devine Reservoirs, a daily timeseries is used. For all other reaches, a monthly average timeseries is used.

PI Timeseries Example

Table 2 is an example of a monthly PI timeseries for the Sherwood to Mouse River Park reach in North Dakota for the year 2000. The PIs in this reach that use monthly timeseries are Water Supply, Fish and Wildlife Habitat, and Erosion. To compute each PI value for each month, the monthly average flow computed by the ResSim model is compared to the corresponding PI curve.

Table 2 - Monthly PI timeseries example

Month	Year	Modeled Avg. Flow	Water Supply	Fish & Wildlife	Erosion
Jan	2000	5.8	0	0	0
Feb	2000	6.1	100	0	0
Mar	2000	20.7	100	10	0
Apr	2000	25.4	100	10	0
May	2000	73.8	100	10	0
Jun	2000	79.8	0	10	0
Jul	2000	140.3	0	10	0
Aug	2000	91.7	0	10	0
Sep	2000	15.0	0	0	0
Oct	2000	4.5	0	0	0
Nov	2000	30.2	0	10	0
Dec	2000	6.4	0	0	0

Yearly PI Timeseries Generation

In order to create useful plots of PI data, all PI timeseries for a given study reach (daily, monthly, and yearly) are aggregated into a yearly PI timeseries. Table 3 displays an example of yearly PI timeseries for the Downstream of Towner reach in North Dakota. The PI values displayed in this table are compared to the corresponding PI values in the baseline or secondary alternative simulation to create a PI results plot for the Downstream of Towner reach.

Table 3. Yearly PI timeseries example

Year	Bridge Detour	Fish Kill	Boating Safety and Fishing…	>5 Days Out of Bank	Fish & Wildlife Habitat	Erosion	Agricultural Damages	Structural Damages	Inundated Cultural Sites
1930	1849372	1667.8	594.13	0	60	0.436	55458	0	0
1931	1859955	2532.7	249.08	0	20	0.128	31558	0	0
1932	1934142	2376.5	380.07	0	30	0.143	122207	0	0
1933	1934148	1854.4	625.97	0	40	0.271	191453	0	0
1934	1912945	2275.7	176.36	0	20	0.131	9825	0	0
1935	1928842	2473.5	404.0	0	40	0.131	110725	0	0
1936	1928849	2382.5	1004.06	0	50	0.278	78091	0	0
1937	1934143	2550.8	414.17	0	30	0.166	68673	0	0
…38	…373…	19…	…19	0	1…	[illegible]	…811…	[illegible]	0

Results Plots

To aid the study team in the evaluation of the ResSim model results, PI results plots are developed as a tool to compare two ResSim simulations. To create the plots, the summed, yearly PI results for a given alternative's model run are plotted against the summed, yearly PI results for a second model run. In Phases 2 and 3, all PI results are plotted against the PI results for the baseline simulation. For this study, the baseline model run is the HEC-ResSim model representative of current conditions, which include the operating plan described in Annex A and Annex B of the 1989 International Agreement (Reference 1 and Reference 2). In Phases 4 and 5, PI results for one alternative are plotted against PI results for a secondary alternative, such that the PI results plots show how the two alternatives differ. In all cases, differences between two model simulations are used to draw conclusions about the effectiveness of certain operational changes.

There are three types of PI results plots utilized by the technical team throughout the study. The first and most widely used is the Frequency plot. PI Frequency plots are displayed in the technical appendices of this study and can be used by non-study members to evaluate alternative model results. Two additional PI plots, a Box and Whisker plot, and a Magnitude plot, are also used by the technical team to evaluate the magnitude of impacts to various PIs. However, in an effort to limit the content displayed in the report, these two plots are not shown in the technical appendices. If a reader is interested in seeing these plots for a given alternative, they may be shared upon request.

It is important to note the PI plots used to evaluate alternative model results are a statistically-based tool. Like other statistical metrics, such as mean, maximum, and minimum, they provide information about a complex dataset, but they cannot describe the full breadth of the model results. Other tools, such as hydrographs at critical flow locations, must be used to fully characterize the effects of a given alternative reservoir operation.

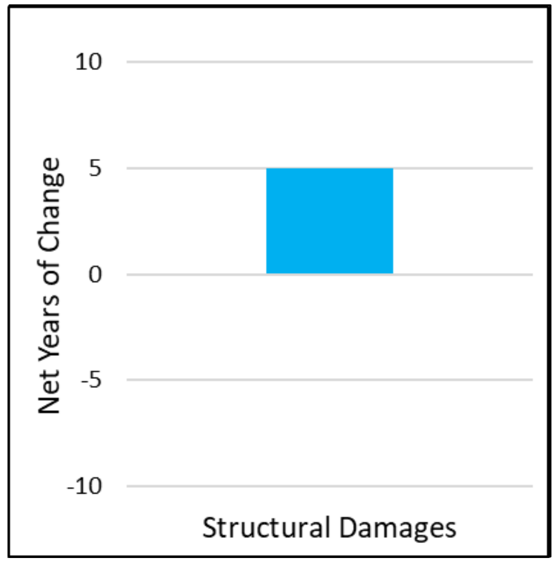
Frequency Plots

PI Frequency plots show how an alternative simulation compares to a secondary simulation. The plots utilize a "tug-of-war" approach, showing how many years one simulation outperformed the other for a given PI. The y-axis displays each PI evaluated in a given reach, and the x-axis displays the *net years of change*.

Net years of change for a given PI are determined by comparing the PI value for each year between the two simulations. For example, consider simulation A is being compared to simulation B over a 10-year period. For each of the 10 years, the relative difference between the yearly PI values for A and B are computed. If the relative change is less than 5%, there is not considered to be a difference between the two simulations. However, if the difference is 5% or greater, that year is considered a year of change. The change is then considered to be favoring A or B. If A performed better than B (e.g. less structural damages, less fish kills, etc.), the change favors simulation A. If A performed worse than B, the change favors simulation B. For the sake of this example, consider a change favoring Alternative A to be *positive* and a change favoring Alternative B to be *negative*. The total number of negative years is subtracted from the total number of positive years to determine the *net years of change*. For example, if A showed lower structural damage than B in 6 years but higher structural damages in 1 year, the net years of change would be +5. A graphical example of this computation is shown in Figure 3.

PI: Structural Damages (lower PI Total is better)

Year	PI Total (A)	PI Total (B)	Relative Change	Classification
2005	115	50	-57%	(-)
2006	560	560	0%	No change
2007	200	230	15%	(+)
2008	425	800	88%	(+)
2009	120	205	71%	(+)
2010	320	420	31%	(+)
2011	1250	1250	0%	No change
2012	80	425	431%	(+)
2013	630	620	-2%	No change
2014	630	870	38%	(+)



+6 positive -1 negative
= **+5 net years**

Figure 3. Example PI frequency plot computation

An example of a PI Frequency plot for the Manitoba reach is shown in Figure 4. This plot compares the PI results for Phase 5 Alternative 502a to the PI results for the baseline simulation over the period of record 1930-2017 (88 years). If a bar is shown to the right of zero, it means Alternative 502a performed better than the baseline simulation for that PI. Conversely, if a bar is shown to the left of zero, that PI scored better in the baseline simulation than in Alternative 502a. If no bar is displayed for a given PI, the net years of change for that PI are zero.

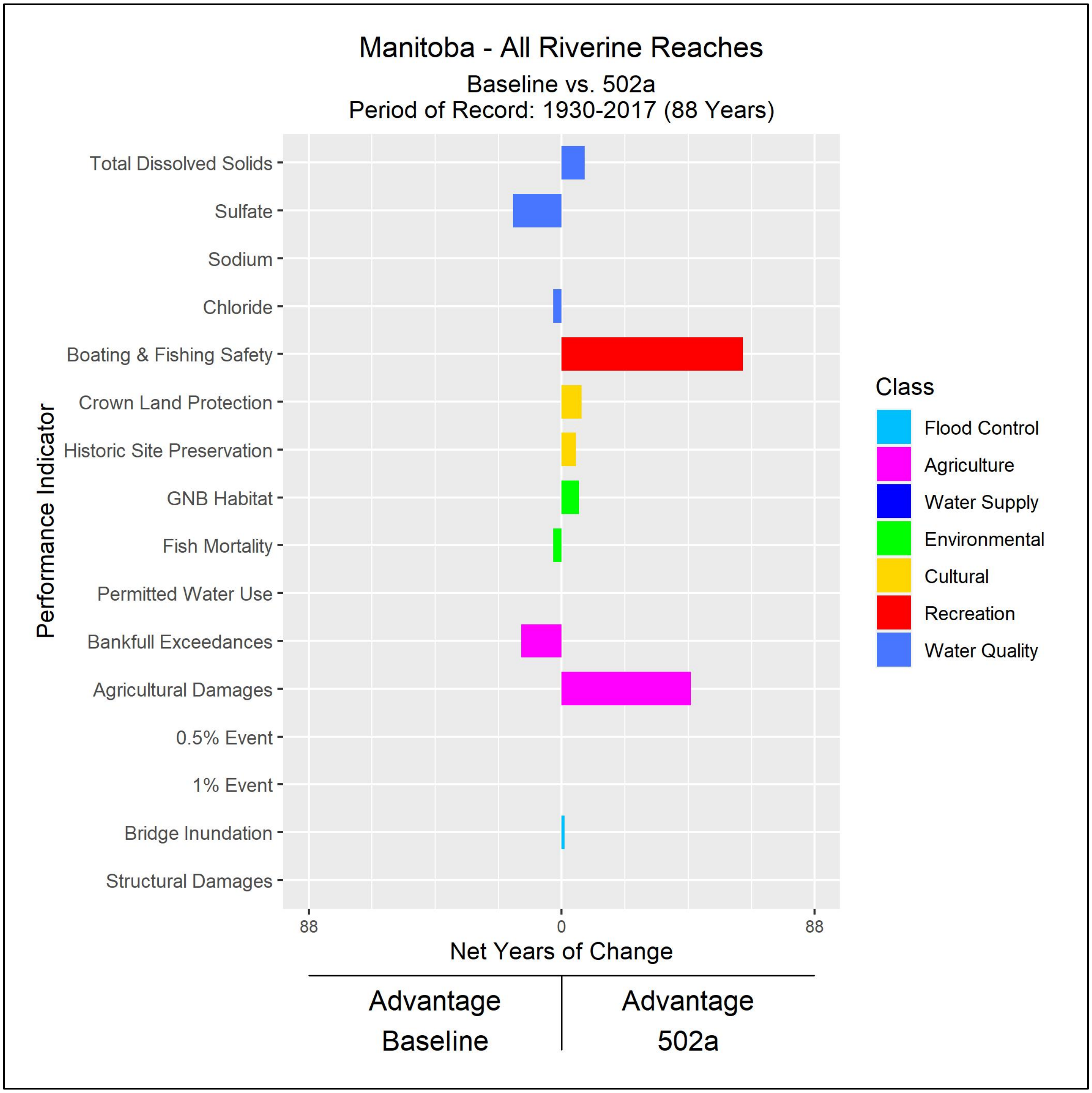


Figure 4. PI frequency plot example

Box and Whisker Plots

The Frequency Plots show how many years change to a given PI occurs, but they do not show the magnitude of change within those years. It is possible two alternatives could show change from the baseline simulation in the same number of years, but one alternative may result in great improvement to a PI, while another may only show moderate improvement. An example of this is shown in Figure 3. In 2012, there was a very large difference in PI totals between A and B (+431%). In 2007, there was a much smaller difference (+15%). However, both of these years only counted as one year of change on the corresponding Frequency Plot.

To ensure differences in the magnitude of change to PIs are accounted for in the evaluation of alternatives, the technical team developed Box and Whisker plots that show statistical metrics of the *relative change* observed between each alternative. These plots display the mean, 25th and 75th quartile, 1.5 times the interquartile range, and any outlier values of the relative change to each PI. “Boxes” significantly above zero indicate a higher magnitude of positive change throughout all years in the plotted period. Boxes below zero indicate a higher magnitude of negative change. An example PI Box and Whisker plot for the Manitoba reach is shown in Figure 5. This plot compares the PI results for Phase 5 Alternative 502a to the PI results for the baseline simulation over the period of record 1930-2017 (88 years). Note the axes of this plot are flipped relative to the PI frequency plot. Positive y-axis values represent an advantage for Alternative 502a, and negative y-axis values represent an advantage for the baseline simulation.

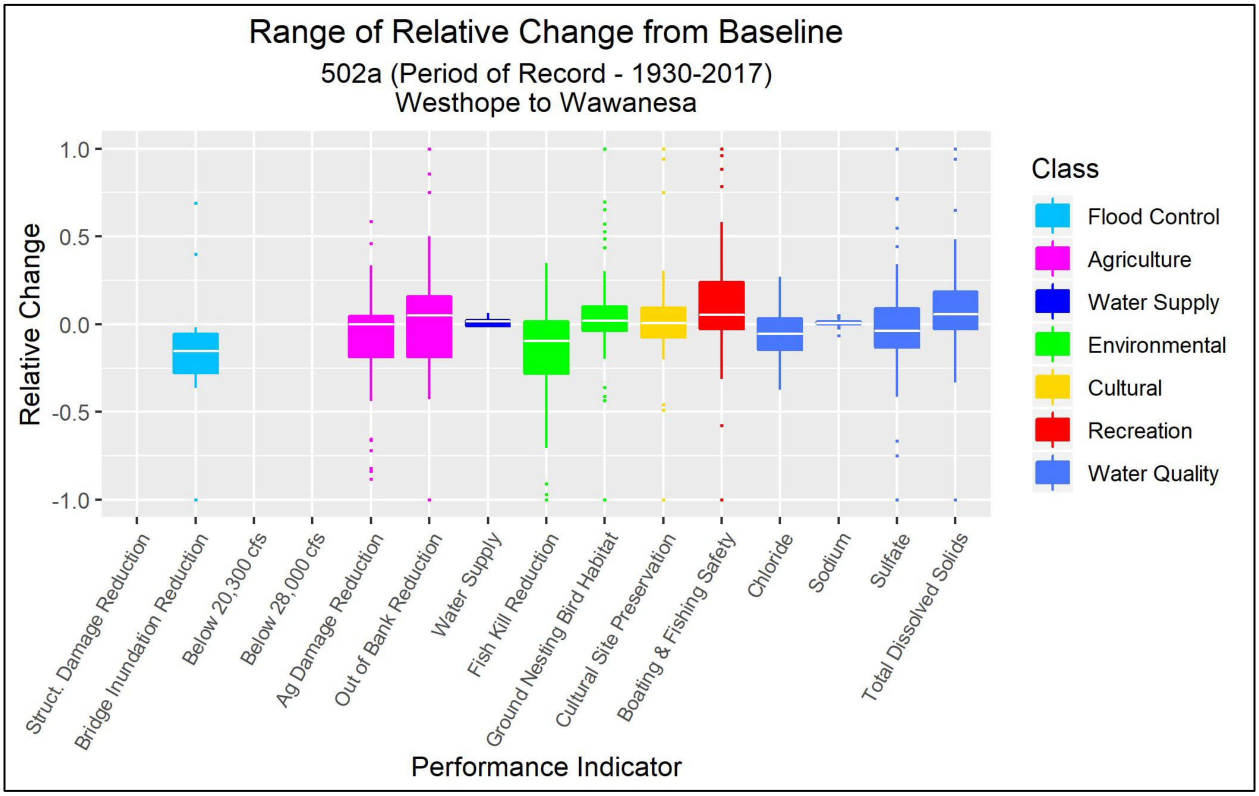


Figure 5. PI box and whisker plot example

IMPORTANT: Box and Whisker plots are not shown in report documentation for the Plan of Study but may be obtained upon request.

Absolute Magnitude Plots

While the Box and Whisker plots show the magnitude of *relative change* between two simulations, they do not show the *absolute change* for a given PI. The absolute change is the magnitude of benefit to a given PI in that PI's respective units. For the Structural Damages PI, the absolute change is the actual monetary difference in damages expected between two simulations. Identifying absolute change is necessary, because it is possible for one year to show a large difference in PI value on a percentage basis but only a moderate difference in PI value overall. An example of the importance of the difference between relative change and absolute change is shown in the years 2008 and 2012 in Figure 3. These two years show a large difference in relative change between simulations A and B (88% vs. 431%), but the actual difference in the amount of structural damages between the two simulations is similar (375 vs. 345).

To ensure differences in the absolute magnitude of changes in PI scores are accounted for in the evaluation of alternative operating plans, PI Magnitude plots are created for each PI in a given reach. The plots display the absolute magnitude of change of that specific PI between the two simulations for each year in the period of record (1930-2017). PI Magnitude plots are used by the technical team to validate the results shown on the Frequency and Box and Whisker Plots. These plots are also used to identify years with significant change to each PI so that those years may be more closely examined.

An example PI Magnitude plot for the Manitoba reach is shown in Figure 6. This plot compares the PI results for Phase 5 Alternative 502a to the PI results for the baseline simulation over the period of record 1930-2017 (88 years). This plot shows the 502a alternative led to the greatest increase in fish kills in Manitoba in 1955 and 1973. The plot also reinforces the results shown on the Frequency and Box and Whisker plots for the Fish Kill PI (Figure 4 and Figure 5).

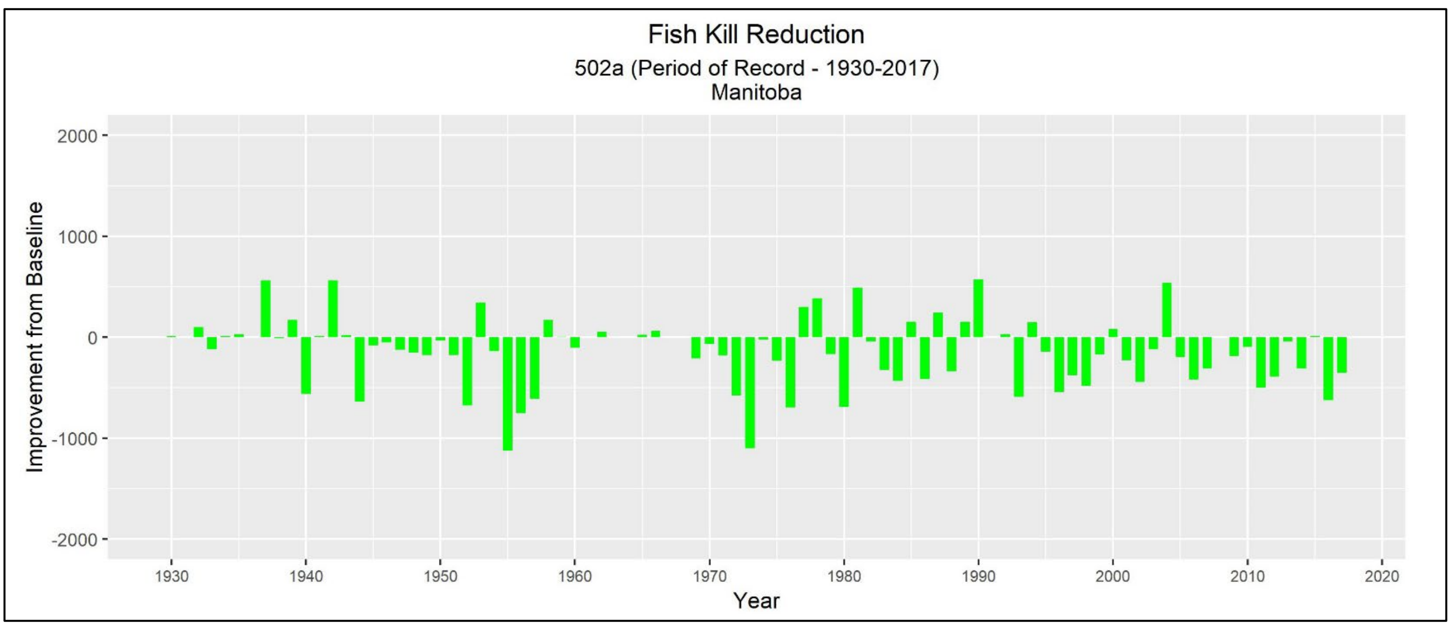


Figure 6. Example PI magnitude plot

IMPORTANT: PI Magnitude plots are not shown in report documentation for the Plan of Study but may be obtained upon request.

Notes on Evaluating Performance Indicator Results

Since PIs vary in complexity, use different units, and are computed using different flow and elevation timeseries, evaluating the PI plots generated for each reach can be challenging. Reading the Data Collection for the Analysis of Alternatives Report (DW4) along with Appendix A-8 of the PF2 report is strongly recommended prior to using the PI plots to judge the results of a modeled scenario. The following sections provide some additional insight readers can use when evaluating the PI plots presented in the Plan of Study.

Lack of Weighting

Although PIs are plotted together for each reach, they are NOT weighted relative to one another. This means the difference in *net years of change* (or length of the bar) between two PIs does not provide any information regarding the importance of their potential impact or benefit relative to one another. For example, in Figure 8, the Structural Damages, Agricultural Damages, and Historic Site Inundation PIs all show similar net years of change (approx. 70 years) favoring the baseline simulation. This does NOT mean the increase in structural and agricultural damages expected under Alternative 08a has the same magnitude of economic, social, or cultural impacts to the basin as the expected increase in flooding of historic/archaeological sites.

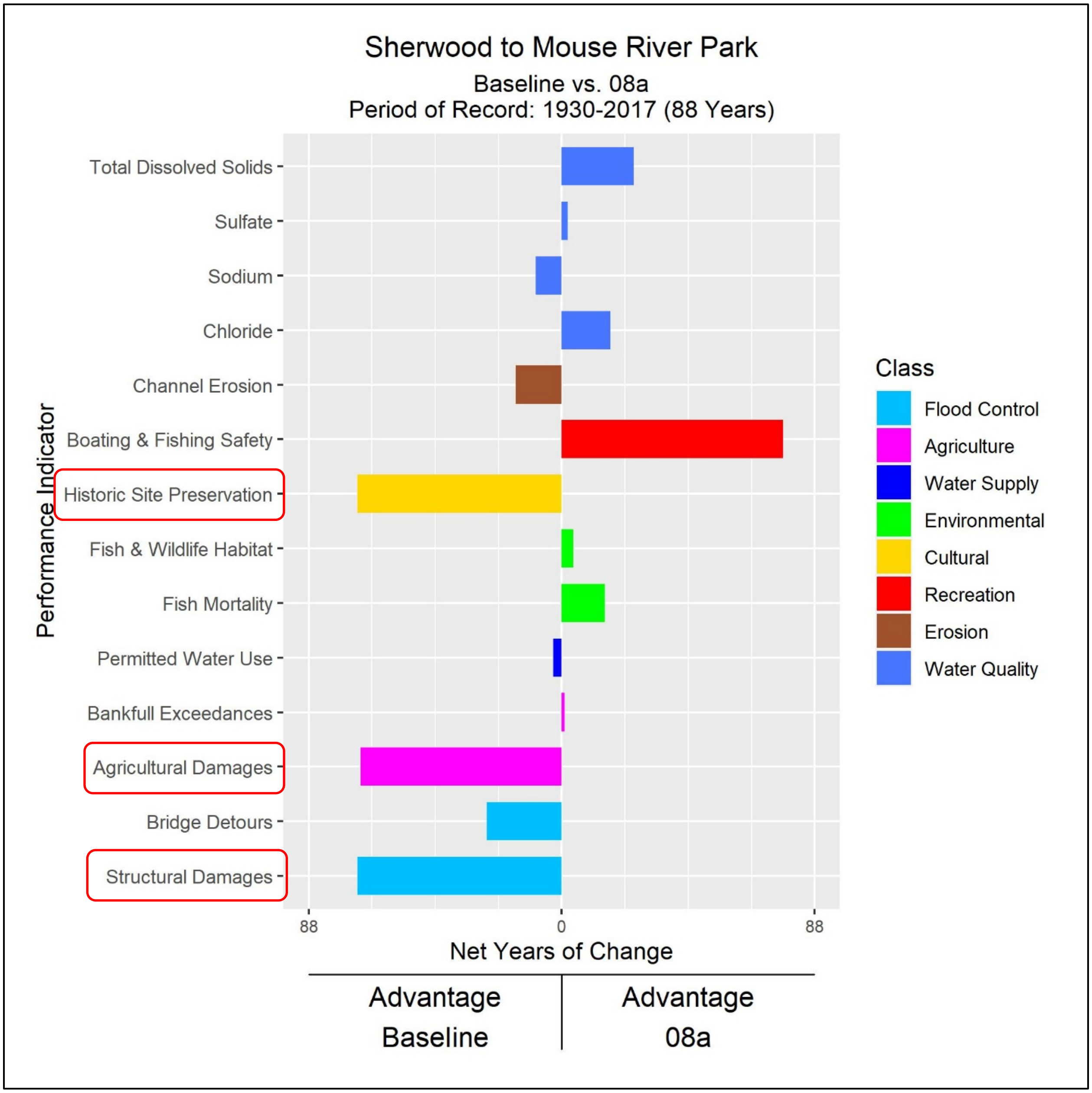


Figure 7. Example PI frequency plot showing similar net years of change for multiple PIs

Basin Variability

The Souris River basin, like any river system, has innate variability. Basin characteristics such as bankfull capacity, channel slope, and rural and urban development have a large impact on the PIs developed for each reach. It is possible there could be a positive impact to a PI in one reach and a negative impact to the same PI in another. A common example of this is Bridge Inundation. Since bridge height and the distribution of bridges varies considerably from reach to reach, it is very possible a change in river levels could inundate some bridges more and some bridges less.

Time Window

PIs were developed to provide a summary of the benefits or impacts to various study themes over varying time periods. In Phases 2, 3, and 4, PI plots show cumulative results over the entire period of record (1930-2017). This allows the reader to get a sense of the long term effects of a given change of operation without analyzing hydrographs for each year in the simulation. However, computing PIs over the entire period of record can hide potential benefits or impacts if the modeled operation only deviates from the baseline in a limited number of years. For example, summer floods are relatively rare in the Souris River basin. If an operating plan was modeled that only deviated from the baseline during summer floods, changes from baseline may not be obvious in the PI plots, since, in most years, the alternative and baseline flows would be identical. For this reason, PI plots are generated for smaller subsets of years in Phase 5. Subset are chosen based on the specific change to the operating plan being evaluated. The time window for a given PI plot is specified in the plot's title block (see Figure 8).

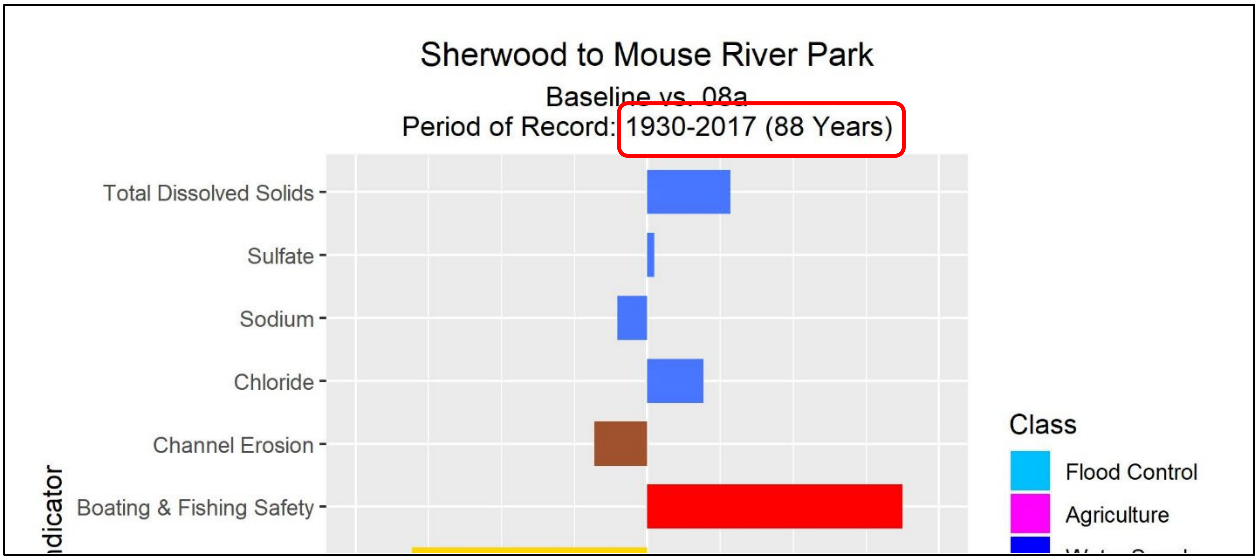


Figure 8. Time window corresponding to PI results shown

References

1. Canada and USA, 1989. Agreement between the Government of Canada and the United States for Water Supply and Flood Control in the Souris River Basin.
2. Canada and USA, 2000. Amendment to the Agreement between Canada and the United States for the Water Supply and Flood Control of the Souris River Basin. Interim Measures As Modified For Apportionment of the Souris River.
3. Department of Defense, U.S. Army Corps of Engineers, Hydrologic Engineering Center (2018). "HEC-ResSim, Reservoir System Simulation, Version 3.3," Davis, CA.
4. R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/