TO: PRRIP TECHNICAL ADVISORY COMMITTEE (TAC)

FROM: EXECUTIVE DIRECTOR’S OFFICE (EDO)

SUBJECT: WET MEADOW CHAPTER 5 UPDATE

DATE: OCTOBER 8, 2025

In early 2025, the Program retained Dr. Calvin Miller as a Special Advisor in hydrogeology. He was tasked with revising Chapter 5 of the 2023 Wet Meadow Hydrology Study to address peer review comments. The revised chapter is included with this memorandum. Dr. Miller will be present at the October TAC to provide an overview of the revised analysis and results, and answer follow up questions. Following the presentation the EDO is requesting TAC discussion and recommendations on:

1) The technical content and conclusions of the revised chapter.
2) What should be done upon Program acceptance of the revised chapter. For example, this chapter could possibly be resubmitted to the critical peer reviewer or just accepted with the entire study forwarded to the GC with a TAC recommendation to accept as final.

5. Modeling

A shallow, seasonally variable groundwater table is necessary for supporting sustained periods of inundation (Brinley-Buckley et al., 2021), wetland vegetation, and habitat associated with diverse species at wet meadow sites (Henszey et al., 2004; Davis et al., 2006). Previous studies have shown that river stage exerts the predominant influence on wet meadow groundwater levels in the CPRV, followed by precipitation, and, to a lesser degree, evapotranspiration (ET) (Whiles and Goldowitz, 1998; Wu, 2003; Wesche et al., 1994; Chen, 2007).

Hydrologic models can be used to predict how groundwater levels will respond to a given hydrologic stress and therefore may be used as tools to guide and test management actions at wet meadow sites. In this section, we present a numerical model-based analysis which was calibrated to match field data and then used to predict how changes in Platte River stage and surface additions of water (managed artificial recharge) would modify groundwater levels at wet meadow sites.

Previous studies have also used numerical models to evaluate hydrology at wet meadows. Chen (2007) used a three-dimensional numerical model to evaluate river-aquifer-vegetation hydraulic connections in the CPRV (approximately 5 miles west of the Fox site). They identified river stage as having a predominant influence on groundwater levels and described the river-groundwater system as highly connected based on groundwater levels responding rapidly to fluctuations in river stage. Loheide and Gorelick (2007) developed a finite-element model of variably saturated groundwater flow to assess hydro-ecologic functions of a wet meadow system in the Last Chance watershed in North Central California. They identified drainage to the stream as an important control for groundwater levels that in turn affected local vegetation.

In 2012, the Program developed an analytical model based on Glover's bank storage equation to test how changes in stage affect groundwater levels at wet meadow sites (PRRIP, 2012). That analytical model computes how changes in river stage at the edge of the aquifer propagate across the aquifer as a function of: (1) time, (2) distance from the river, and (3) aquifer properties (aquifer permeability and storativity). However, the Glover equation was developed for a single stream boundary and would have to be modified to apply it to the Fox site due to the site being relatively narrow and bounded by two river channels (**Figures 5-1 to 5-3**). Such modifications are possible, using image-well methods, but would be complicated by the fact that the stages of the two stream channels occasionally change independently. The channel stages most commonly move approximately in tandem, but by using another modeling method there was an opportunity in this evaluation to take advantage of at least one flow event when the two channel stages changed independently—a sharp rise in the north channel with no rise in the south channel in February 2014—to increase confidence in the model's predictive ability across the site.

Additionally, Glover's bank-storage equation cannot account for the slightly non-parallel stream boundaries found just upstream of the Fox site and, more importantly, it cannot be modified to account for adding managed artificial recharge (MAR) which is an option to be examined in this this section. Due to these limitations of the analytical model, a numerical finite-difference model was the method selected for this new study. The model is used to examine (1) how river stage changes drive groundwater level changes across the Fox site and (2) if it is feasible to add recharge to the site to raise groundwater levels.

5.1. General Method

The numerical finite-difference model was constructed using the common groundwater modeling code MODFLOW-2005 (McDonald and Harbaugh 1988; Harbaugh 2005). The complexity of the model was able to be narrowly limited by using it as a superposition model where only the changes in water levels are simulated rather than simulating absolute water level elevations directly. This approach is directly analogous to what the Glover bank-storage equation computes, but here it is done with a different mathematical solution method which is less restricted in its ability to be tailored to site geometry and additional conditions such as recharge.

This simplified MODFLOW model uses the principle of superposition which is a foundational and once-common analysis method in groundwater hydraulics. In essence, most analytical equations—such as the Theis equation, the Glover bank-storage equation, and related methods such as the Glover-Balmer stream-depletion equation—rely on superimposing their computed changes on top of the underlying conditions that are otherwise not under consideration.

The use of MODFLOW for superposition models was particularly common in past decades when computing power was limited. The technical principles and advantages of using MODFLOW as a superposition model have been described by Reilley et al (1987) and Leake (2011). Again, the use of superposition model is very similar conceptually to using Glover's analytical bank-storage equation yet using the finite-difference approach (e.g., MODFLOW) adds the ability to consider: (1) two non-parallel stream channels, (2) independent stage changes in the two channels, (3) aquifer properties that may be spatially non-uniform, and (4) the addition of managed artificial recharge to the Fox site. The resulting model provides a useful tool for testing water management scenarios, with improved predictions as compared to previous models, as indicated by good matches between observed and modeled groundwater levels.

5.2. Illustration of Relevant Hydraulics

Although this study is using the finite-difference method via MODFLOW, it is useful to still review the Glover Bank Storage equation (Eq. 1) (Glover, 1964) since it illustrates the hydraulic behavior being simulated by the MODFLOW model. As analyzed by Glover, the change in groundwater level (*s*) some distance (*x*) from a river is estimated at time (*t*) given an instantaneous step change in river stage (s_0) (e.g., Figure 15). The parameter α is hydraulic diffusivity defined as $\alpha = T/S$ where T is transmissivity (L^2T^{-1}) and *S* is storativity (dimensionless). Since the aquifer at the Fox site is unconfined, S is equal to specific yield (Sy) which is the volume of water released under gravity from storage per unit cross-sectional area per unit decline in water table (Freeze and Cherry, 1979). The function "erfc" is the complimentary error function which is related to a probability integral which is found through Glover's derivation.

$$s(x,t) = s_0 \, erfc\left(\frac{x}{\sqrt{4\alpha t}}\right) \quad \text{Eq. 1}$$

The principle of superposition in time can then be used with Glover to calculate stepwise changes in groundwater level caused by, in this case, daily changes in stage (Eq. 2).

$$s_{(x,t)} = \sum_{i=1}^{n} \Delta s_i \, erfc\left(\frac{x}{\sqrt{4\alpha(t-t_i)}}\right) \; ; t \geq t_i \quad \text{Eq. 2}$$

Notably, Equations 1 and 2 do not model groundwater flow, but rather vertical changes in groundwater level due to stepwise changes boundary stresses (i.e., stage changes at edge of aquifer). Similarly, the MODFLOW model used here also computes the changes in levels without simulating all flow components through the aquifer and instead only computing the displacement caused by the stage change.

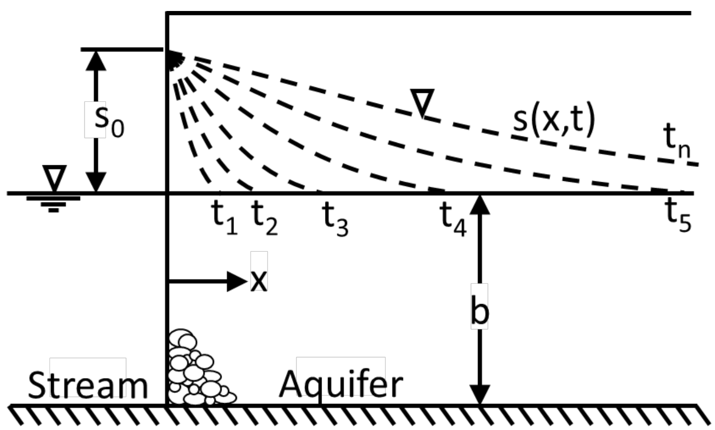


Figure 1 - Schematic illustrating variables in the Glover Bank Storage equation (Sanders, 2001).

5.3. Modeling Approach Decisions

Evapotranspiration

Evapotranspiration (ET) was not included in this modeling study since ET has relatively smooth season-scale trends and creates only slow and cumulative effects while the goal of this study was to be able to simulate large and short-term fluctuations in the water table caused by river stage changes. Previous studies have also concluded that river stage exerts the predominant influence on wet meadow groundwater levels in the CPRV, followed by precipitation, and, to a lesser degree, evapotranspiration (Whiles and Goldowitz, 1998; Wu, 2003; Wesche et al., 1994; Chen, 2007). In simpler terms, the slow and steady pace of ET losses from groundwater below the meadow are small compared to stage-driven changes, plus ET losses are slow enough to be replaced by water entering the aquifer from the river and not be significant for the short-term scale changes modeled here.

Precipitation

Typically, only a small fraction of precipitation reaches the water table, often on the order of 5 to 10% of annual precipitation in semi-arid areas (e.g., Arnold 2010) and not a much higher fraction in transitional climate zones like in central Nebraska. And for any individual rainfall event, the fraction of rainfall that reaches the water table—as opposed to being retained in the topsoil to later evaporate, or leaving the site as surface runoff—is highly variable and depends on myriad factors such as antecedent soil moisture, local variations in topsoil type, and storm intensity and duration. Additionally, there is often a time lag and attenuation (arrival peak diminished due to spreading out over time) between a rainfall event and its water reaching the water table. For all these reasons, it was concluded there were too many variables involved to accurately include net precipitation in this exercise.

The decision to not include net recharge from precipitation in this model is supported in part by previous studies which have concluded that river stage exerts the predominant influence on wet meadow groundwater levels in the CPRV, followed by precipitation, and, to a lesser degree, evapotranspiration (Whiles and Goldowitz, 1998; Wu, 2003; Wesche et al., 1994; Chen, 2007). Additionally, and more site-specifically, the Fox site data (Figures 5-4 through 5-9) indicates that groundwater fluctuations caused by stage changes at this site are typically larger than fluctuations caused by rainfall. This conclusion is nuanced since rainy periods often coincide with rises in the river stage and those stage changes then drive groundwater rises, but the hydrographs also show some examples with independent event behavior from which conclusions can be drawn. For example, there was large rise in both stage and groundwater levels from mid-May 2015 through early June 2015 (Figure 5-5) for which at least half the rise preceded the rainfall period in early June 2015, thus showing much of the rise from the stage change. This is underscored by a roughly similar prior period of rain in April of that year (similar to the June rain during the large rise) which did not coincide with a large stage change and was associated only with a relatively small groundwater rise. For another example, there was a rainfall event in late July 2015 (Figure 5-5) which occurred while the stage and groundwater levels were both rapidly falling. The rain appears to have created a small and short-lived spike in the falling hydrograph, but that event too makes it clear that the major change was being driven by the river stage and not the rain event.

Selection of Calibration Year for Fox Site

The hydrograph time periods highlighted as examples in the previous paragraph support the conclusion of precipitation having a secondary role in wet meadow groundwater levels. However, there are some counter examples to be acknowledged. For example, there was a significant rainfall event in mid-April 2016 (Figure 5-6) that clearly led to a large and unusually steep (fast) rise in groundwater levels and with only a moderate stage change coinciding with that period. Rainfall recharge to groundwater was apparently significant for that individual storm event and the model used in this study without rainfall would not be well-suited to simulate that period. Therefore, it was decided to limit the model's calibration to time periods without significant rainfall events. The 2014 hydrograph (Figure 5-4) shows only two large rainfall events and no rain events appear to have influenced groundwater levels as much as stage changes. Stage changes were the predominant drivers of groundwater fluctuations in that year, making 2014 a good candidate for calibrating the model.

Note that the mid-April 2016 rainfall event is likely complicated by a pumping well also shutting off at the same time, with that presumably happening at the same time due to the arrival of the rainfall. The drawdown and recovery pattern seen in MW-112 from late February to mid-April 2016 is distinctly consistent with the shape of pumping drawdown curves. Also, similar periods of apparent pumping drawdown are seen at MW-112 in Oct./Nov. 2016 and Oct./Nov. 2018. This cessation of pumping likely exaggerates the rise seen in mid-April 2016, suggesting rainfall still has a limited effect. Nevertheless, this complication shows that the decision to avoid rainfall events for calibration is sound.

The decision to avoid modeling significant rainfall events is also consistent with the goals of this study which is to quantify how river stage changes drive groundwater rises. In other words, it is helpful to calibrate to those periods mostly driven by stage changes since that is the condition of interest to reproduce in management scenarios.

Additionally, selecting 2014 as the calibration year appears to avoid both large rainfall events in groundwater and pumping events. The pumping could be simulated if the pumping rates were metered and available, but at this time that information is not available.

The logic to avoid calibrating the model to rainfall events applies also to the goal of using the calibrated model to simulate managed recharge events, because the goal of calibration is to estimate aquifer parameters, not rainfall infiltration variables. Aquifer parameters govern the groundwater rise created by sustained managed recharge. If large rainfall events were included in the calibration period, that would complicate the identification of aquifer parameters because it would introduce many more uncertain variables (share of rain that infiltrates and how fast). Relatedly, managed recharge is typically done with a pond and with sustained application of water. This leads to nearly all the applied water reaching the water table because runoff is prevented (pond shores/berms) and because the continued application of recharge saturates the underlying vadose zone. In contrast, rainfall events have a large, irregular, and unknown fraction of water that reaches the water table which, again, introduces more calibration variables and lowers confidence in the calibration of aquifer parameters.

<u>2014 Calibration Targets for Fox Site</u>

Since the modeling approach selected for this study is a superposition model (or "change model"), the hydrographs of water elevation (Figures 5-3 through 5-9) are converted to change targets instead of elevation targets for calibration. This is the same as computing drawdown targets (changes in water level) from pumping test water level observations in which the computed changes are analyzed to interpret aquifer parameters.

All wells were used in the model and its calibration, but only key wells are shown in Figure 5-10 for clarity. Figure 5-10 is also focused on the early part of the year to better show the two key periods with large stage changes, but the entire year was used in the model and its calibration.

The set of wells highlighted in Figure 5-10 covers relative locations (see Figure 5-1) which highlight bank-storage hydraulic behaviors: very near the north channel (MW-109), slightly further from the north channel (MW-116), then a similar distance from the south channel (MW-112), and almost exactly halfway between the two channels (MW-114).

<u>Time Discretization for Model Calibration</u>

Simulating transient behavior in finite-difference models requires dividing the simulation period into smaller stress periods and then smaller computational time steps within each stress period. The Program's prior analytical models used daily steps in stage changes, but a different approach to time discretization was used for this MODFLOW model. First, the Year 2014 hourly data set was first processed by the Program into daily averages, and the daily averages were used as targets. That is the same as in prior Program work. Next, we divided the year into 68 model stress periods which correspond to key points in time with distinct changes in applied boundary conditions (i.e., river stage). For example, the start of a seasonal stage rise, the peak of that rise, and the end of that rise would be the starts of three different model stress periods. Finally, each stress period is divided into smaller computational time steps, and each time step varies in length. The calibration simulation of 2014 data had a total of 68 model stress periods ranging in length from 1 to 25 days, and a total of 336 time steps ranging in length from 0.16 to 6 days, depending on the stress period and their position within the stress period.

We used a boundary condition formulation for river stage which allowed the applied stage level to change at each time step in a linear fashion, rather than be steady within a stress period. This approach reduced the number of stress periods and the total time steps needed to adequately represent the year of daily stage data. The smooth linear changes in stage used by the model within a given stress period can be seen, for example, from July 9 to August 8, 2014, in Figures 5-11 to 5-16, and by comparing that to the actual daily stage changes during that period in Figure 5-10. Note also that some periods were simplified with this approach, such as the period from Sept. 4 to Oct. 10, which had multiple small stage fluctuations simplified into just two stress periods with one rising and one falling limb (e.g., Figure 5-11). Finally, note the calibration plots presented here display the modeled stage for comparison to modeled water table, while the actual stage changes were shown in Figures 5-10 and 5-4.

5.4. Fox Site Results

Field-Observed Hydrograph Changes

First, even before the use of the numerical model for interpretation and confirmation of the site behavior, key target behaviors are directly apparent from a review of Figure 5-10. In February 2014, there was a sharp rise in the north channel but no rise in the south channel (Figure 5-10). This disparity between the two channels is relatively rare in the data set and it provided a good test case for the model. Due to this difference in channel changes, there is consequently a difference in observed field behavior: a large rise recorded near the north channel (MW-109 and MW-116) but a time-lagged and greatly attenuated rise in MW-112 which is near the south channel. There was intermediate behavior at the mid-meadow location, MW-114 (Figure 5-10). These field observations of a delayed and attenuated peak with increasing distance from the channel are directly consistent with the idealized behavior expected theoretically from the Glover bank-storage equation. Note also that there was no significant precipitation during this period (Figure 5-4) and, even if there were, this observed behavior of lagged and attenuated rise vs. distance from the channel could not be explained for precipitation. Using this period as a key part of the calibration data set confirms the decision to exclude rainfall from the model and to avoid it for the selected calibration period.

Modeled Hydrographs

The key time-lagging and attenuation behaviors observed in field data from February 2014, as discussed in the prior paragraph, were successfully recreated by the calibrated model. Example results at key wells are shown in Figures 5-11 through 5-16. In particular, the model captured the sharp and large rise near the channel at MW-109 (Figure 5-11), the slightly smaller rise at MW-116 (Figure 5-12), and the greatly lagged and attenuated rise far from the north channel at MW-112 (Figure 5-13).

Similar behaviors are observed and successfully modeled during the more typical seasonal river rise that occurred in both channels in June 2014. MW-109 (Figure 5-11) and MW-103 (Figure 5-14) are both near a channel, on opposite sides of the meadow, and both saw a similar rise, similar in time and scale, to the river stage change. In contrast, at MW-114 which is halfway between the two channels, the rise was lagged and attenuated (Figure 5-15). This lag occurs even with both channels changing because the MW-114 location is distant from each channel. The model successfully simulates this observed field behavior.

Results demonstrate an excellent overall fit between modeled and observed groundwater levels for the target year of 2014. Longer time scale trends are accurately captured, and short time-scale events are in sync with field observations.

Aquifer Parameters – Fox Site

Model calibration for the Fox site (Figures 5-11 through 5-16) was achieved with a uniform hydraulic conductivity (K) equal to 500 ft/day. Based on prior Program modeling work and information from Program staff, aquifer saturated thickness was set at 80 ft in the model.

Specific yield (Sy) was calibrated with two zones, with west half of the meadow at Sy = 0.25 and east half, starting east of MW-114 and covering both MW-116 and MW-115, at Sy = 0.15. These aquifer parameters are squarely within the expected range for braided river deposits in this area and similar to values reported in studies conducted nearby (e.g., Hurr, 1983; Chen, 2004; Song and Chen, 2010; Yue et al., 2016).

Model Suitability for Application

The site data set has extensive coverage over the meadow and over many years. It is a strong data set that captures key behaviors over many seasons and under different conditions. It is suitable for its intended purposes.

Site data were not sufficient to calibrate vertical hydraulic conductivity (Kv), and determining Kv is not a common occurrence with models and sites of this scale. Relatively unique data tests are typically required to also identify Kv. The model was, however, constructed with two computation layers, with the river channels only in a thin upper layer, so that reasonable ranges of Kv could be tested in the calibration and used in the recharge simulations in the following section. The Kv used in the calibration was Kv = 100 ft/day. Having Kv set a one-fifth of horizontal K (Kh) is near typical generic assumptions (Kv/Kh = 1/10 is a default or common rule of thumb) and is a typical expectation for relatively homogenous alluvial deposits such as these. Similar vertical anisotropy ratios on the scale of 1/5 (and milder) have been reported by Chen in streambed sediments of the Platte River in Nebraska. This Kv value is suitable for testing managed recharge scenarios (next section) with the assumption that topsoil may be removed for recharge ponds, if necessary.

This model is well calibrated and has the simulation capabilities necessary to test and form the conclusions presented in the next section. If the model were to be used to design and implement site-specific management plans, such as managed recharge or artificial stage changes, then it would be prudent to perform additional modeling work such as sensitivity analysis on the calibration and predictions, and to complete a more detailed model construction report. As a screening tool, however, the model is sound and clearly well suited for its current application. The applications are discussed in the next section.

5.5. Discussion

As described previously, groundwater depths at the Fox site were found to be too deep over the majority of the site to support key wetland vegetation groups as estimated using the L7th DTGW statistic. Groundwater level increases of up to 0.93 m, and on average 0.59 m, were estimated as necessary to achieve a hypothetical management target of 50% spatial coverage with wetland vegetation during 2018. To demonstrate the utility of this model developed for the Fox site, we use it to evaluate and estimate groundwater level changes that could be produced with two conceivable management actions at the Fox site, as follows.

For the first management scenario, we considered how an artificial increase in river stage (through upstream reservoir releases) could be applied to increase groundwater levels at the Fox site by 0.59 m (just under 2 feet). In the second scenario, we used the calibrated model to test how recharge water could be applied at the site to similarly achieve the target change in groundwater level.

For the stage-increase scenario, we considered a two- to four-week increase in river flow to be accomplished via water releases. The model can be used for this, but it is also apparent, from the model calibration hydrographs made from the field observations (e.g., Figure 5-10), that the required magnitude of stage increase would be at least 2 feet (> 0.59 m) for locations near the channel and, for locations in the center of the meadow, the stage rise would need to be well over 4 feet for short durations and over 3.5 feet (a little over one meter) for locations further from the channel. Wells further from the channel require larger stage increases and/or longer duration of the increase to reach goals.

<u>Managed Stage Change - Conceptual Illustration based on Observations</u>

For illustration, we considered that during June of 2018, Platte River discharge ranged from just under 5.7 cubic meters per second (cms) (200 cfs) to 70 cms (2,472 cfs). Based on the stage-discharge curve reported for the USGS Kearney gage (USGS #: 06770200), a 1.0 m to 1.5 m stage increase would correspond to an increase in discharge of 10,000 to 20,000 cfs (Figure 2). Also, for reference, the regulatory flood stage at this gage station, eight kilometers upstream of the Fox Site, is 2.1 feet, corresponding to a discharge of 507 cms (17,904 cfs). Therefore, the example scenario demonstrates how artificial stage increases are not a viable method for increasing groundwater levels to target levels, particularly along inland portions of the site. For areas closer to the channel where lower magnitude stage changes could reach groundwater targets (e.g., 0.6 m), stage increases could be achieved, relative to low water conditions, with discharge releases in the range of about 5,000 to 10,000 cfs. However, a sustained release of even 5,000 cfs for 2 weeks is an enormous volume of water, at around 140,000 acre-feet. This is highly unlikely to be a viable option.

Managed Recharge Simulation

Next, we used the calibrated model to simulate the application of recharge water to the Fox site and to determine what application rate would be required to increase groundwater depths by the target value of 0.59 m.

Based on prior work done by the Program and reviewed as part of this model calibration effort, it is clear that the Binfield site exhibits very similar river-aquifer hydrograph behavior as the Fox site. The Binfield site has similar size, geometry, and hydrogeology, and it appears and to have an aquifer that is equally as transmissive as, and likely higher than, the Fox site. It therefore follows that the managed recharge simulation results presented here for the Fox site indicate that as much or more recharge water would be required to raise water levels at the Binfield site. Further site-specific modeling should be undertaken for the Binfield site if managed recharge plans ever reach the design and implementation stage, but at this management-option screening stage it is a sound conclusion that Binfield recharge requirements and results would be very similar to these Fox site simulations.

For the managed recharge simulations, we considered that recharge applied very near the channels would not raise water levels efficiently due to the drainage effect of the channels. Therefore, we applied the recharge to a smaller central area of about 180 acres. The simulated recharge zone was a quadrilateral (irregularly shaped square) with its four corners at MW's 112, 113, 116, and 115 (see well locations in Figure 5-1).

In the first recharge simulation, we found that an initial rate of 10,000 gpm would be needed for a few days to initially create the desired rise of 2 feet, and that 3,000 to 4,000 gpm would be required to maintain the rise for however long the rise was desired. A range of rates is given here because the exact rate depends on how the recharge is distributed (more rise is achieved in the middle than the edges if applied uniformly) and varies slightly with the exact shape and acreage of the recharge zone. For 180 acres, that application rate is 3 inches/day initially and 1.2 inches/day to maintain.

In the second recharge simulation, we considered that the high-rate capacity requirements of the initial period (10,000 gpm) could be avoided if recharge was used to extend the duration of an already elevated groundwater period rather than to also create the rise during low-water conditions. This is illustrated by the green dashed lines in Figures 5-15 and 5-16. The line "model w/MAR" means the same calibrated model simulation as the black dashed line but with the managed aquifer recharge added.

In this second simulation, recharge began around July 9, 2014, when the seasonal rise was still present but in decline, and we extended that annual season rise by about 4 weeks by applying recharge until about August 7th. We applied approximately 4,200 gpm over the 180 acres for those four weeks.

The results vary by location. For example, MW-114 is in the middle of the recharge zone and would experience a large rise of 2 ft over the natural conditions at the start of the period, and a nearly 4 ft rise over the natural conditions that would have been in place at the end of the seasonal rise (i.e., compare the black dashed line to the green dashed line in Figure 5-15).

The impact at MW-116 is smaller (Figure 5-16) since it is near the channel and the river channel provides drainage. At MW-116, the rise achieved over natural conditions is about 1.0 ft during the early part of the recharge period and under 2 ft during the later part. Note that in both cases the elevated water table persists about another week after recharge ceases, as it takes time for the water to drain and return to natural conditions.

These recharge simulations considered only mounding within the aquifer and did not consider potential limitations in infiltration rate from topsoil cover, nor did it consider local ponding on soils with that ponding not connected to the water table and existing instead in a temporarily perched condition.

The first recharge simulation appears to not be viable since 10,000 gpm is a relatively large pumping rate likely requiring multiple wells. The second case may be plausible at 4,000 gpm, but it would require further site-specific design work and operational management to distribute the water in a manner that achieves the desired rise uniformly. Additionally, pumping 4,000 gpm for 4 weeks is a large volume of water (> 500 acre-feet) and would incur power expenses.

In these scenarios, the recharge water would need to come from diverted surface water or, if it came from groundwater pumping, then the pumped wells would need to be located far way in order for their aquifer drawdown not to counteract the mounding achieved from the recharge effort.

<u>Summary</u>

Overall, it is clear that river flow augmentation, performed to increase stage for the purpose of increasing groundwater levels, is not viable since it would require a large and sustained release of water from reservoir storage to meet goals, amounting to a very large total water volume released.

Managed aquifer recharge applications appear to be within the realm of plausibility, but the water delivery requirements are relatively large if done by pumping. The simulations are not encouraging about the practicality of that approach considering it would likely require significant modifications to the site grading and topsoil conditions, such as to retain water in ponds or to evenly distribute the applied water.

One alternative to consider, instead of pumping the recharge water onto the site, is to divert the water from the river upstream and then direct it into recharge ponds or leaky recharge trenches on the site. Except for potentially significant initial construction costs of the diversion dams and channels, and likely some periodic maintenance of the recharge trenches (siltation), this approach would have low energy and operational costs and have low consumption of water, even for a high gross diversion rate, as the water would migrate directly back to the river nearby either overland (excess of what recharges) or in the aquifer (as part of successful aquifer recharge).

Alternatively, it may be more viable to identify candidate restoration locations where the relationship between channel elevation and overbank topography is similar to that at archetypal wet meadow sites. This concept is explored in Chapter 6.

DRAFT REVISED TEXT 10/01/2025

Citations to add to list at back of report:

Arnold, L.R. (2010). *Hydrogeology and steady-state numerical simulation of groundwater flow in the Lost Creek designated ground water basin, Weld, Adams, and Arapahoe Counties, Colorado*. U.S. Geological Survey Scientific Investigations Report 2010–5082, 79 p. https://pubs.usgs.gov/sir/2010/5082/

Harbaugh, A.W., 2005, *MODFLOW-2005, The U.S. Geological Survey modular ground-water model—the Ground-Water Flow Process*: U.S. Geological Survey Techniques and Methods 6-A16

Leake, S.A. (2011). Capture—rates and directions of groundwater flow don't matter! Ground Water, 49(4), 456–458. https://doi.org/10.1111/j.1745-6584.2010.00797.x

Reilly, T.E., Franke, O.L., and Bennett, G.D., 1987, *The principle of superposition and its application in ground-water hydraulics*: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter B6, 28 p., https://doi.org/10.3133/twri03B6.

Citations which Miller deleted from Chapter 5 and which should be deleted from the full list if they don't appear elsewhere in report:

- Gerla
- Rosenberry & Winter
- Andualem

Figure 1. Fox Site water table elevation May 1, 2014 - Example of typical low-river conditions.

DRAFT

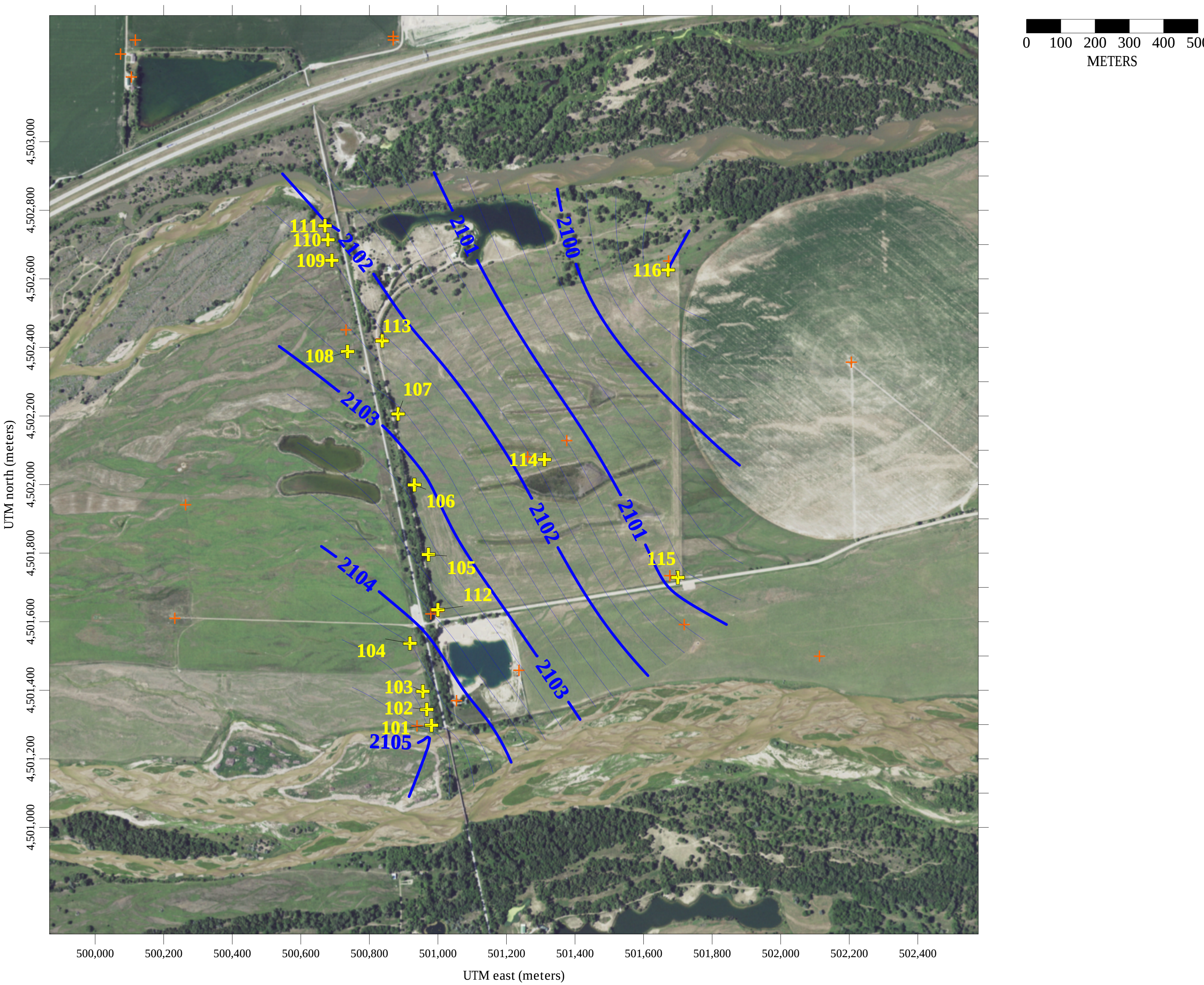


Figure 2. Fox Site water table elevation June 15, 2014 - Example of typical high-river conditions.

DRAFT

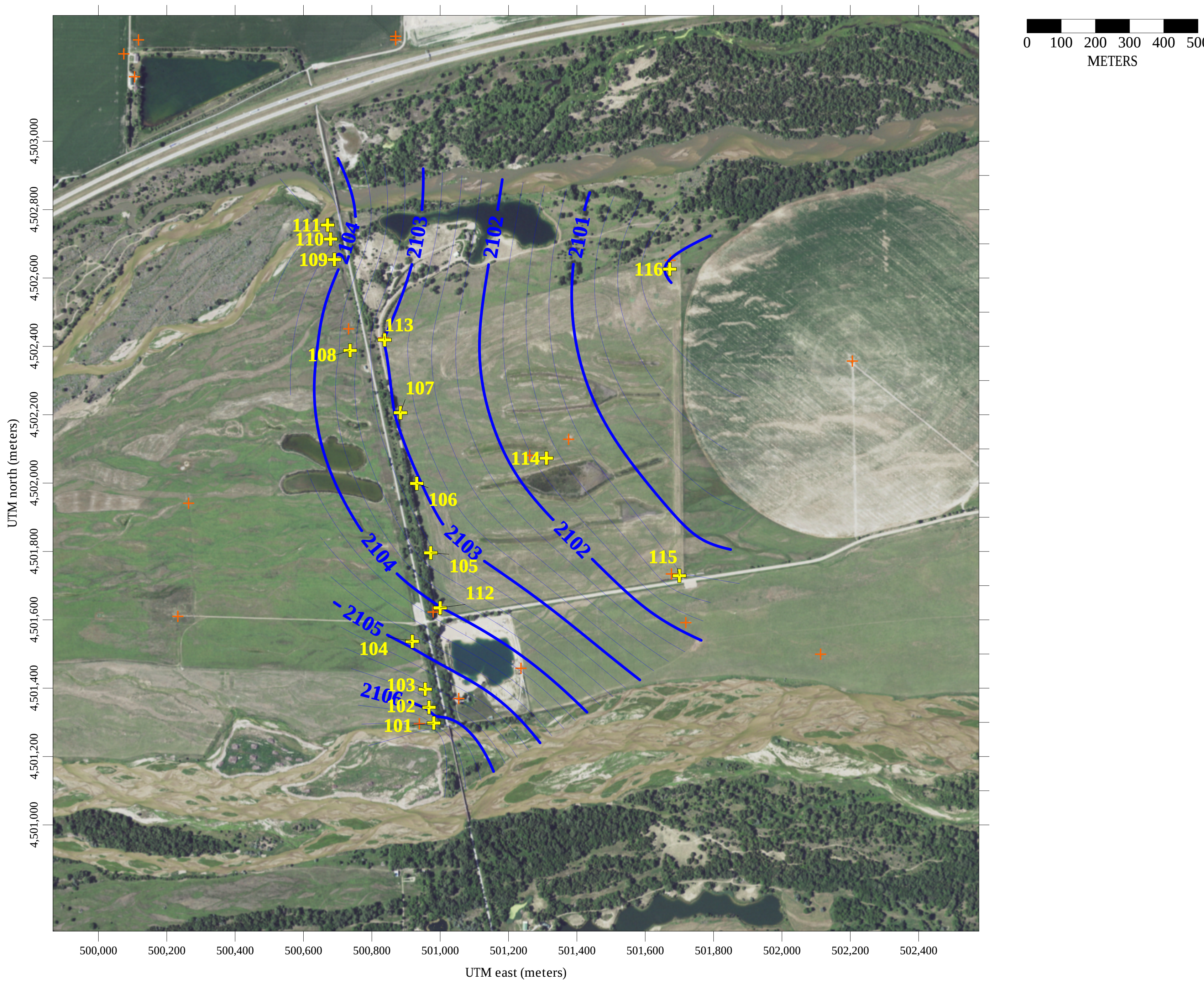
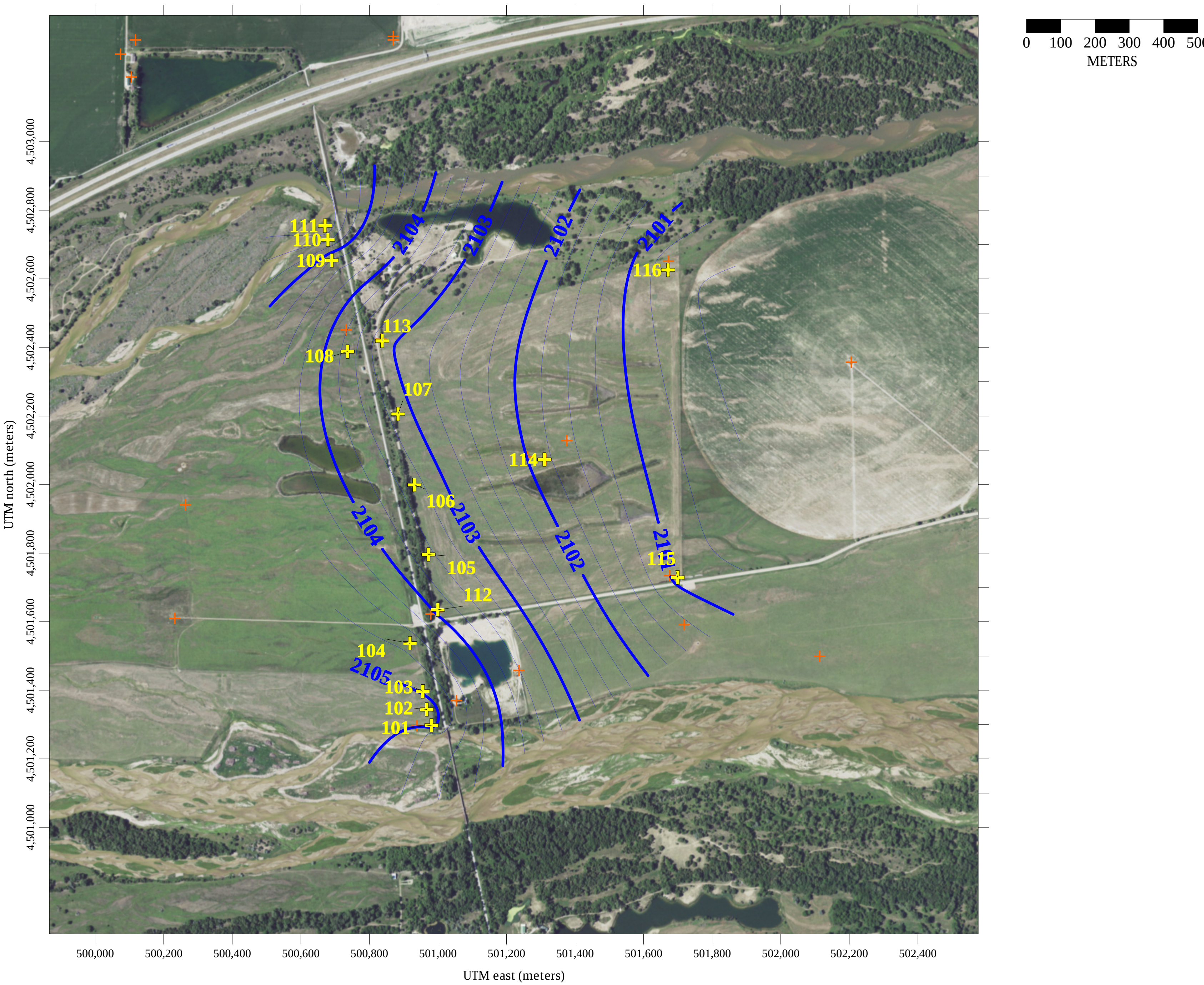


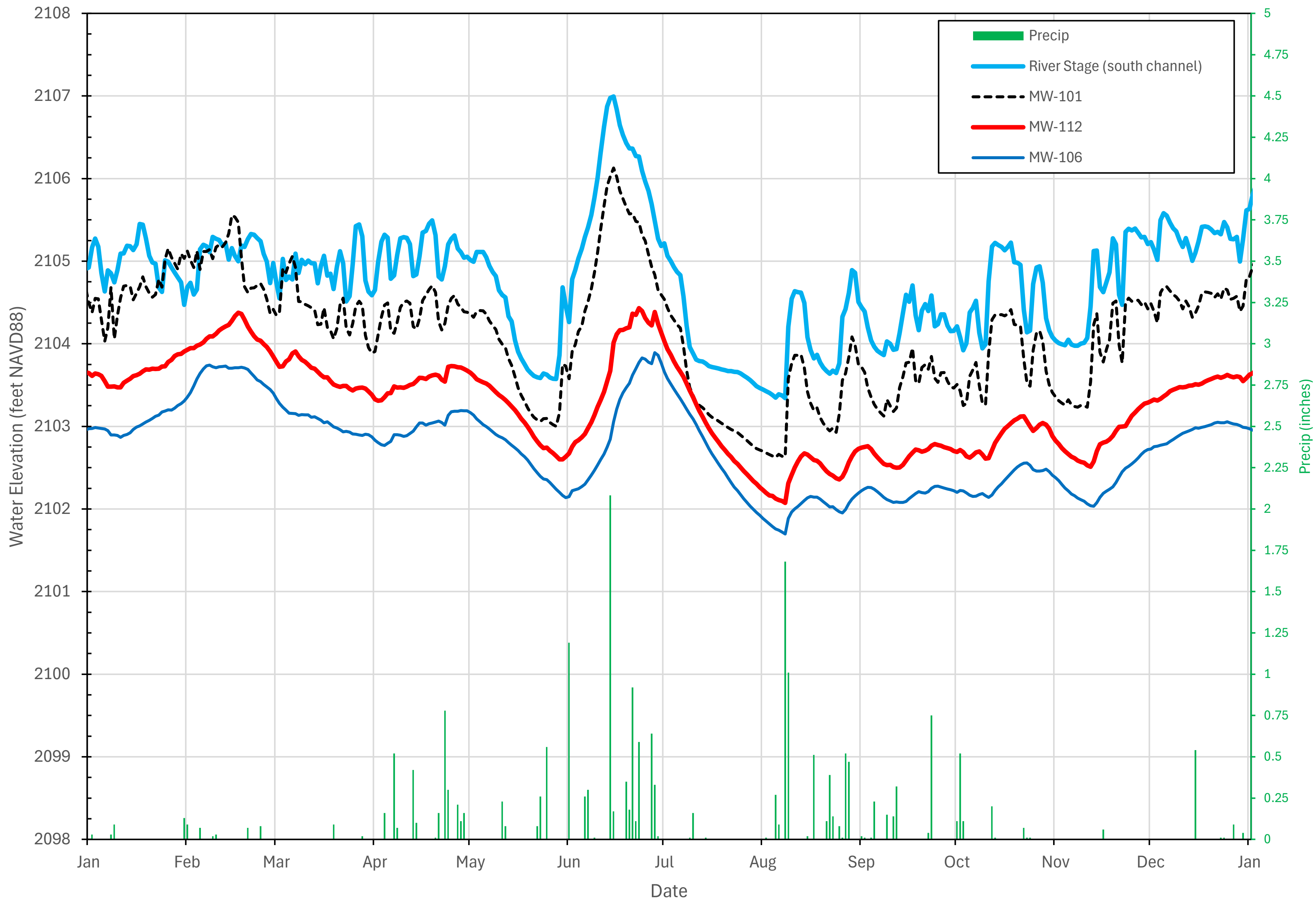
Figure 3. Fox Site water table elevation February 1, 2014 - Example of atypical rise occuring only in north channel.

DRAFT



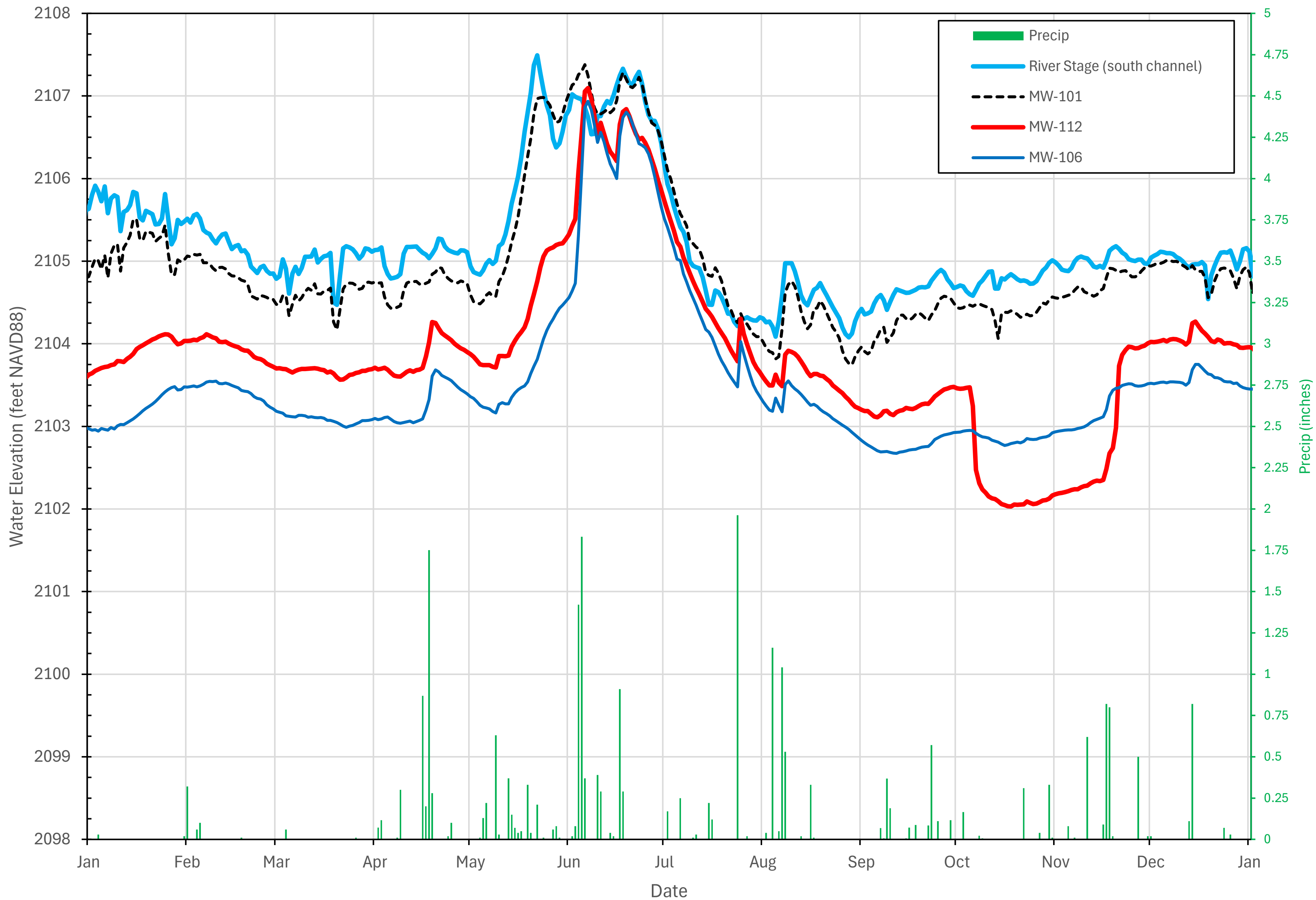
DRAFT

Figure 4. Fox site - water level data (example wells) for 2014.



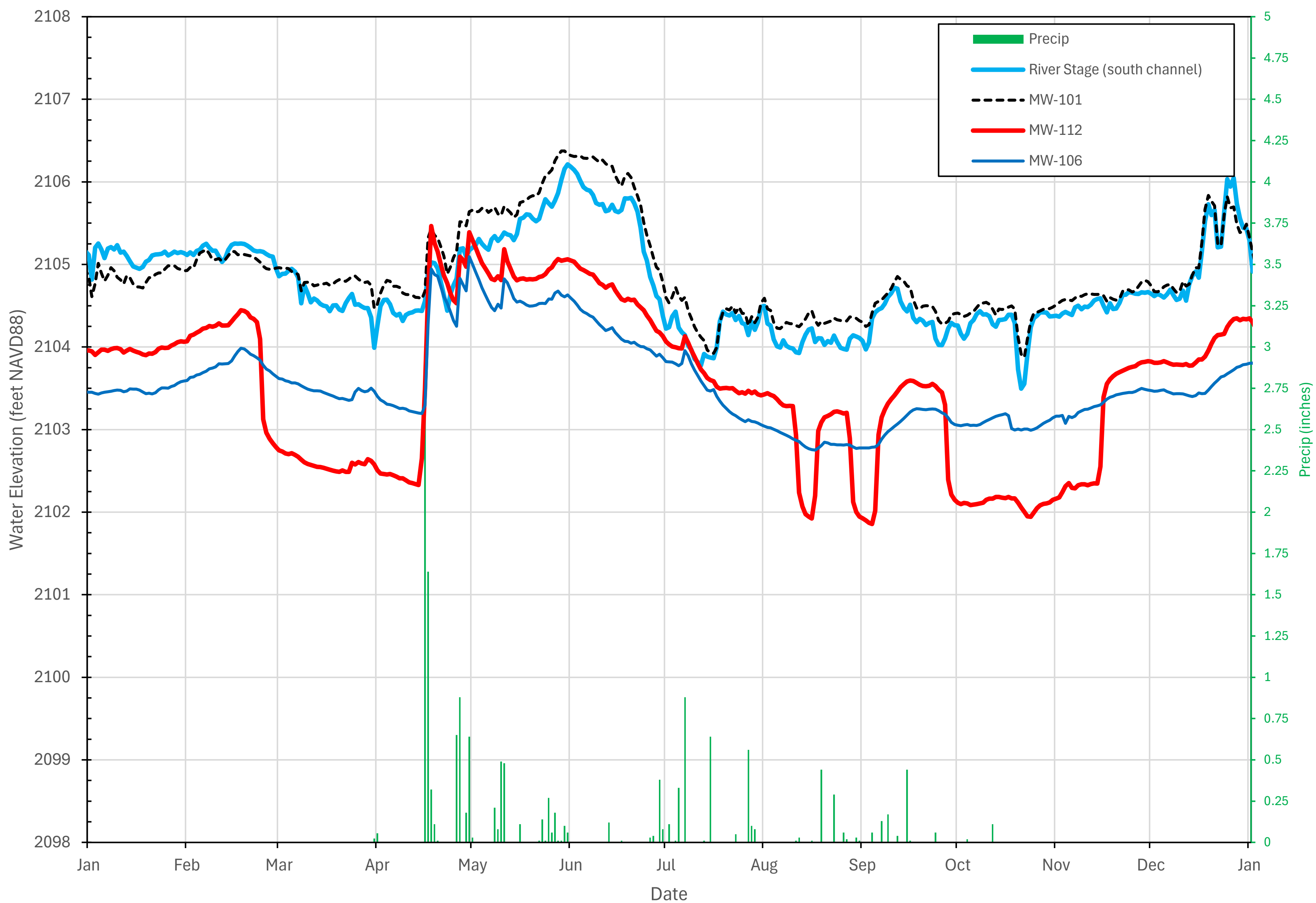
DRAFT

Figure 5. Fox site - water level data (example wells) for 2015.



DRAFT

Figure 6. Fox site - water level data (example wells) for 2016.



DRAFT

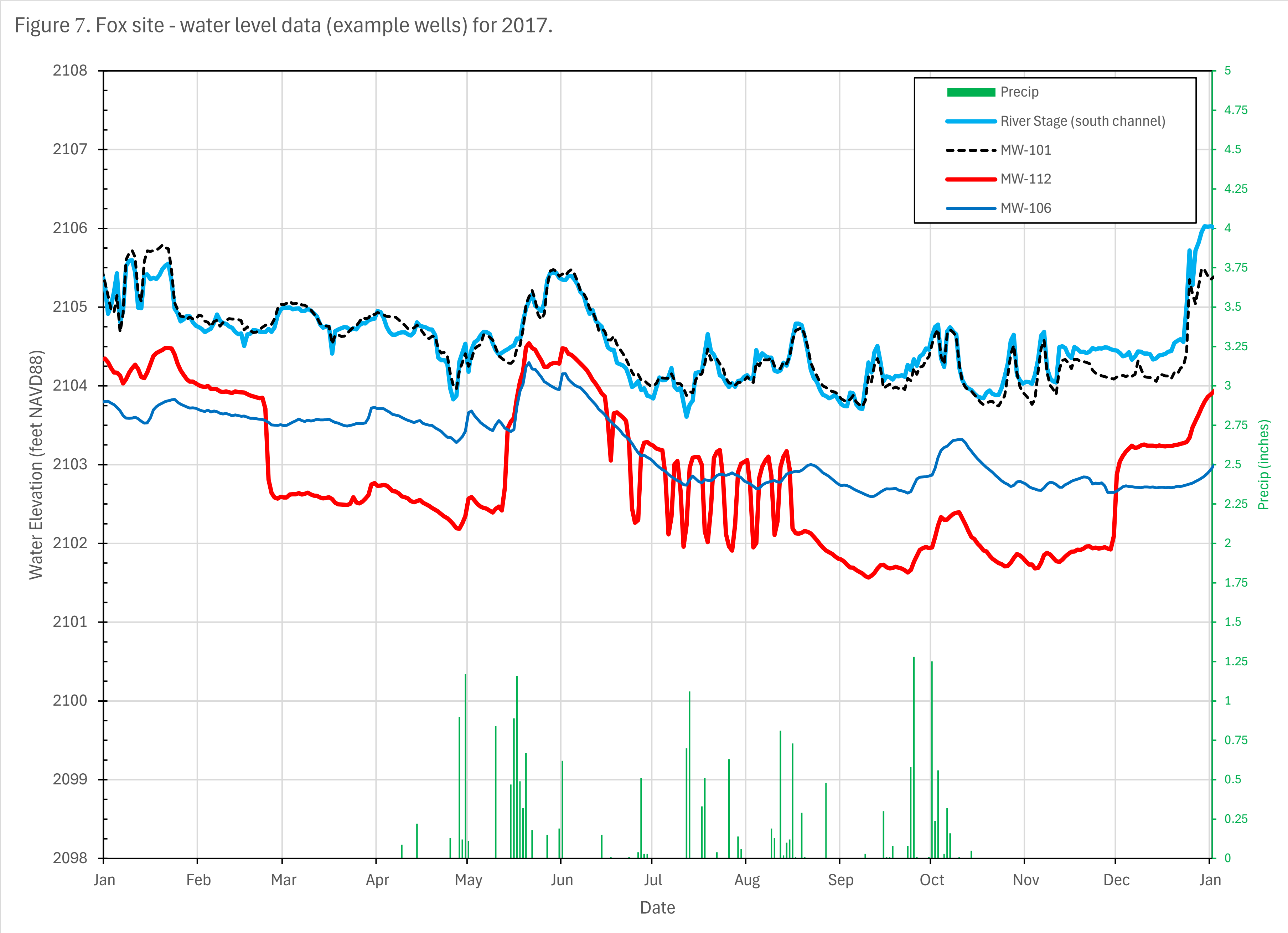
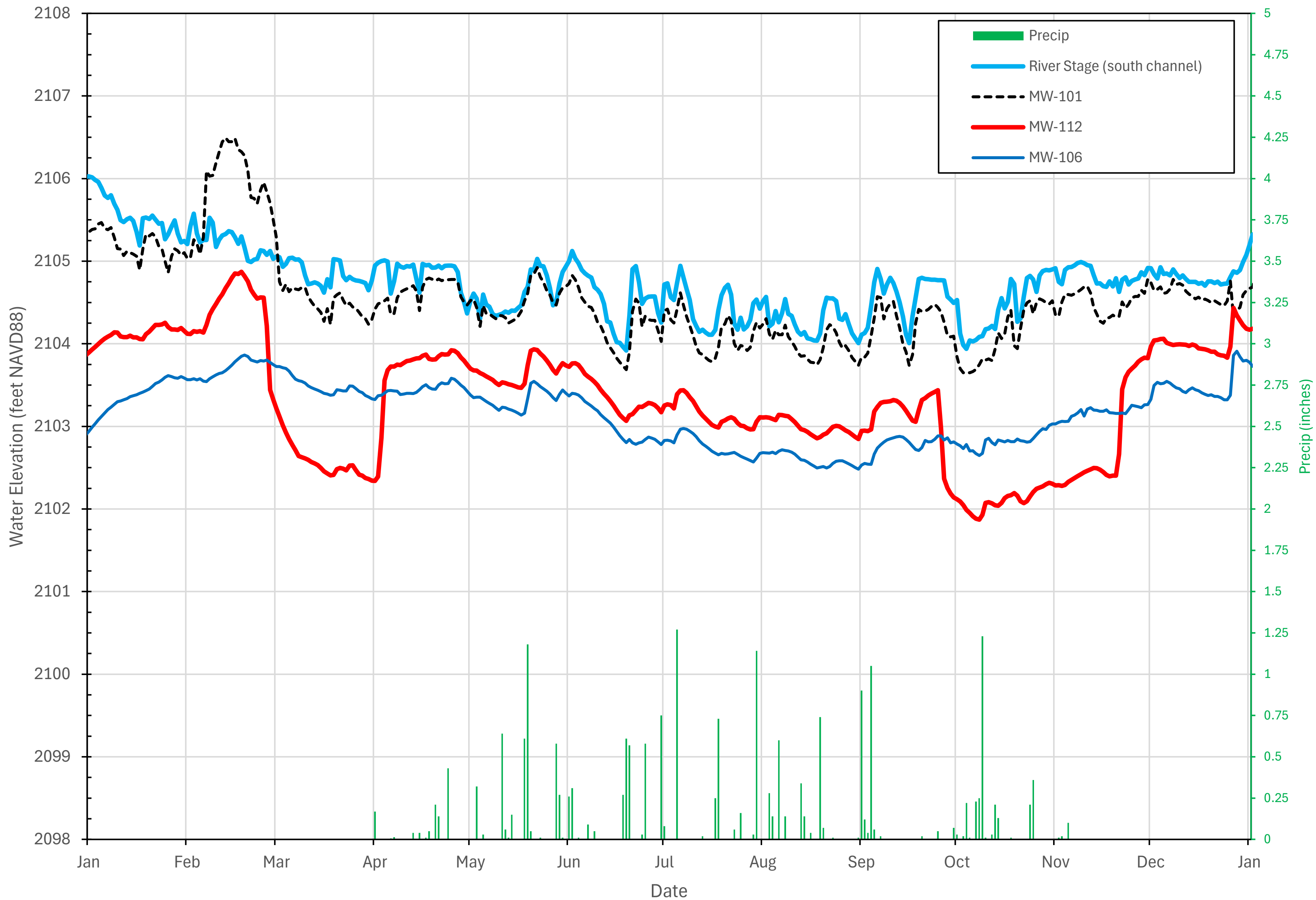


Figure 7. Fox site - water level data (example wells) for 2017.
Precip
River Stage (south channel)
MW-101
MW-112
MW-106
Water Elevation (feet NAVD88)
Precip (inches)
Date
2108
2107
2106
2105
2104
2103
2102
2101
2100
2099
2098
5
4.75
4.5
4.25
4
3.75
3.5
3.25
3
2.75
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan

DRAFT

Figure 8. Fox site - water level data (example wells) for 2018.

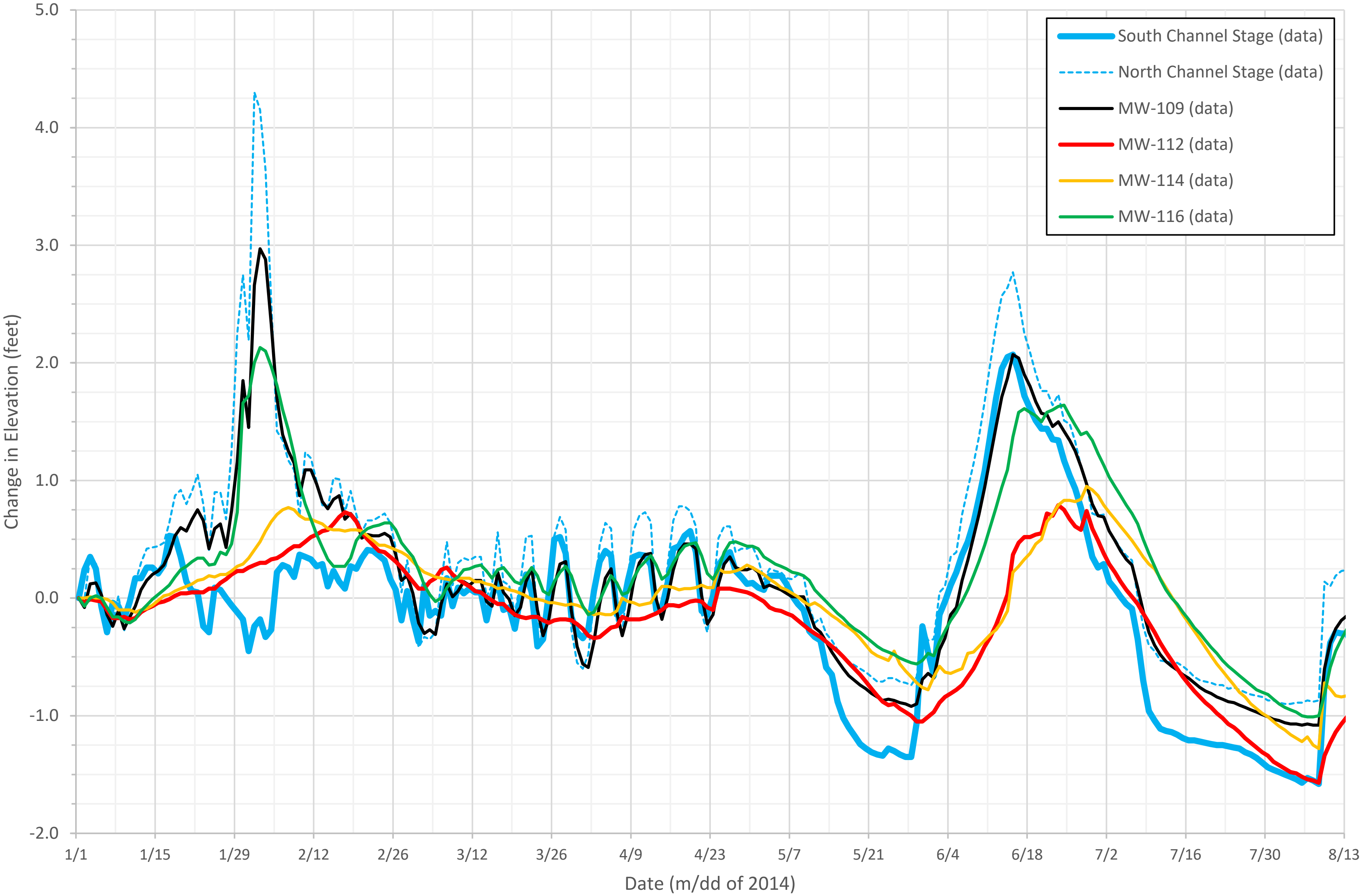


DRAFT

Figure 9. Fox site - water level data (example wells) for 2019.

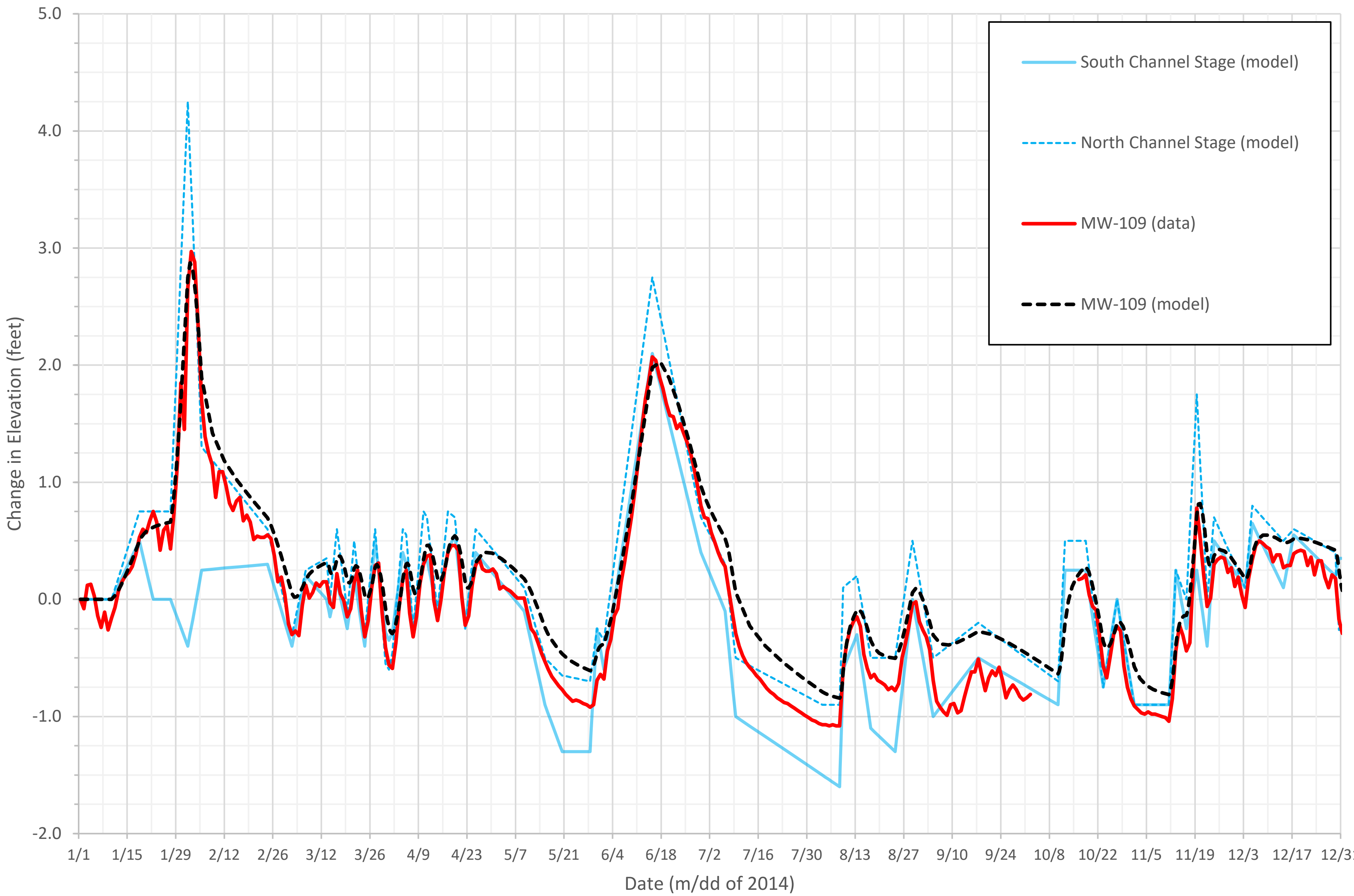
DRAFT

Figure 10. Observed water level changes in early 2014 (Jan-Aug) at key monitoring well locations.



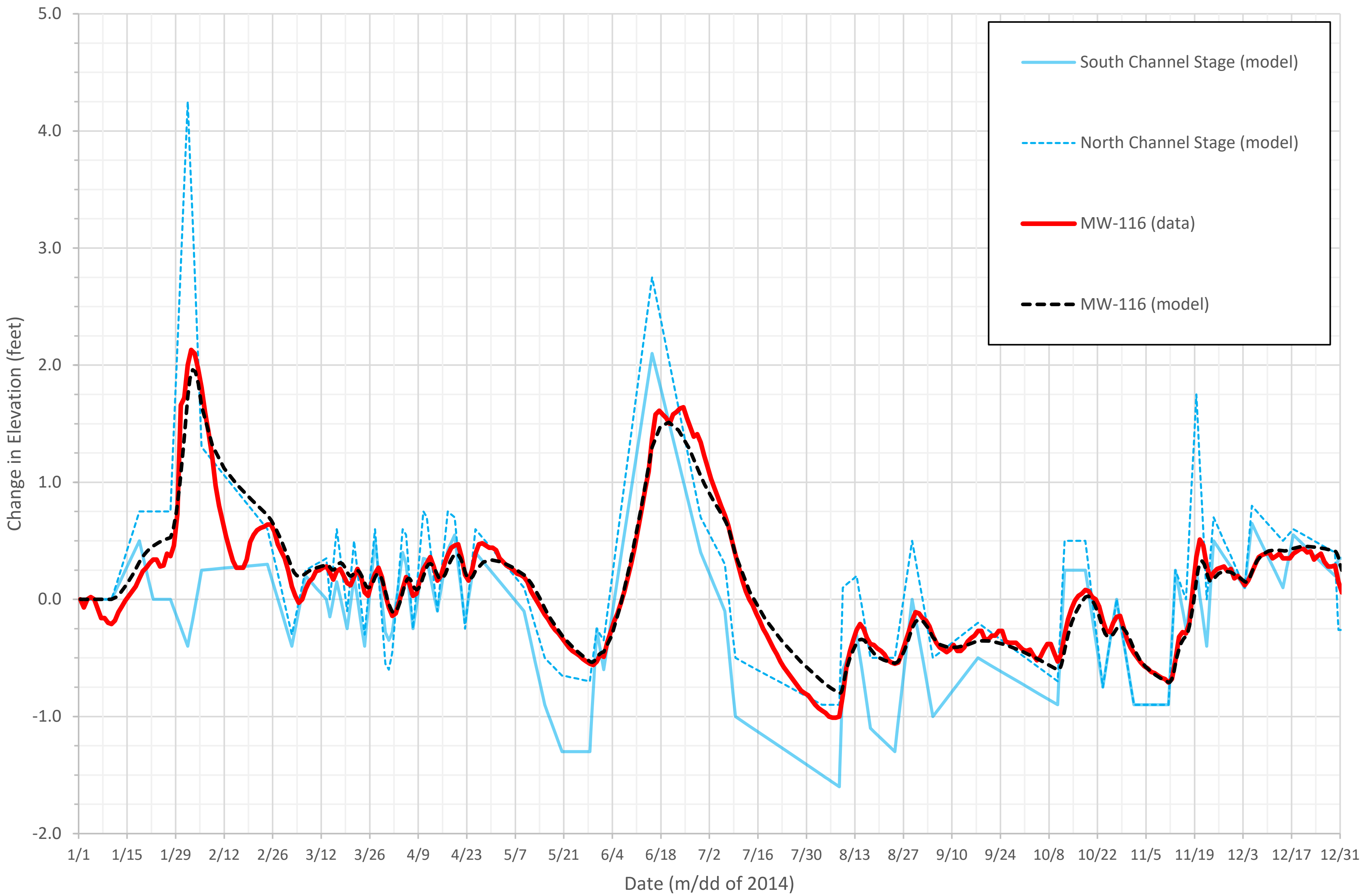
DRAFT

Figure 11. 2014 Observed and modeled water level changes at MW-109 (near north channel).



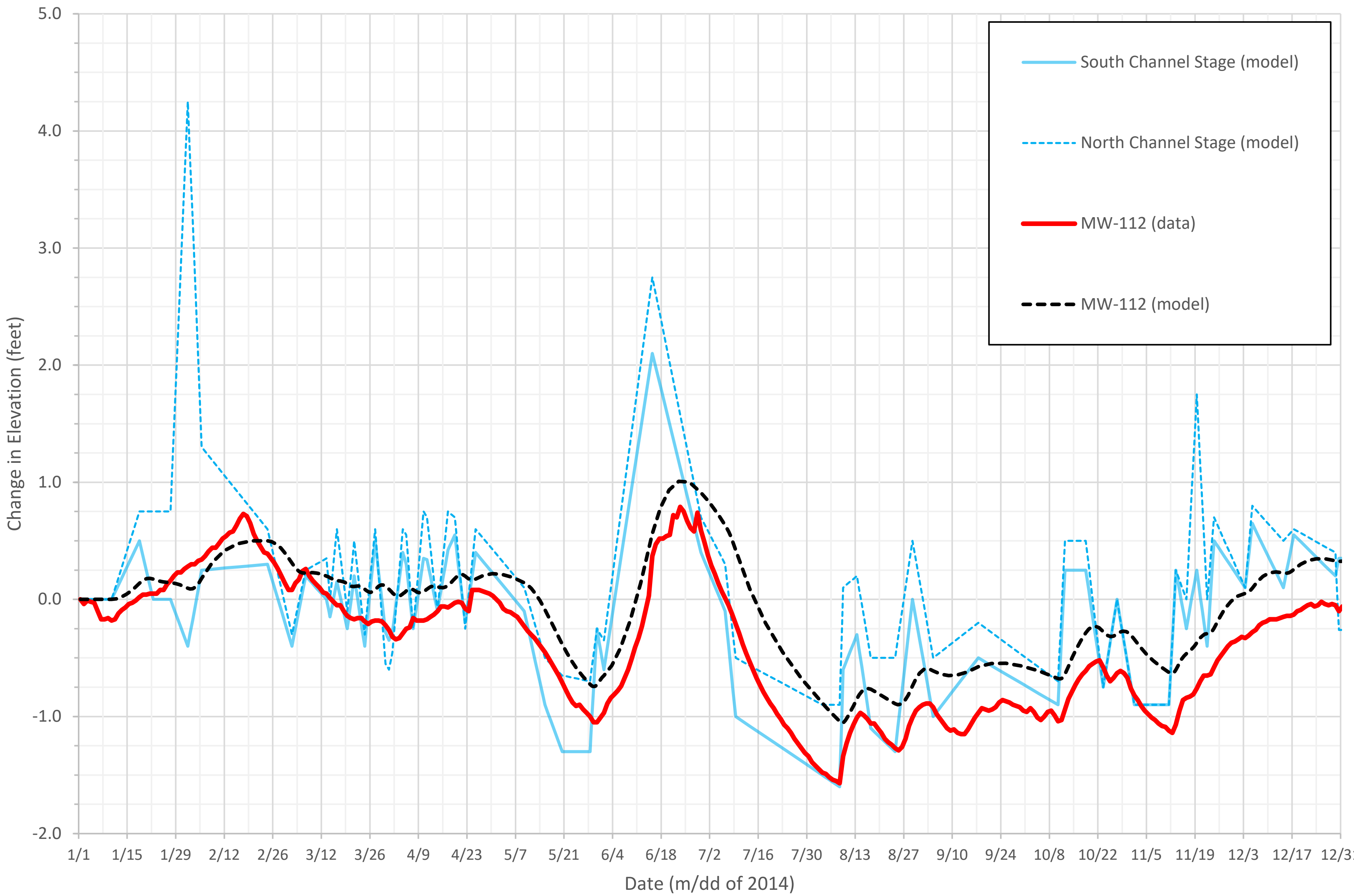
DRAFT

Figure 12. 2014 Observed and modeled water level changes at MW-116 (further from north channel).



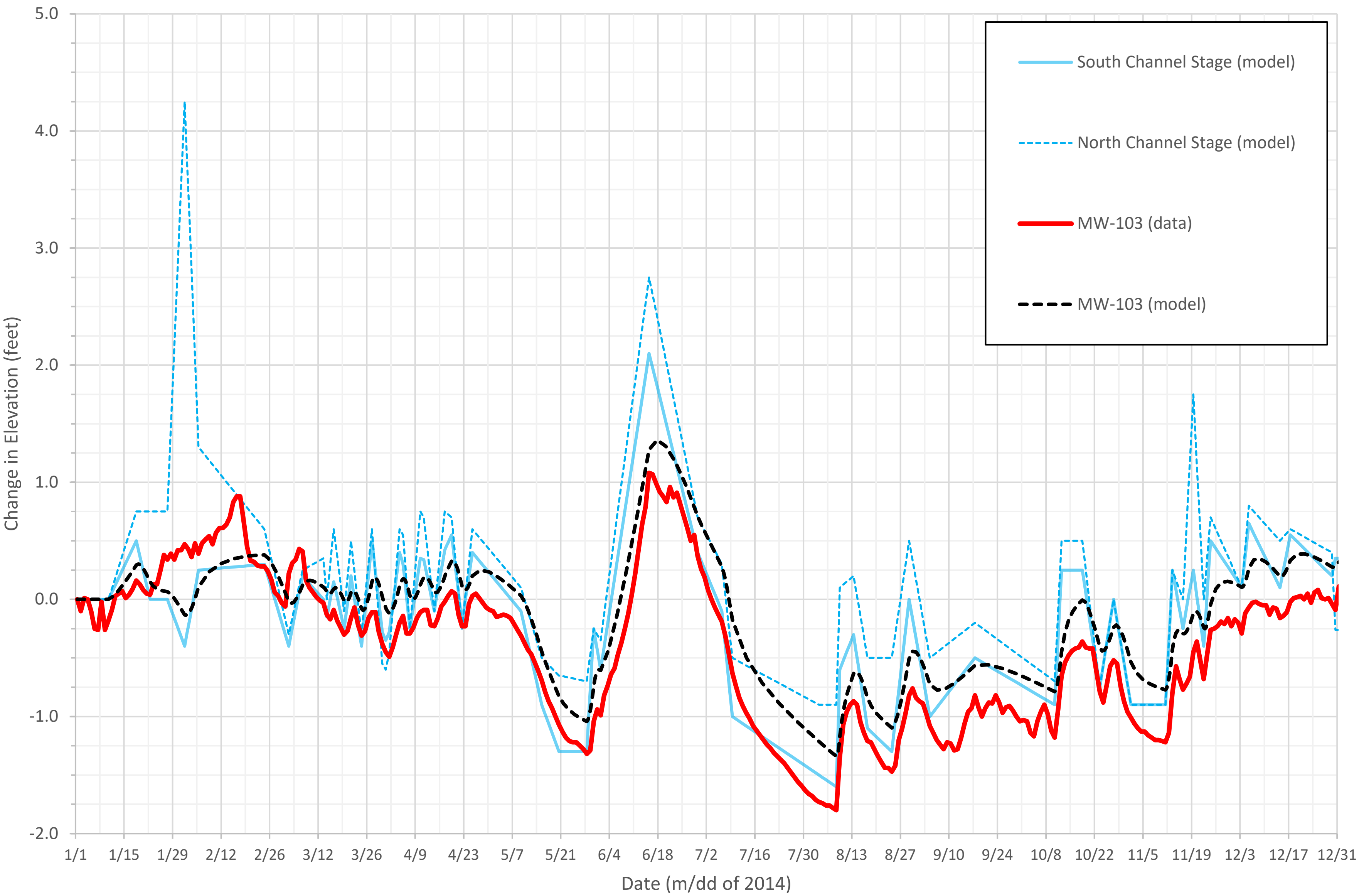
DRAFT

Figure 13. 2014 Observed and modeled water level changes at MW-112 (far from north channel).



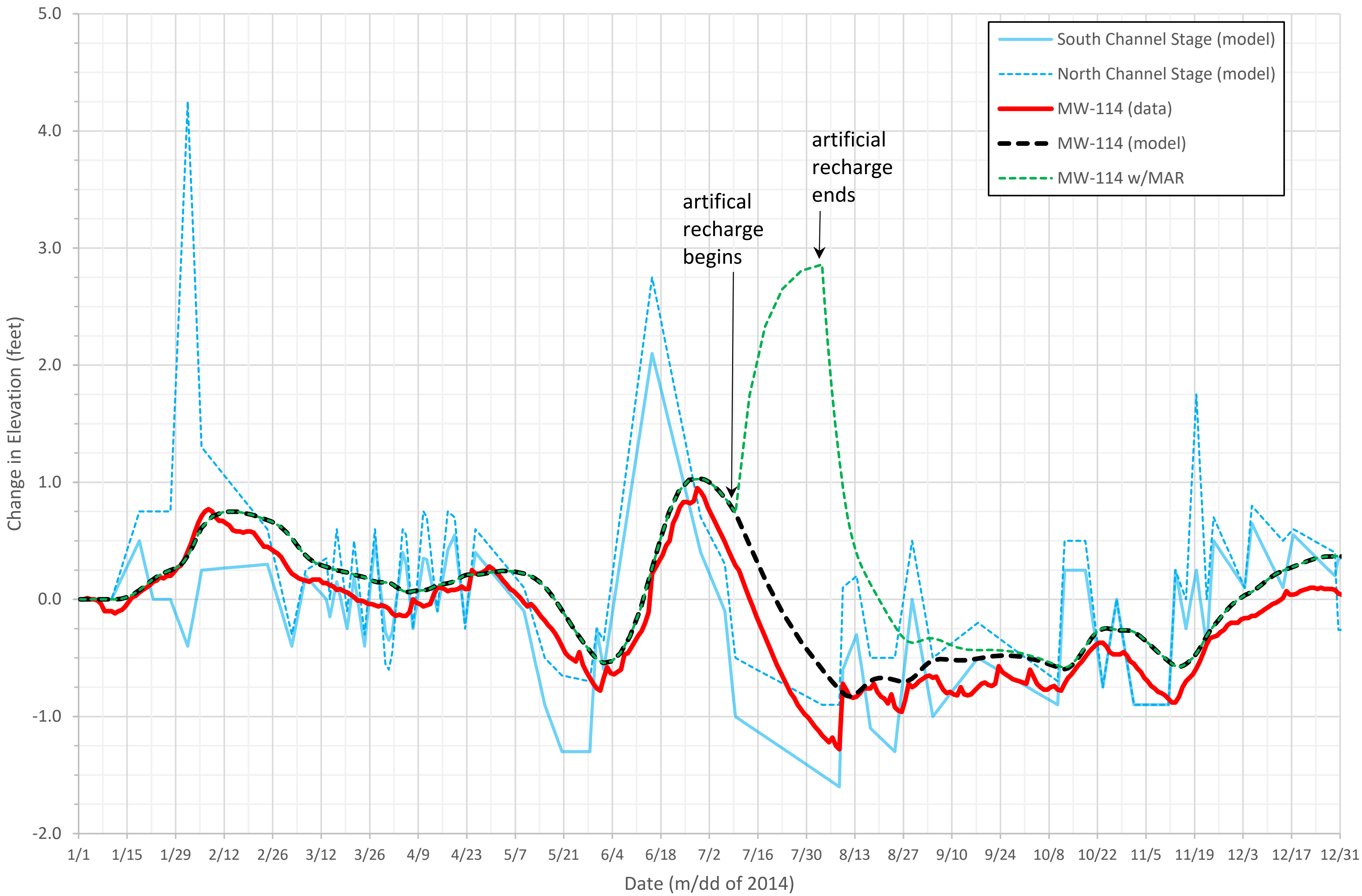
DRAFT

Figure 14. 2014 Observed and modeled water level changes at MW-103 (close to south channel).



DRAFT

Figure 15. Observed & modeled water level changes at MW-114, plus simulation with managed aquifer recharge (MAR).



DRAFT

Figure 16. Observed & modeled water level changes at MW-116 plus simulation with managed artificial recharge (MAR).