TO: THE NEBRASKA DEPARTMENT OF NATURAL RESOURCES

FROM: EXECUTIVE DIRECTOR'S OFFICE OF THE PLATTE RIVER RECOVERY IMPLEMENTATION PROGRAM

SUBJECT: ISSUES USING THE COHYST CYCLE WELL DATA TO DEVELOP UNIT RESPONSE FUNCTIONS FOR PROGRAM WAP PROJECTS

DATE: MARCH 20, 2020

I. INTRODUCTION

The staff of the Executive Director's Office (EDO) of the Platte River Recovery Program (PRRIP or the Program) completed a technical review of a portion of the data generated by the Nebraska Department of Natural Resources (DNR) using their cycle well program in combination with the groundwater model portion of the COHYST integrated model. This review was done with the intent of developing a unit response function from the cycle well analysis data for the scoring evaluations for several of the Program's Water Action Plan groundwater recharge projects. The EDO staff believes the cycle well data is not suitable for the develop of unit response functions and decided to develop the unit response functions using an analytical solution.

The EDO staff were not able to develop unit response functions from the cycle well data because of oscillations in the monthly stream response values. The cycle well unit response functions bounce from positive to negative values and the magnitude of most of the oscillations exceeded the expected maximum stream response estimated from an analytical solution. The EDO believes the monthly oscillations in the cycle well data may be the result of the relatively small pumping impulse used in the cycle well analysis, or they may reflect some non-linear behavior of the model. In either case, the small pumping impulse appears to get lost in these oscillations (the model noise).

II. BACKGROUND

The DNR performed the cycle well analysis by conducting a series of runs of the MODFLOW groundwater component of the COHYST integrated model. In each run, a pumping well was added to a single cell of the model and the resulting change in stream flow was compared to a baseline model run. Separate model runs were made for each model cell to determine the impact of a pumping impulse on stream flow from every model cell.

The pumping impulse used for the cycle well analysis was 10,000 ft^3/day, equivalent to 0.12 cubic feet per second (cfs), 0.23 acre feet per day (AF/day), or 51.9 gallons per minute. For comparison, most agricultural wells in the Platte Valley pump around 800-1,000 gallons per minute. This impulse was applied to each model cell with dimensions of 0.5 mile by 0.5 mile or 160 acres. The corresponding depth of the applied pumping impulse was 0.0014 ft per day (0.017 inches per day) or 0.043 ft per month (0.5 inches per month). To place this in context, the difference between total inflows and outflows in the model, a metric MODFLOW uses to estimate the magnitude of the error in the model's solution for each timestep, fell between

100,000-200,000 ft^3/day for most timesteps of the COHYST groundwater model[1]. The 10,000 ft^3/day pumping impulse used in the cycle well analysis was 5-10% of the model's discrepancy or a full order of magnitude smaller.

While the pumping impulse is small when evaluated on a monthly basis, evaluating the stream depletion resulting from continuous pumping over the entire 50-year model simulation can show a distinct relationship between pumping a model cell and stream depletion. The DNR used the results of the cycle well analysis in this fashion to evaluate the impact of pumping on stream depletion on a cumulative basis over the entire model run. The DNR calculated stream depletion factors (SDF, a unitless value[2]) from the cycle well data by dividing the change in cumulative stream depletion by the cumulative pumping, as shown in **Figure 1**, which was provided to the EDO by the DNR. The example provided in **Figure 1** is hypothetical. An example of the resulting SDF values is shown in **Figure 2** below based on actual data.

[1] Determined from the *.LST output file from MODFLOW

[2] The EDO notes that the SDF term used by the DNR differs from the SDF definition commonly found in groundwater literature and originally defined by Jenkins in his 1968 paper "Techniques for computing rate and volume of stream depletion of wells." The SDF value is defined by Jenkins as the elapsed time over which cumulative streamflow depletion volume is equal to 28 percent of the cumulative withdrawal volume. Jenkins definition applies to both streamflow depletions resulting from pumping and streamflow accretions resulting from recharge. It is calculated as

$$SDF=d^2/D$$

where d is the distance between the pumped well and the stream and D is the hydraulic diffusivity of the aquifer equal to T/S where T is transmissivity and S is the storage coefficient. The Jenkins SDF has units of time. This differs from the unitless SDF value calculated by the DNR as the cumulative stream response divided by the cumulative pumping.

Calculation of SDF

$$SDF = \frac{Q_s' - Q_s}{Q_w}$$

Q_s' is the cumulative stream leakage after the new well

Q_s is the cumulative stream leakage of the baseline

Q_w is the total pumping from the new well

Stress Period	Pumping	Stream Leakage	Cumulative Pumping	Cumulative Stream Leakage	Calculation	Stream Depletion Factor
1	1000	0	1000	0	(0-0)/1000=	0.000
2	1000	5	2000	5	(5-0)/2000=	0.003
3	1000	10	3000	15	(15-0)/3000=	0.005
4	1000	20	4000	35	(35-0)/4000=	0.009
5	1000	40	5000	75	(75-0)/5000=	0.015
6	1000	80	6000	155	(155-0)/6000=	0.026
7	1000	130	7000	285	(285-0)/7000=	0.041
8	1000	190	8000	475	(475-0)/8000=	0.059
9	1000	250	9000	725	(725-0)/9000=	0.081
10	1000	310	10000	1035	(1035-0)/10000=	0.104

Figure 1. Description of the SDF calculations from the cycle well data provided by the DNR

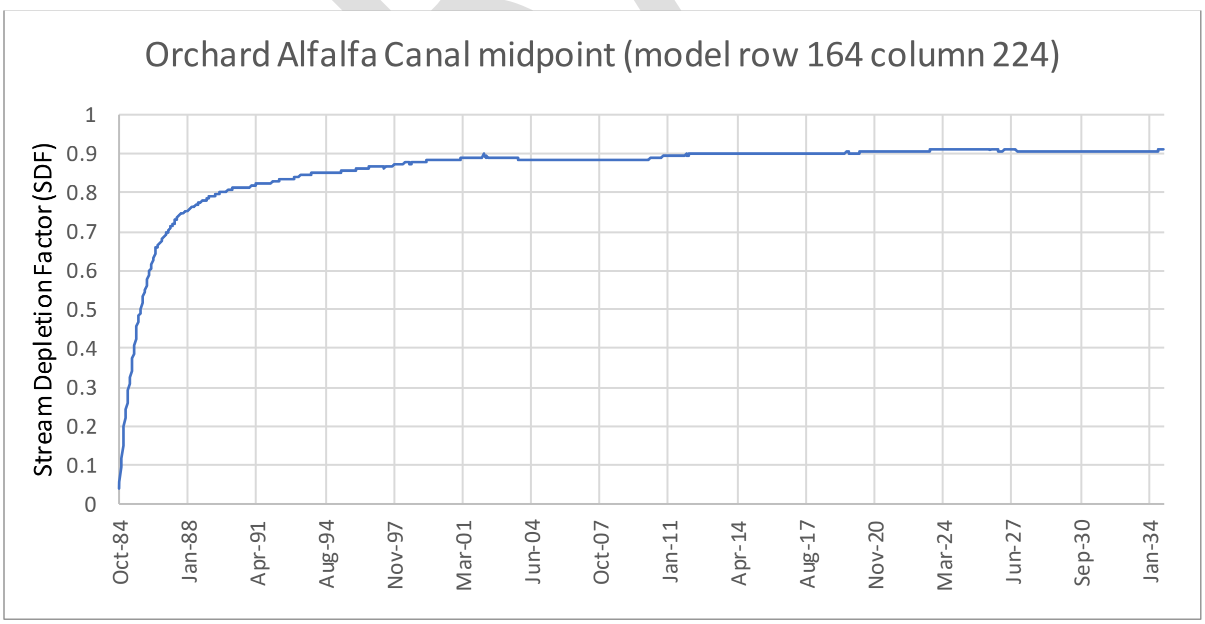

Figure 2. Cumulative stream depletion from the cycle well data (derived from the cycle well data provided by the DNR)

While both the DNR and unit response function methods are used to show the stream depletions resulting from a pumping well, the SDF values developed by the DNR differ from unit response functions the EDO needs to evaluate its recharge projects in several ways. Unit response functions determine the stream depletions (the stream's response) from pumping for a short period of time (in this case, one month) while the DNR's SDF values look at the impact of cumulative pumping over the model's duration of 50 years. Unit response functions normalize the monthly stream response by the pumping rate, thus giving the stream response for one "unit" of pumping. Unit response functions typically show an initial increase in the stream's response to pumping followed by a decrease in response with a long tail that asymptotically approaches zero over an extended period of time, as seen in the example URF for a location on the Gothenburg Canal in **Figure 3** below. Unit response functions can be used to track stream accretions resulting from a single recharge event as well as stream depletions resulting from a pumping event by simply reversing the sign of the resultant impact on the stream. For example, a unit response showing stream depletions (a negative stream response) resulting from 100 AF of pumping can be used to calculate the stream accretions (positive stream response) resulting from 100 AF of recharge in the same location. The EDO is seeking to account for the monthly returns resulting from a monthly recharge event for its scoring process and is using unit response functions to accomplish this.

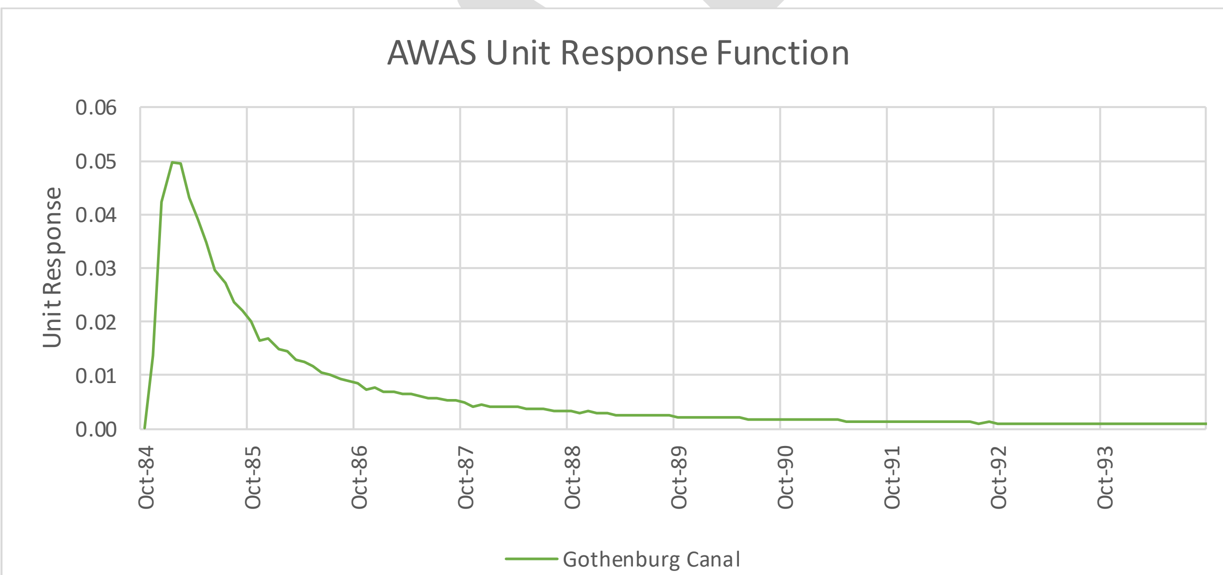

Figure 3. Unit response function for a location on the Gothenburg Canal developed using AWAS

III. ANALYSIS AND RESULTS

A. COHYST Cycle Well Data URF Attempt

The EDO originally sought to develop unit response functions from the cycle well results. The DNR provided the EDO with the SDF values obtained from the cycle well analysis for each cell in the model and every time step. The EDO reversed the calculations shown in **Figure 1** to arrive at the monthly results of the cycle well data and then developed unit response functions from the data using the following steps, with an example shown in **Table 1**:

1. Start with the end of month SDF value for a given model cell of interest.
2. Multiply the end of month SDF values by the cumulative pumping volume to get the cumulative end of month stream depletion (in ft^3). The cumulative monthly stream depletions result from continuous pumping during the entire model run.
3. Determine monthly depletions by calculating the month-to-month change in cumulative depletions. This provides the end of month stream depletion from continuous pumping during the entire model run (in ft^3).
4. Lag the end of month stream depletion (resulting from continuous pumping) by one month and subtract the lagged values from the original end of month stream depletion to get the stream depletion from a single pumping event in month 1 (in ft^3). This analogous to adding a continuous recharge pulse beginning in month two of the model run. It is an application of the principle of superposition[3].
5. Divide the stream depletion from a single pumping event by the monthly pumping volume to get the unit response function. This value shows the dimensionless response of the stream to a single pumping event.

[3] Reilly TE, Franke OL, Bennett GD. The Principle of Superposition and its Application in Ground-Water Hydraulics. USGS Open-File Report 84-459

Table 1. Unit response function development example (from DNR data)

Orchard Alfalfa canal midpoint (COHYST Model Cell: Row 164, Column 224)						
Date	Oct-84	Nov-84	Dec-84	Jan-85	Feb-85	Mar-85
Step 1: start with end of month values						
End of month values	0.05	0.12	0.17	0.22	0.26	0.29
Step 2. SDF multiplied by the cumulative pumping volume:						
Cumulative pumping volume (ft^3):	310,000	610,000	920,000	1,230,000	1,510,000	1,820,000
Multiply end of month SDF by cumulative pumping (ft^3):	16,895	70,748	160,181	273,171	388,402	534,716
Step 3. Monthly depletions: subtract monthly change in cumulative depletions						
Calculate monthly change in cumulative depletions (ft^3):	16,895	53,853	89,433	112,990	115,232	146,314
Step 4. Response from one month of pumping: lag and subtract monthly depletions						
Lag monthly depletions by one month (ft^3):		16,895	53,853	89,433	112,990	115,232
Subtract lagged monthly depletions (ft^3):	16,895	36,958	35,581	23,556	2,242	31,082
Step 5. Unit Response Function: monthly response lagged & subtracted						
Monthly pumping volume (ft^3):	310,000	300,000	310,000	310,000	280,000	310,000
Unit stream response (unitless):	0.05	0.12	0.11	0.08	0.01	0.10

The resulting unit response functions, shown in **Figure 4**, developed from the cycle well data do not exhibit the expected behavior shown by the example in **Figure 3** but instead oscillate between positive and negative values. **Figure 5** compares the AWAS unit response function for a location on the Gothenburg Canal shown in **Figure 3** to the cycle well unit response function for the same location.

Several model cells were evaluated to check that the oscillations were not unique to a single model cell, including cells on the Central Platte Natural Resource District (CPNRD) and the Nebraska Public Power District (NPPD) canals. All five of the locations showed a similar pattern of oscillations and **Table 2** shows the model row and column locations for each cell evaluated.

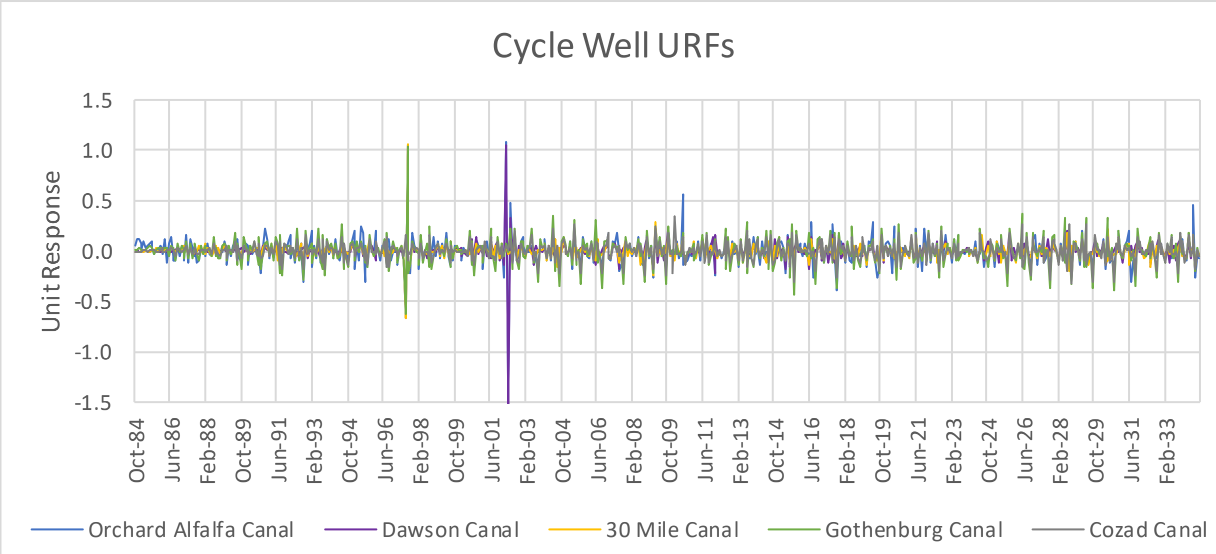

Figure 4. Unit response functions developed from the cycle well data

Table 2. Cells in the COHYST groundwater model evaluated

Canal	Distance to River, ft	Distance to River, mi	Model Row	Model Column	Location
30 Mile Canal	14,300	2.71	158	206	Midpoint of main canal
Cozad Canal	17,650	3.34	152	222	Midpoint
Orchard Alfalfa Canal	5,300	1.00	164	224	Midpoint
Dawson Canal	23,800	4.51	159	241	Cozad canal termination
Gothenburg Canal	7,000	1.33	5	208	Sharp turn N.E. (10,250 ft from canal headgate)

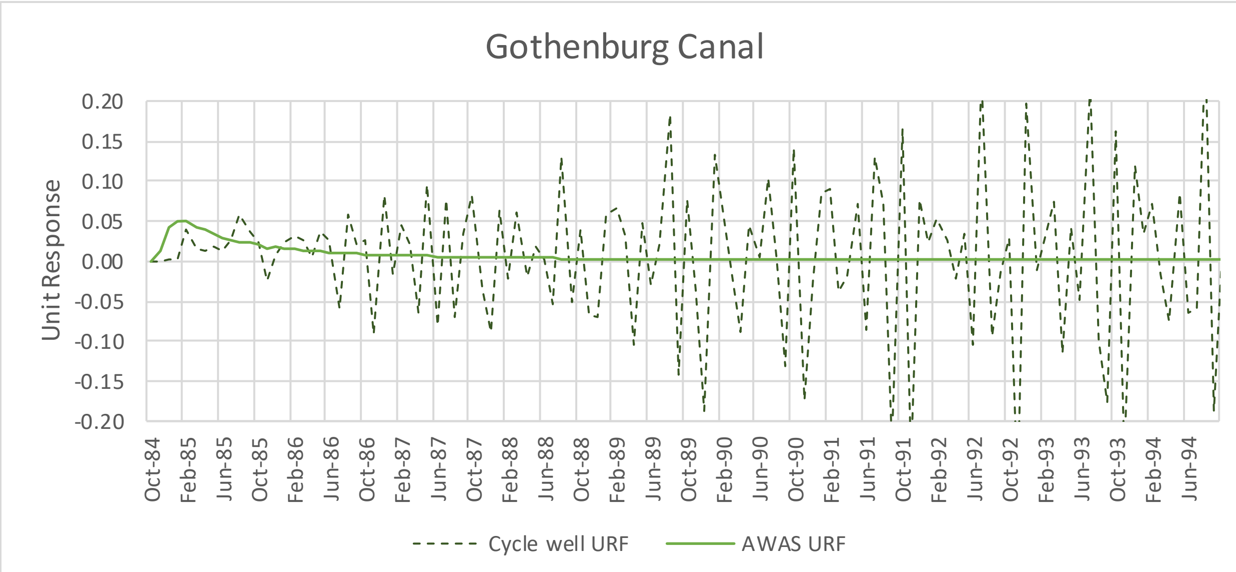

Figure 5. Comparison of the AWAS and cycle well URF for the first ten years at the midpoint of the 30 Mile Canal.

The negative values seen in **Figures 4 and 5** do not make sense in physical reality as they would indicate the stream gaining water as a result of the pumping impulse; pumping inherently represents a withdrawal from the (alluvial) aquifer and by hydrologic connection, the stream itself. The presence of negative values in this context represents the opposite response and is a strong indication that the model is not able to track the pumping impulse. The impulse appears to get lost in the background fluctuations of the model's inputs and aquifer head. The amounts of recharge, pumping, and evapotranspiration vary with each timestep and the pumping impulse may be too small relative to these fluctuations.

Another factor contributing to the oscillations seen in the unit response function could be that the pumping impulse is smaller than the model's error term. As the MODFLOW software solves the fundamental groundwater equation[4], the user specifies the closure criteria which indicates the amount of acceptable error for any given model run. For a large regional model such as the COHYST groundwater model, the error term might be relatively large when compared to model inputs at a local level, such as a single model cell. As MODFLOW solves the equations for groundwater flow for each timestep, the error term might oscillate between positive and negative values. A sufficiently large pumping impulse is needed to exceed the magnitude of the model's noise when the pumping impulse's impact on the stream is evaluated.

Not only do the unit response functions developed from the cycle well data have positive to negative oscillations, the magnitude of the oscillations is greater than expected. By definition, a unit response function does not exceed a value of 1 as all the values are normalized by the pumping impulse. The stream response resulting from the pumping impulse does not exceed the magnitude of the impulse. The maximum monthly values of the unit response functions derived

[4] MODFLOW-2005: USGS Three-Dimensional Finite-Difference Ground-Water Model. USGS Techniques and Methods 6-A16. Harbaugh, 2005.

from the DNR's cycle well analysis exceed 1 for the 30 Mile Canal cell, the Orchard Alfalfa Canal cell, the Dawson County Canal cell, and the Gothenburg Canal cell.

B. AWAS URF Development

After determining that unit response functions could not be successfully developed from the COHYST cycle well data, the EDO developed unit response functions to evaluate recharge accretions using an analytical approach for comparison. The Alluvial Water Accounting System (AWAS)[5], a software program that solves the analytical equation described by Glover[6] to determine stream depletion from a pumping or recharge impulse, was used to develop the comparison unit response functions. The "New Modified" version of AWAS was run with an "Alluvial Aquifer" boundary condition. The distance between the river and the aquifer's edge was roughly based on the distance between the river and the start of the valley terrace. This distance was approximately 25,000 ft on the south side of the river (for the 30 Mile and Orchard Alfalfa canals) and 50,000 ft on the north side of the river (for the Cozad, Gothenburg, and Dawson County canals). The aquifer parameters used in the AWAS run are shown in **Table 3** in addition to the distance to river values shown in **Table 2**.

Table 3. Inputs for AWAS

Canal	Hydraulic Conductivity, k (ft/day)	Aquifer thickness, b (ft)	Transmissivity, T (ft^2/day)	Transmissivity, T (GPD/ft)	Storage Coefficient, Sy (unitless)
30 Mile Canal	200	80	16,000	120,000	0.18
Cozad Canal	200	80	16,000	120,000	0.18
Orchard Alfalfa Canal	200	80	16,000	120,000	0.18
Dawson County Canal	200	80	16,000	120,000	0.18
Gothenburg Canal	200	80	16,000	120,000	0.18

A single recharge impulse was added to the first month of the AWAS run and the resulting stream response over a 50-year period was determined. Separate AWAS runs were conducted to correspond to the locations of each of the model cells shown in **Table 2**. The AWAS results were divided by the pumping impulse to develop a Unit Response Function for each location. The resulting unit response functions are shown in **Figure 6** below.

[5] Integrated Support System http://www.ids.colostate.edu/projects.php?project=awas&breadcrumb=IDS+AWAS+-+Alluvial+Water+Accounting+System

[6] Transient groundwater hydraulics. Glover, R.E. Water Resources Publications 1977.

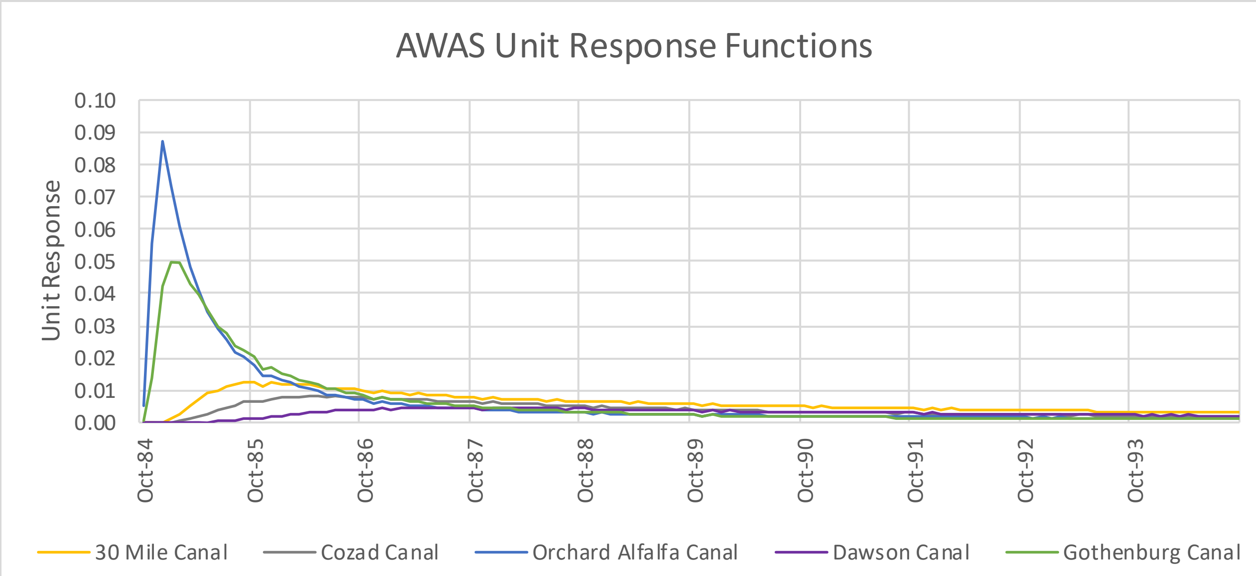

Figure 6. Unit response functions for the five canal locations developed using the AWAS program (only the first 10 years are shown).

To compare the DNR SDF results to the AWAS and cycle well unit response functions, the AWAS and cycle well unit response functions were plotted on a cumulative basis for each canal alongside the DNR SDF values. As seen in **Figures 7-11** below, the SDF and AWAS results for the Orchard Alfalfa canal most closely match while the curves for the other canals have a similar general shape but the DNR SDF values consistently show smaller stream responses compared to the AWAS stream responses. With the exception of the Orchard Alfalfa canal, the AWAS results show recharge water returning to the river more quickly than the cycle well results provided by the DNR. The Orchard Alfalfa canal is closer to the river than the other canals, indicating that the cycle well results match the AWAS results at locations closer to the river. The second closest canal is the Gothenburg Canal which shows the second-best match between the DNR SDF and AWAS results. The differences in the results could be explained in part by the negative values seen in the cycle well data as these negative values will result in a lower cumulative response. They might result from some of the simplifications and assumptions inherent in the AWAS analytical solution and the assumed dimensions of the alluvial aquifer. While the unit response functions developed using the AWAS program are constrained by the assumptions that underly the AWAS equations, the EDO believes they provide reasonable estimates of the stream response to a pumping or recharge event and are therefore valid to use in the score analysis and accounting of Program groundwater recharge projects.

When plotted on a cumulative basis, the cycle well unit response functions still show large monthly oscillations. The unit response functions initially rise in a similar fashion to the cumulative AWAS unit response functions then start to decline after about ten years of the model simulation. It is not entirely apparent what is driving this behavior but it does not follow the expected pattern of asymptotically approaching a maximum cumulative response.

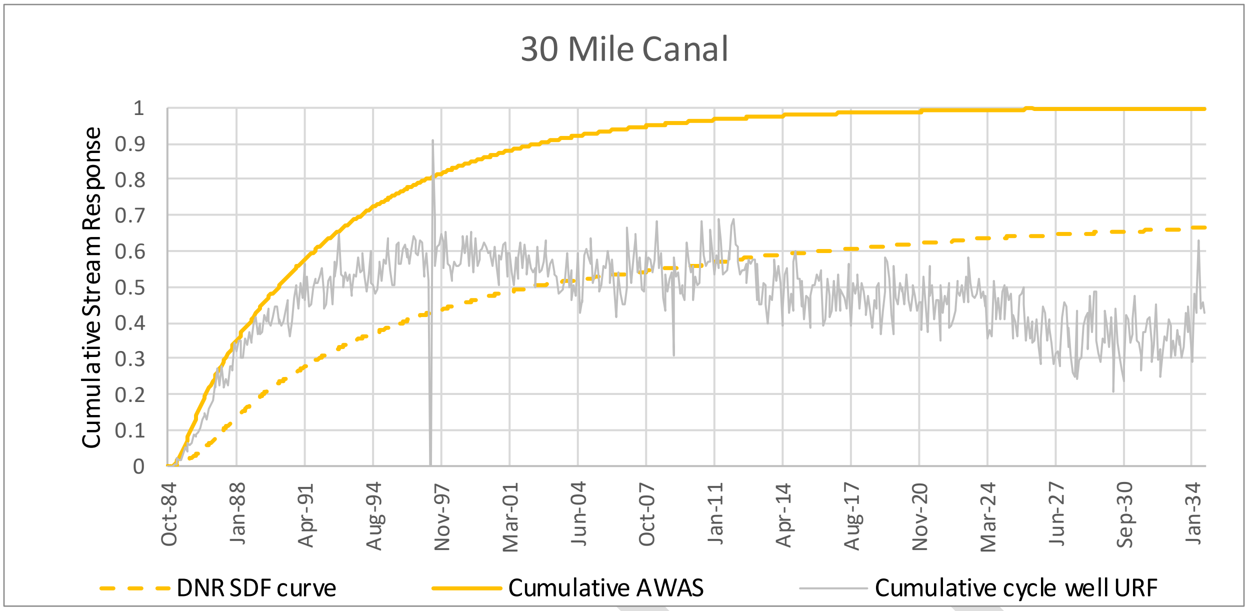

Figure 7. 30 Mile canal DNR SDF curves and cumulative AWAS and cycle well URF curves

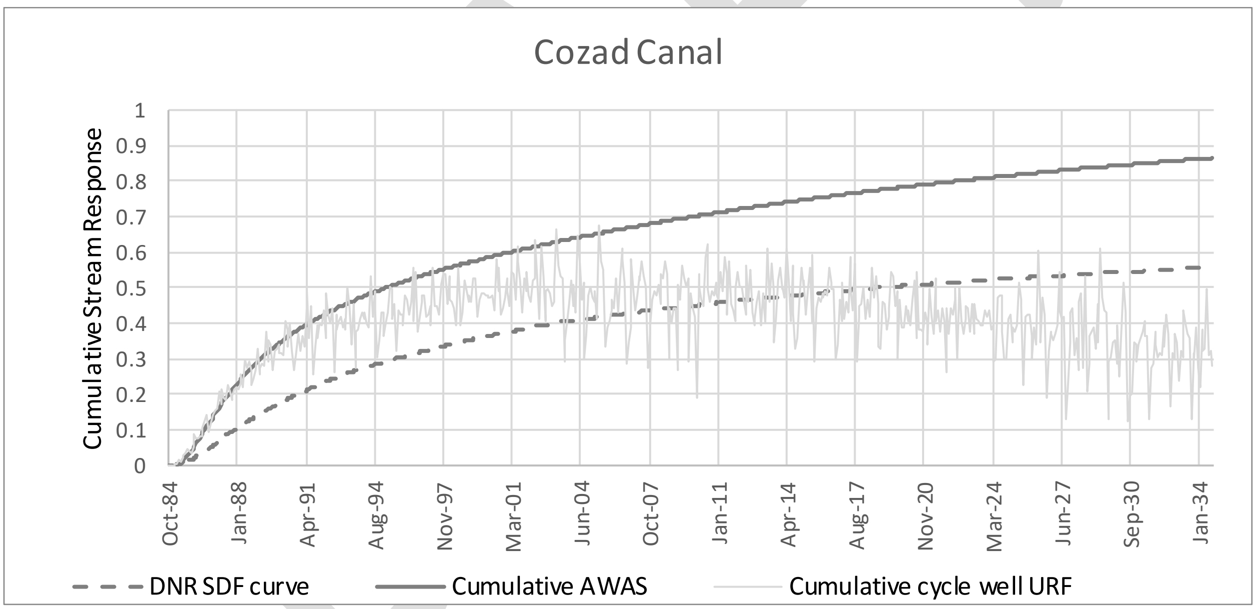

Figure 8. Cozad canal DNR SDF curves and cumulative AWAS and cycle well URF curves

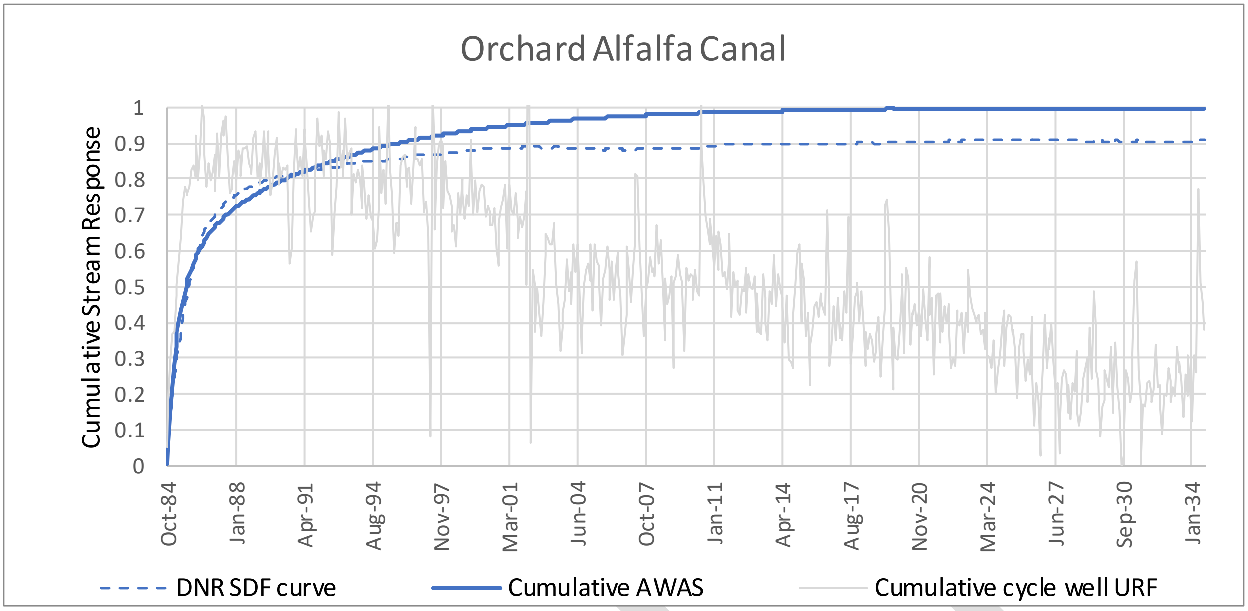

Figure 9. Orchard Alfalfa canal DNR SDF curves and cumulative AWAS and cycle well URF curves

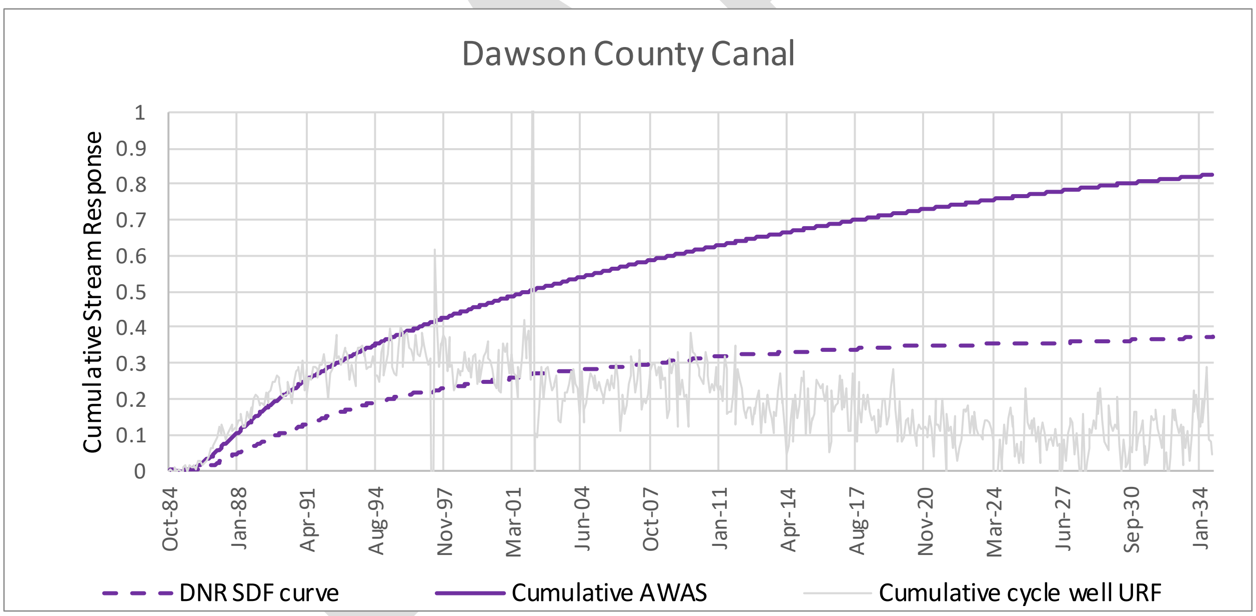

Figure 10. Dawson County canal DNR SDF curves and cumulative AWAS and cycle well URF curves

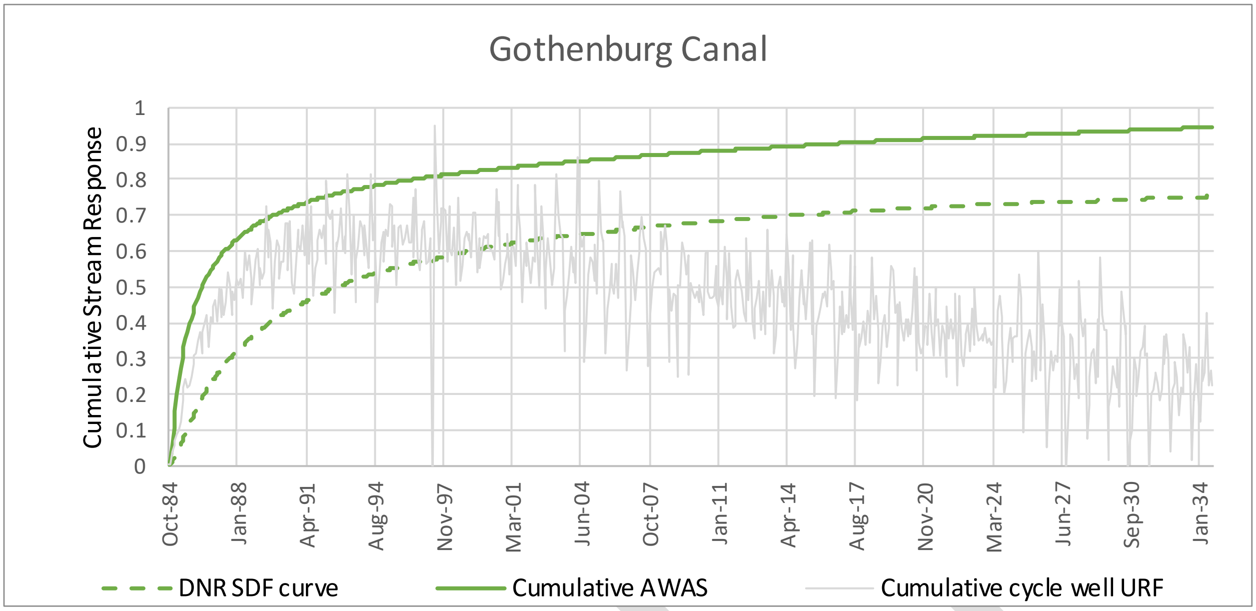

Figure 11. Gothenburg canal DNR SDF curves and cumulative AWAS and cycle well URF curves

IV. CONCLUSIONS

The EDO was not able to develop unit response functions from the cycle well data provided by the DNR. The unit response functions oscillated from positive to negative values and the oscillations had magnitudes greater than the largest expected monthly response. The EDO believes this erratic behavior is most likely due to the small pumping impulse used in cycle well analysis compared to the fluctuations in the model's inputs and error term. The EDO opted to develop unit response functions using the analytical approach applied by the AWAS program for its scoring of the CPNRD and NPPD canal recharge projects.