Supplement to the *Republican River Basin-Wide Plan*

Methodology for MHO B

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Purpose and Background

Statute requires that the *Republican River Basin-Wide Plan* include Measurable Hydrologic Objectives (MHOs) to ensure that reasonable progress is being made toward achieving the goals and objectives of the plan (*Neb. Rev. Stat.* § 46-755). Five MHOs were agreed-upon during the planning process and adopted as part of the basin-wide plan. For MHOs B and C, which are more technically complex than the basin-wide plan's other three MHOs, it was important to members of the Stakeholder Advisory Committee that more specific assessment methodology be developed by the Nebraska Department of Natural Resources (NeDNR) and Natural Resources Districts (NRDs) than was feasible during the stakeholder process. NeDNR and the NRDs committed to developing assessment procedures before the basin-wide plan's first annual meeting, to be appended to the basin-wide plan upon completion. This document describes the assessment procedures for MHO B. MHO B is shown in Figure 1, along with contextual information about where it fits within the plan's goals, objectives, and action items.

Goal 1. Maintain Nebraska's compliance with the Republican River Compact and applicable state laws

Objective 1.3. Assess progress toward meeting the goals and objectives of the Plan, and share the results of this assessment with the Public and the Nebraska Legislature

Action Item 1.3.2. Evaluate progress toward each of the Plan's measurable hydrologic objectives at the intermediate dates specified in the Plan for each one

MHO B. Limit groundwater depletions to streamflow to a relatively constant level over the long-term both across the basin as a whole and within each NRD

Figure 1. MHO B is one of the *Republican River Basin-Wide Plan*'s Measurable Hydrologic Objectives (MHOs). The MHOs are part of Action Item 1.3.2, Objective 1.3, and Goal 1.

Introduction

MHO B is to "Limit groundwater depletions to streamflow to a relatively constant level over the long-term both across the basin as a whole and within each NRD." Developing methodology for MHO B requires defining and setting parameters for what the terms in MHO B mean and how they will be evaluated.

Groundwater Depletions to Streamflow

Baseflow is the water which flows between the stream and the aquifer. When groundwater is used, less baseflow flows from the aquifer to the stream than would have flowed to the stream had groundwater not been used. **"Groundwater depletions to streamflow"** are the difference in baseflow with and without groundwater use, and they are estimated using a groundwater model. For this procedure, groundwater uses within each NRD are evaluated with the Republican River Compact Administration (RRCA) model, using a modified 32-run procedure that isolates impacts to streamflow due to pumping within each NRD. Groundwater data that have been exchanged between the NRDs and NeDNR and remaining model data that have been approved by the RRCA are to be used in this analysis, unless there is a delay in RRCA approval of data for any year. In the event of a delay in data approval by the RRCA, then the most recent provisional data are used instead.

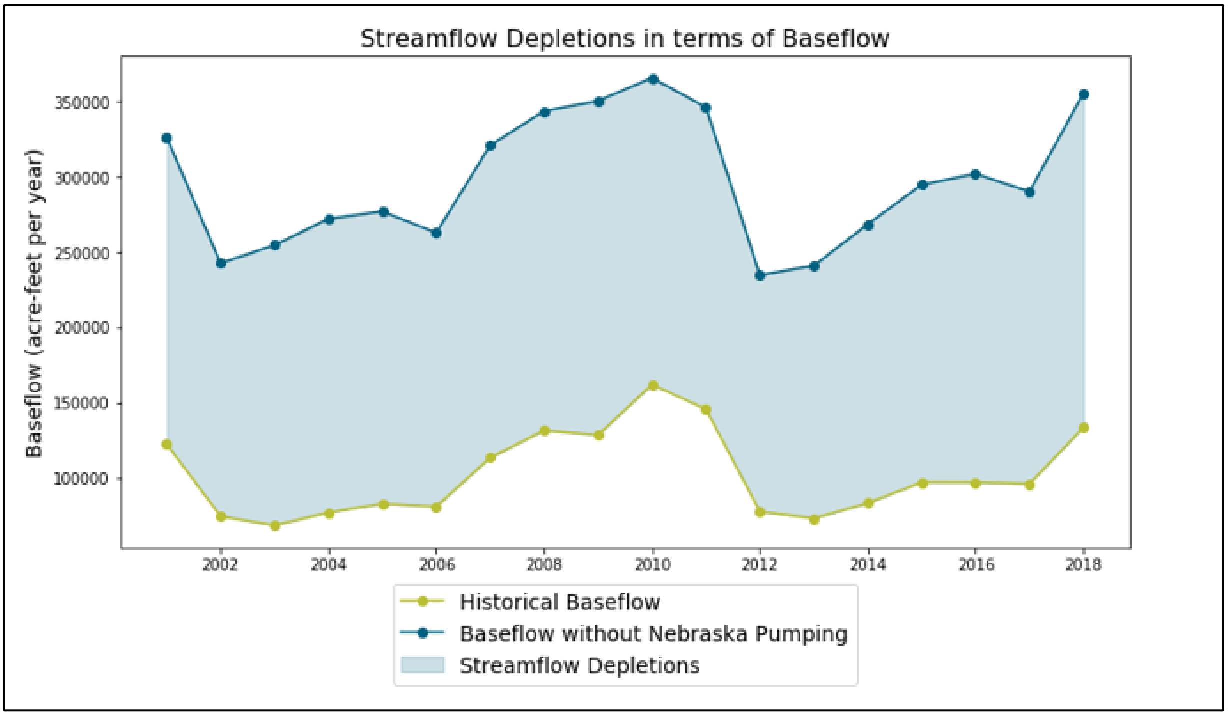

Figure 2. Illustration of groundwater depletions to baseflow. Depletions are calculated using a groundwater model as the difference between simulated baseflow with and without groundwater pumping using a groundwater model.

Relatively Constant over the Long-Term

During basin-wide plan development, the intent discussed among the parties was that MHO B was to be consistent with the requirements of the existing Integrated Management Plans (IMPs) for the Republican River Basin NRDs; therefore, the time periods selected for the analysis of **"relatively constant over the long-term"** differ among the four NRDs due to differences in the requirements of the IMPs for each NRD. For the Upper Republican, Middle Republican, and Lower Republican NRDs, the analysis of "relatively constant over the long-term" includes depletions during all years beginning with 2008. The 2008 start date for these three NRDs corresponds with the adoption of their second generation IMPs, which introduced the compliance standard requiring maintenance of groundwater depletions to streamflow at a relatively constant level over time for those NRDs. For Tri-Basin NRD, the analysis includes depletions during all years beginning with 2013. Using a 2013 start date for Tri-Basin NRD will allow the MHO B assessment to maintain consistency with the current *hydrologically balanced* test from the IMP for the Republican River Basin portion of Tri-Basin NRD. The evaluation of whether groundwater depletions to streamflow have been relatively constant over these time periods is based on a statistical trend analysis, described below.

Statistical Trend Analysis

Groundwater depletions to streamflow from each NRD[1] are assessed for being relatively constant over the long-term by the trend analysis statistics discussed in this section. These statistics are applied to each of the following:

- Unmodified groundwater depletions to streamflow
- Groundwater depletions to streamflow decorrelated for precipitation
- Groundwater depletions to streamflow decorrelated for undepleted baseflow, and
- Groundwater depletions to streamflow decorrelated for Virgin Water Supply.

The temporal trends in groundwater depletions decorrelated for precipitation, undepleted baseflow, and Virgin Water supply provide additional information over the trend in unmodified groundwater depletions but should not be used in an additive manner as the variables are not independent. The statistical test used is described in the next section. Decorrelation for precipitation, undepleted baseflow, and Virgin Water Supply is described beginning on page 5.

Mann-Kendall Trend Test

The trend test used for this analysis is the **Mann-Kendall Trend Test**[2,3] (MK test). The MK test is a non-parametric test for monotonic linear or non-linear trends. "Non-parametric" means that no assumptions need to be made about the distributions of the depletions data. "Monotonic" means that the trends detected will be consistently increasing or decreasing. "Linear or non-linear" means that the test will detect changes that are well represented by a line, curve, or step change. In addition to these features of the MK test, it has the advantage of not being dependent on the magnitude of the depletions, i.e., the presence of a trend will not be skewed by the magnitude of any extreme depletions values. A limitation of the MK test is that, as with many other statistical trend tests, statistical confidence increases with size of the dataset; however, the MK test is one of the few statistical trend tests which is recommended for use on small datasets like those being analyzed here.

The MK test is calculated by pairwise comparison of each annual depletion value to each previous annual depletion value. If the later depletion is greater than the earlier depletion, 1 is added to the MK test statistic. If the later depletion is less than the earlier depletion, 1 is subtracted from the MK test value. If the pair of depletions are the same, the MK test value does not change. After comparing all pairs, if the MK test value is a large positive number, then an

[1] For Tri-Basin NRD, groundwater depletions to streamflow are evaluated as the net of groundwater depletions to streamflow and the mound credit, for consistency with the requirements of the Tri-Basin NRD IMP.

[2] *Statistical Methods in Water Resources* by D.R. Helsel and R.M. Hirsch, chapter 12 'Trend Analysis'. Book 4 in the Hydrologic Analysis and Interpretation Series by USGS (https://pubs.usgs.gov/twri/twri4a3/twri4a3.pdf).

[3] Pacific Northwest National Laboratory Visual Sample Plan (VSP) 6.0 documentation, Mann-Kendall Test For Monotonic Trend (https://vsp.pnnl.gov/help/Vsample/Design_Trend_Mann_Kendall.htm)

upward trend in depletions is shown. If the MK test value is a large negative number, then a downward trend in depletions is shown. If the MK test value is near 0, then no trend is shown.

The significance of the MK test value depends on the number of years in the test. If the number of years is less than or equal to 10, then the MK test value is compared directly to a table of probabilities.[4] If the number of years is greater than 10, then the variance of the MK test value is calculated as a function of the number years and the number of identical depletion values. The MK test statistic is then calculated as a function of the MK test value and the variance of the MK test value. The MK test statistic is then compared to the corresponding Z value for the desired significance.[5] For the MHO B assessment, a p-value of 0.05 is used as the threshold to determine significance. Example MK test results are shown in Figure 3.

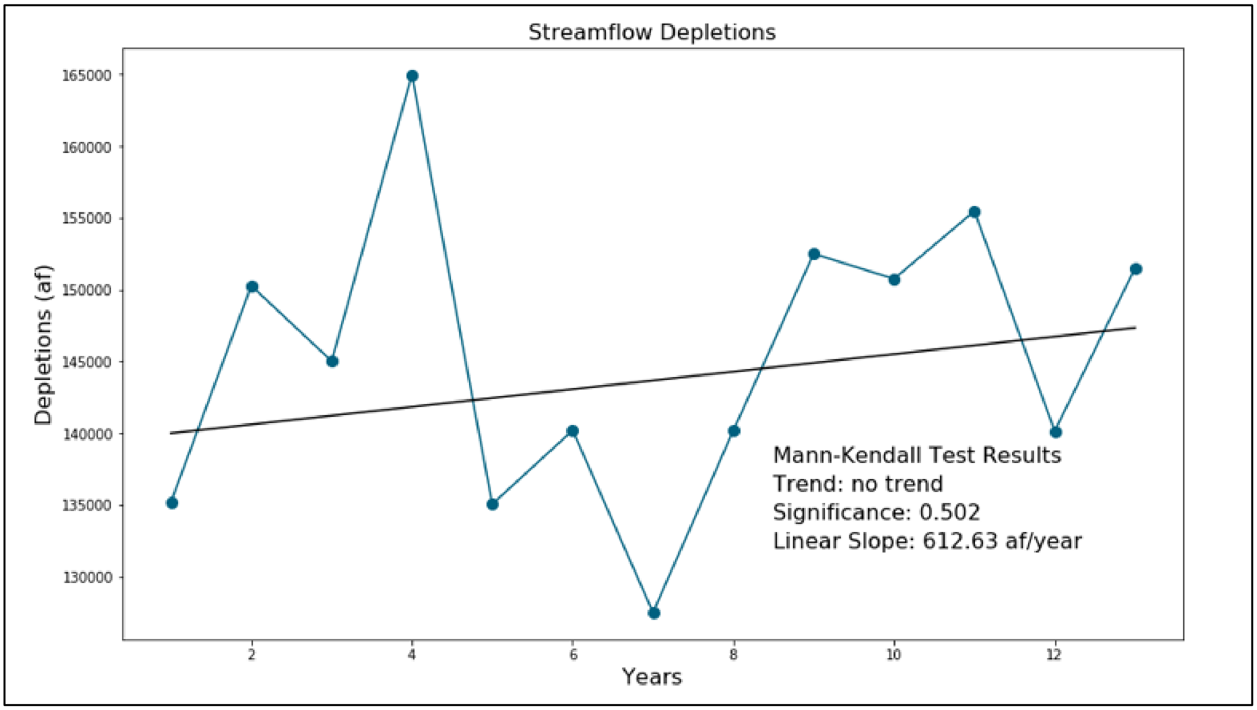

Figure 3. Example Mann-Kendall test results using made-up data.

Decorrelation

The objective of this analysis is to identify a trend in depletions attributable to groundwater pumping. Annual depletions are also affected by factors outside of the management of the NRDs, such as weather, climate, and hydrologic conditions. If only unmodified groundwater depletions are evaluated, then trends in these ambient conditions over the time period of this analysis could result in the analysis either identifying a trend in depletions that is not directly

[4] Pacific Northwest National Laboratory Visual Sample Plan (VSP) 6.0 documentation, Mann-Kendall Test For Monotonic Trend (https://vsp.pnnl.gov/help/Vsample/Design_Trend_Mann_Kendall.htm)

[5] Pacific Northwest National Laboratory Visual Sample Plan (VSP) 6.0 documentation, Mann-Kendall Test For Monotonic Trend (https://vsp.pnnl.gov/help/Vsample/Design_Trend_Mann_Kendall.htm)

attributable to groundwater pumping, or failing to identify an existing trend that is directly attributable to groundwater pumping or other land use factors within the control of water users.

For these reasons, we have included associations with non-pumping variables on depletions and attempted to remove the correlative effect of the variable on NRD groundwater depletions to streamflow. For this analysis, annual NRD groundwater depletions to streamflow are each linearly decorrelated for annual precipitation, annual undepleted baseflow, and Virgin Water Supply separately. An ordinary least squares linear fit of depletions to each of the variables is performed. The resulting residuals between the observed depletions and the fit are used as the decorrelated depletions for each variable.

Annual precipitation has been found to be greatly correlated to annual depletions. The correlation relationship is multilayered and interconnected; there are both direct influences, for example through precipitation recharge, and indirect, such as its influence on crop irrigation requirements or groundwater pumping. Gridded annual precipitation is collected for the RRCA groundwater model pre-processor input files. Precipitation from 34 locations is obtained from the National Climatic Data Center TD3220 Cooperative Summary of the Month dataset which is interpolated to the model grid. Model-wide total precipitation appears to be a sufficient indicator of hydrology, thus, the model-wide gridded precipitation values are totaled for this analysis (Figure 4).

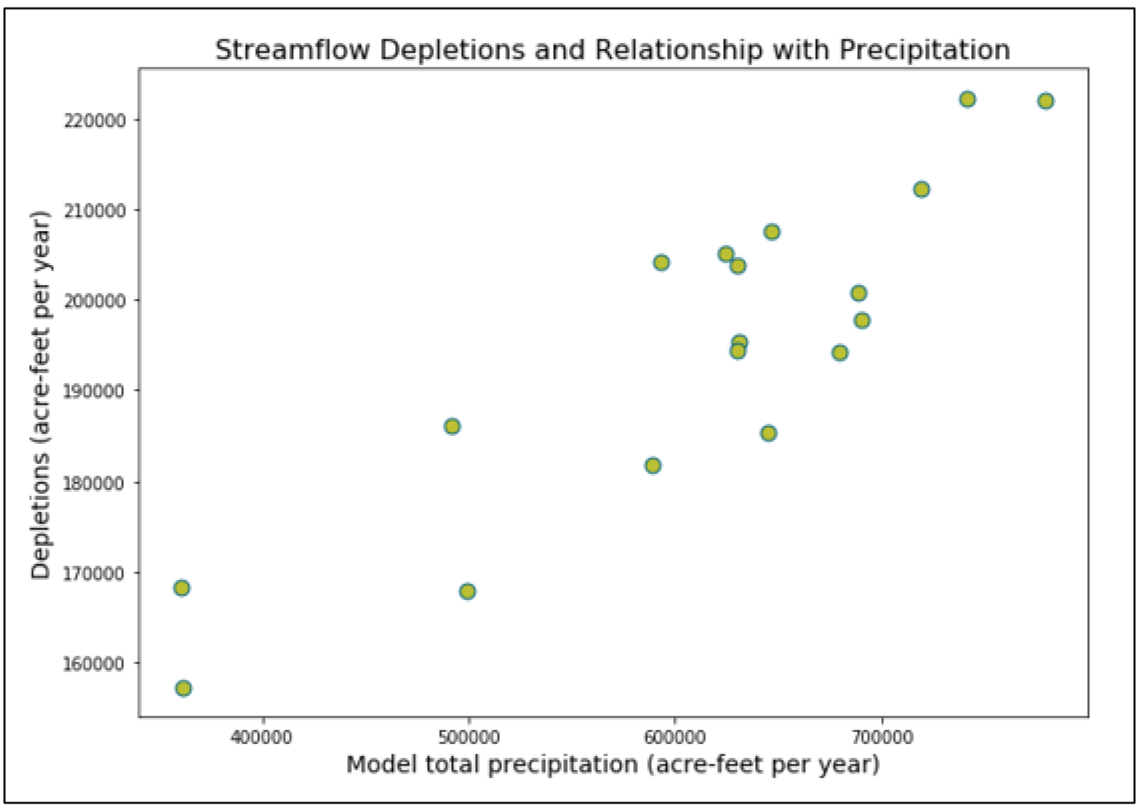

Figure 4. Relationship between Nebraska streamflow depletions and RRCA model-wide precipitation, 2008–2018.

Annual undepleted baseflow sets the annual limit of baseflow available for depletions. Conceptually it is the closest variable to the dependent variable and is mathematically most similar, incorporating nearly the same calculation assumptions and uncertainties. Annual undepleted baseflow is estimated from the RRCA groundwater model run with Nebraska pumping turned off (not included) as executed for the RRCA 5-run procedure for determining each depletions attributable to pumping from each state. The baseflows to the Republican River and major tributaries are used in both this analysis and the depletions quantifications. The use of the exchange between the major reservoirs and the aquifer is suggested to be considered for further assessment in this analysis (Figure 5).

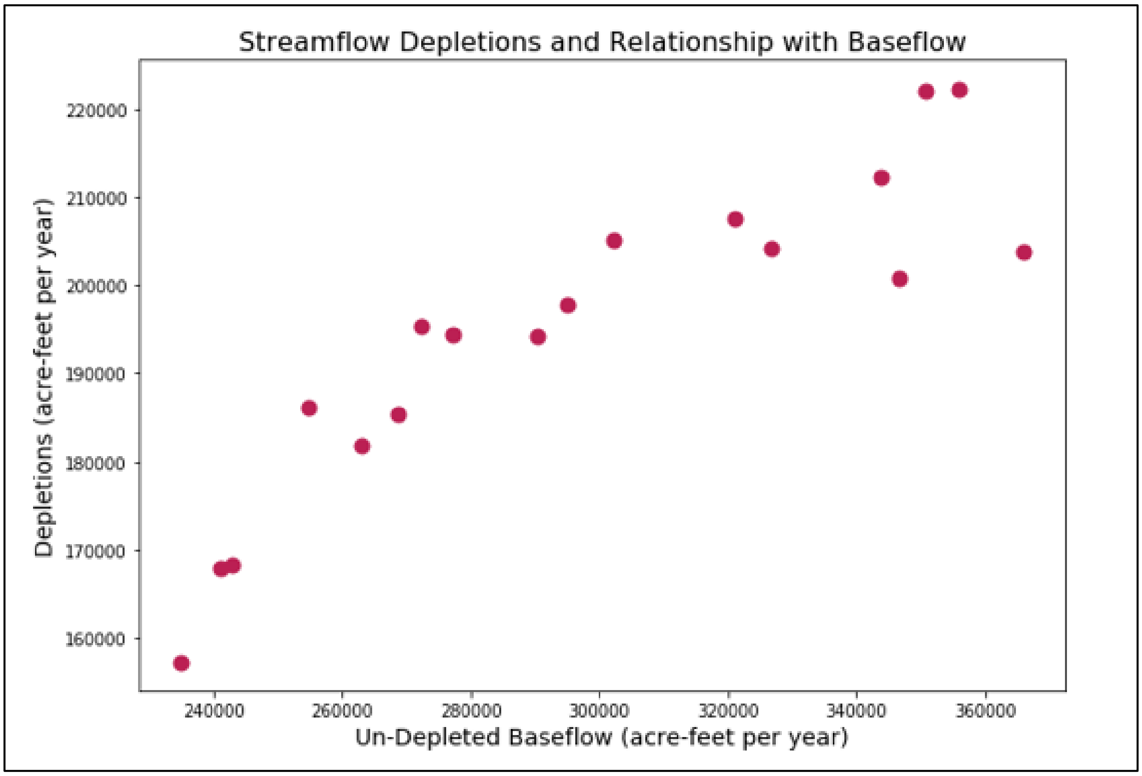

Figure 5. Relationship between Nebraska streamflow depletions and undepleted baseflow, 2008–2018.

Virgin Water Supply is defined in the FSS/Accounting Procedures as the streamflows within the Republican Basin undepleted by the activities of man, excluding water supply imported by a State from outside the basin resulting from activities of man. Virgin Water Supply is calculated in the RRCA Accounting Procedures essentially by summing annual streamflow, computed consumptive use of streamflow resulting from select activities of man, and the change in reservoir storage less the imported water. Groundwater depletions to streamflow are a component of consumptive use, therefore groundwater depletions are a portion of the Virgin Water Supply. Virgin Water Supply is a broad indicator of hydrology incorporating both baseflow and other sources of streamflow including precipitation (Figure 6).

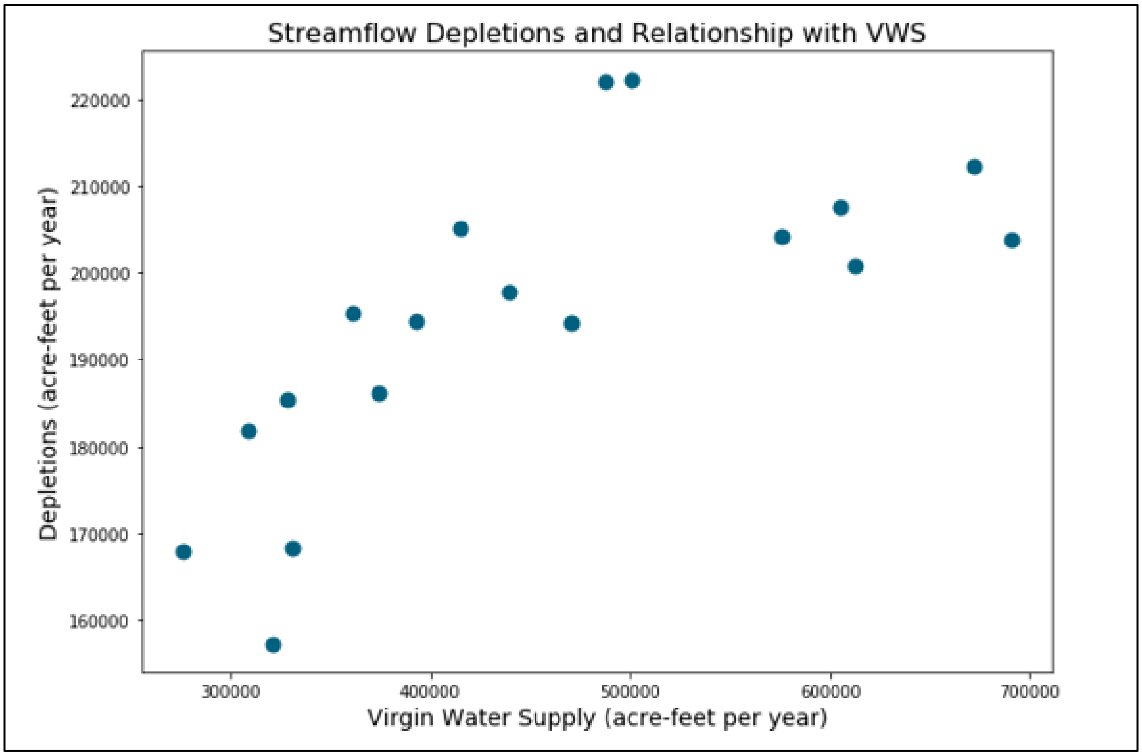

Figure 6. Relationship between Nebraska streamflow depletions and Virgin Water Supply, 2008–2018.

For this statistical trend analysis, the MK test (page 4) is applied to unmodified groundwater depletions data for the analysis period and to the same data decorrelated for each of the factors described above. Evaluation of all four MK test results will determine whether management actions are needed as a result of MHO B, as described beginning on page 9.

Future Work

We are continuing to assess the influences of weather, hydrology, and other outside factors on NRD depletions to streamflow in order to capture a trend in depletions that is only representative of factors within NRD control. Precipitation, undepleted baseflow, and Virgin Water Supply do not have the same correlation to each NRD's depletions, e.g., over the period analyzed, precipitation had a stronger correlation to upstream NRD depletions, while baseflow had a stronger correlation to downstream NRD depletions. Additionally, the influences of these variables on depletions may not be best removed through a linear fit, which requires additional assessment. We are also continuing to assess if there is a time period over which weather and outside factors could be considered relatively constant, and therefore their effects on depletions to streamflow would be relatively constant.

Assessment of Whether Management Actions Are Needed

As described in the basin-wide plan, if NeDNR and the NRDs determine that an MHO is not being achieved, they will determine what actions to take to achieve that MHO in the future. The process described below summarizes the decision framework that is followed to determine whether an NRD needs to take management actions as a result of this analysis of MHO B. The full decision framework is shown in Figure 7.

There are three phases in the decision framework for MHO B: the screening phase, the discussion phase, and management actions. Figure 7 includes details about each phase, including its purpose and timeframe, the decisions that are made during each phase, and what is reported as a result of it.

The screening phase takes place as part of each five-year technical analysis for the basin-wide plan. During the screening phase, NeDNR and the NRDs determine whether or not all four MK tests for an NRD agree either that there has or has not been a statistically significant increase in groundwater depletions to streamflow. Depending on the results of the MK tests, the screening phase could result in one of three determinations for each NRD: no further investigation or management actions are needed because MHO B is being achieved, that management actions are needed because MHO B is not being achieved, or that further consideration of the analysis results is needed due to conflicting results among the four MK tests.

The discussion takes place within approximately one year of when the five-year technical analysis results are presented. During this phase, NeDNR and the NRDs discuss the results of all four MK tests and other relevant information available and decide whether there is enough evidence to conclude that streamflow depletions have increased and that management actions are needed at this time. If management actions are needed, the discussion phase results in identification of what management actions the NRD will take in order to be able to meet MHO B in the future. If management actions are not needed at this time, NeDNR and the NRD still discuss ideas for potential management actions that could be taken if needed following the next five-year technical analysis.

If either the screening phase or the discussion phase identifies that an NRD needs to take management actions because MHO B is not being achieved, the NRD will begin the selected management action or actions no later than the annual meeting that takes place two years after presentation of the five-year technical analysis.

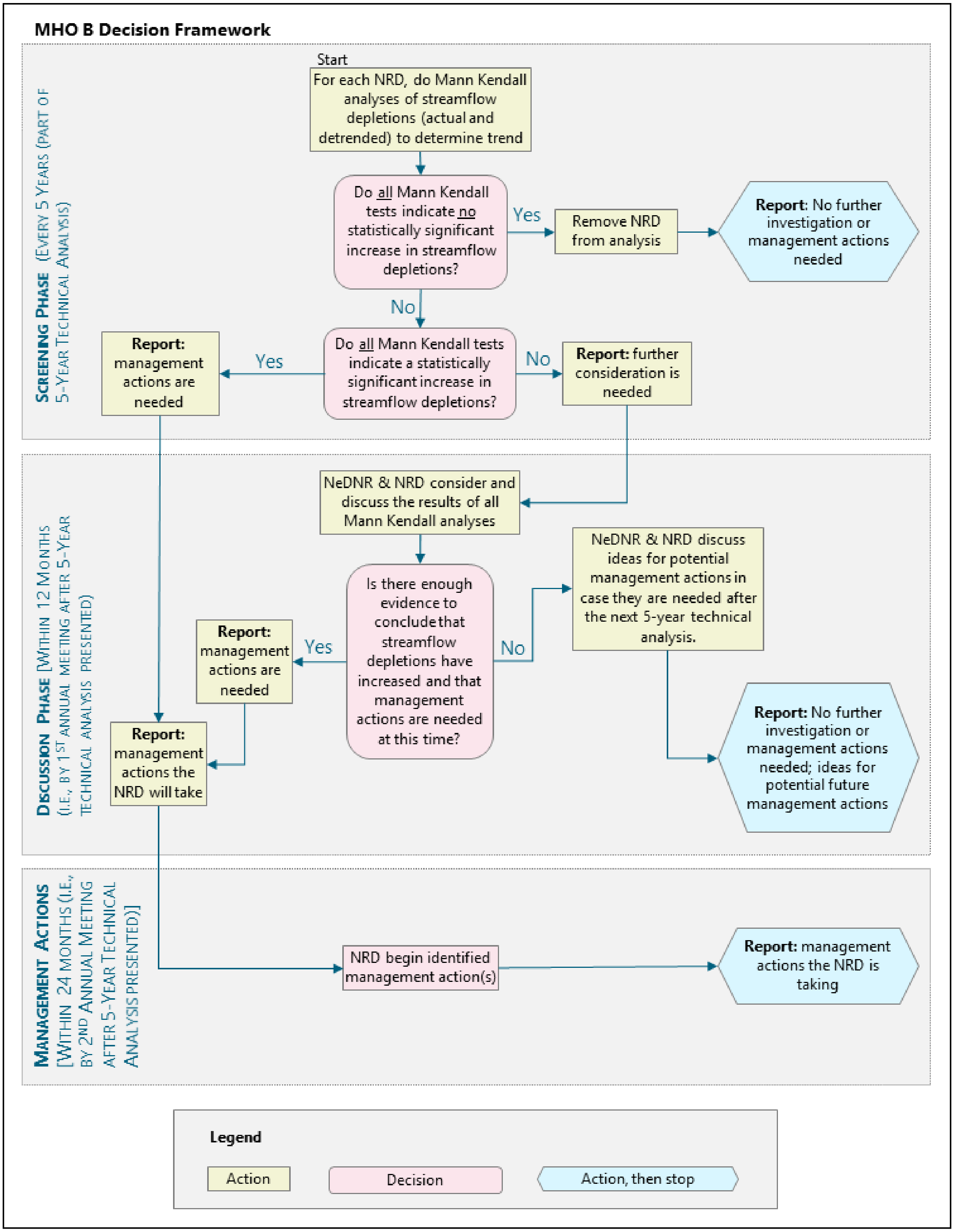

Figure 7. Decision framework for MHO B, outlining details about each phase of the analysis, including its purpose and timeframe, the decisions that are made during each phase, and what is reported as a result of it.