DEPARTMENT OF NATURAL RESOURCES

Evaluation of Conceptual Groundwater-Use Management Actions, Little Rock Creek Area

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PROFESSIONAL GEOLOGIST

I hereby certify that this plan, document, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Geologist under the laws of the state of Minnesota.

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Introduction

The Minnesota Department of Natural Resources (DNR) completed the Sustainable Use of Groundwater in the Little Rock Creek Area action plan (Plan) in September 2018. Figure 1 shows the “focus area” that DNR delineated to select permit holders and other stakeholders for engagement during development of the Plan. The Plan focuses on ensuring that groundwater uses do not have a negative impact on Little Rock Creek.

DNR determined that permitted groundwater use has at times had an adverse impact on Little Rock Creek during the evaluation period from 2006 through 2018 (DNR, 2021a and 2021b). DNR’s analysis concluded that groundwater use diverted groundwater discharge to the stream network and reduced stream habitat relative to a no-use, reference condition, particularly during low flow periods in four of the summers (2006, 2008, 2012, and 2013). Stream base-flow diversions were calculated as the difference between model-computed, base flows under a condition with no groundwater use and under baseline conditions representing actual history.

The DNR is considering imposing sustainable diversion limits at three streamflow monitoring stations on Little Rock Creek to avoid future adverse impacts to stream habitat. Based on stream-habitat analysis, the sustainable diversion limits would be set to no more than 15 percent of the reference August median base flow (the base flow representing no groundwater use) at each of the three continuous stream gauges. The August median base flow serves as an index connecting stream habitat to streamflow and a sustainable diversion limit (DNR, 2016). In proposing these targets, DNR acknowledges uncertainties in actual groundwater use volumes, reference base flow, and computed base-flow diversions.

The DNR’s LRCA (Little Rock Creek Area) action plan (Plan) calls for evaluating five conceptual categories of management actions that could potentially increase base flow in Little Rock and/or Bunker Hill Creeks during summer low flow periods. These actions are:

- Stream augmentation with groundwater;
- Enhancing water conservation methods, including irrigation scheduling;
- Increasing groundwater recharge;
- Supplying irrigation water from wells that are farther away from the creek;
- Modifying existing water appropriation permits.

The other evaluations DNR committed to in the Plan relate primarily to other concerns. This report describes analyses supporting evaluations of the types of actions listed above.

Purpose and Scope

DNR pursued two lines of modeling analysis to explore the potential of the five types of management actions to mitigate base-flow diversions: characterizing the relationships between water use and base-flow diversions in time and space/location, and testing hypothetical scenarios representing management actions. The developed scenarios are conceptual in nature. Implementing one or more of the concepts would require additional, site-specific work such as field testing and engineering feasibility assessment and design.

DNR developed scenarios to test four of the five types of management concepts. Although there may be opportunities to increase groundwater recharge in the areas along or adjacent to Little Rock Creek and its tributaries, DNR did not develop such a scenario. To provide mitigation using enhanced recharge, a project would have to be developed that gets the timing right to benefit base flow during critical summer periods. It may be possible to divert streamflow during high flow periods to downgradient, upland areas, but significant land area would be needed to infiltrate the necessary quantities of water. There could also be water-quality concerns with the infiltrated water. Estimating the potential for wetland restoration to enhance recharge and summer base flow would require substantial field investigations to characterize wetland hydrology.

Previous Studies and Hydrologic Model

DNR developed a hydrological modeling system for the LRCA (DNR, 2021a) that uses three modeling codes (LRCA model): Gridded Surface Subsurface Hydrologic Analysis (GSSHA) developed by the U.S. Army Corps of engineers, a simple unsaturated zone routing scheme developed by DNR, and Modular Groundwater Flow, Unstructured Grid (MODFLOW-USG), developed by the U.S. Geological Survey.

The GSSHA model computes hydrologic processes on the surface, in the soil root zone, and in a two-dimensional, saturated groundwater-flow domain. The GSSHA model uses short, adaptive time steps, is very computationally intensive, and has long run times. Long run times impose limits on the number of model runs and the types of analyses that are practical.

The modeling system routs net groundwater recharge computed by GSSHA to a pseudo three-dimensional MODFLOW-USG model. The MODFLOW-USG model computes groundwater heads and flows from the water table to the bedrock surface and exchanges of water between groundwater and surface-water features using monthly stress periods during which inputs are held constant.

DNR used the LRCA model to compute stream base flows for two key scenarios for an analysis period spanning growing seasons from 2006 through 2018: a baseline scenario representing actual history (reported water use and simplified land cover), and a no-use scenario with no groundwater use and irrigated crops replaced with non-irrigated alfalfa. DNR applied alfalfa in place of irrigated row crops in the no-use scenario because alfalfa has high water demand relative to the range of possible agricultural land covers, has relatively well-established hydrologic properties, and is commonly grown in the LRCA.

The difference between the computed base flows in the no-use model and in the baseline model are the computed base-flow diversions. Notably, this subtraction of base flows from two model runs removes or subtracts out some of the model error that is common to both model runs such as errors in precipitation inputs or recharge in non-irrigated areas (DNR, 2021a).

DNR used the computed base-flow diversions to establish the reference streamflow and base flow representing conditions with no groundwater use. The reference streamflow (base flow) is the sum of the streamflow (base flow) derived from gauging records and the computed base-flow diversion. Again, this approach is more accurate than using the no-use model results directly to represent the reference condition.

Management Goals and Evaluation Points

DNR's analysis in a reach immediately below the upstream, continuous stream gauge (H15029003) indicated that measures of stream habitat differences in August would remain less than 20 percent if August base flow diversions were less than 15 percent of the August median base flow of 5.5 cfs. Base flow diversions during other periods of the year could also be a concern for habitat impacts. Base-flow diversions are largest in August, whereas summer base flows are typically lowest during August. Therefore, August base flow is an appropriate index for setting sustainable diversion limits.

Assuming that the relative index calculated for the stream reach that was studied in the habitat analysis (DNR, 2021b) applies to other reaches of the stream, DNR computed the equivalent index at two other gauges: the long-term gauge (H15029001), and the most down-stream gauge (H15031001). This index is the proposed sustainable diversion limit (SDL) at each gauge. DNR extrapolated data using the long-term gauge for portions of the analysis period without continuous streamflow record at the downstream gauge using the same method applied previously to backfill data for the upstream gauge (DNR, 2021a). The downstream gauge has continuous streamflow data for August 2007, but these data were not included when calculating the median August base flow because 2007 was excluded from the analysis of the other gauges due to missing data at those stations. The calculated flow statistics are shown in Table 1.

Table 1. Reference August flow statistics (2006, 2008 through 2018)

Gauge Station	Periods of Continuous Record	August Median Streamflow (cfs)	August Median Base Flow (cfs)	15 Percent of August Median Base Flow (cfs)
Upstream, 15029003	7/2014 - present	6.58	5.49	0.82
Long Term, 15029001	Multiple non-winter periods 3/1998 – 11/2005, 3/2006 – 11/2006, 12/2007 – 7/2015, 12/2015 - present	8.84	7.19	1.1
Downstream, 15031001	6/2006 – 9/2007, 3/2008 – 11/2008, 3/2009 – 9/2011, 7/2017 - present	21.8	19.2	2.9

Hydrologic Model Testing and System Characterization

Previous Sensitivity Testing, Sources of Uncertainty, and Implications

DNR performed several model tests to explore the sensitivity to model parameters and model assumptions, which are potential sources of uncertainty in model-analysis results (DNR, 2021a). These included an alternative no-use scenario in which irrigated row crops were replaced with non-irrigated row crops (Scenario 1), a preliminary model version with a different scheme for setting parameters that drive crop evapotranspiration (ET), and a scenario that assumed historical groundwater use was actually 80 percent of reported use.

The calculated base-flow diversions were highly sensitive to contrasting land-cover parameters in the two no-use scenarios (Scenario 1 and the chosen no-use version, Scenario 2) that control ET and recharge in irrigated areas, but they were less sensitive to the differences in parameterization schemes between the preliminary model and Scenario 1. A no-use scenario comparable to Scenario 2 was not developed for the preliminary model.

Flow-meter measurements collected from 9 irrigation systems in and near the LRCA during 2018 and 2019 indicated that some water-use reports overestimate actual water use, primarily due to inaccurate estimates of the average pumping rate (DNR, 2021c). Reported water-use accuracy was highly variable, however. Reducing all groundwater uses to 80 percent of reported use decreased the calculated August base-flow diversions by 10 to 160 percent at the long-term gauge (15029001). The maximum monthly base-flow diversion was 24 percent smaller than for the baseline model (1.46 cfs versus 1.93 cfs). Treating the 80-percent scenario as the baseline, representing actual history, also resulted in smaller, reference August median base flow (e.g., 7.0 cfs vs. 7.2 cfs at the long-term gauge). These values would, in turn, result in slightly smaller diversion limits.

Considering a lack of knowledge about the accuracy of reported uses for all of the other permits in the area, DNR continues to use the baseline model that applies reported water use.

Timing and Spatial Relationships of Computed Base-Flow Diversions

The timing and locations of groundwater pumping and irrigation strongly influence the computed base-flow diversions. Seasonal pumping causes seasonal drawdown in confined aquifer pressure and the water table. Drawdown decreases rapidly with distance and is also smoothed out in time. At sufficient distance, drawdown due to individual pumping cycles and seasonal use is spread throughout the year.

The timing and spatial distribution of recharge have similar effects on the water table. Crop irrigation increases groundwater recharge relative to the reference land cover of non-irrigated alfalfa because irrigation increases soil moisture. Enhanced recharge occurs after large summer rainfall events, in the fall as evapotranspiration (ET) rates decrease, and even the following spring if there is a winter soil-moisture deficit for non-irrigated alfalfa.

An important result of the no-use model (Scenario 2) is that the long-term average base flow was smaller than computed for the baseline model (8 percent less at the long-term gauge, 5 percent less at the downstream gauge) despite no groundwater pumping in the no-use model. This contrasts with the generally lower base flows in the baseline model for July through September or October. The lower summer and early fall base flows in the baseline model were offset by higher flows in the baseline model during the rest of the year.

This seasonal pattern of base-flow differences is the net result of differences in groundwater pumping, recharge, and water-table ET between the two models (DNR, 2021a). These model results indicated that net base-flow diversions due to irrigation with groundwater are seasonal, restricted to all or part of the period from July through October.

One implication of this result is that base-flow diversions due to groundwater use for irrigation is not a concern during winter, low flows. Computed, winter base flows are slightly larger in the baseline model than in the no-use model (Scenario 2). Water-level data from observation wells screened in buried artesian aquifers show rapid rises after the irrigation season, which is generally consistent with the seasonal nature of computed impacts.

An implication of average, net recharge being larger in the baseline model is that at a sufficient distance from the stream network, groundwater use for irrigation could not only result in zero base-flow diversion during the summer/early fall, but distant irrigation could actually result in slightly larger computed summer base flows than the no-use land use. This is because at sufficient distance from the stream network, pumping drawdown at the stream caused by the distant well is small and smoothed out in time. This small, smoothed-out drawdown at the stream could be more than offset by the larger, long-term average net recharge corresponding to irrigated crops, which also propagates to the stream.

These model results also indicate that not all of the permits in the LRCA study area contribute to the computed base-flow diversions in Little Rock and Bunker Hill creeks. Even if this was not the case, impacts would vary greatly with well location. Therefore, characterizing the spatial relationships between water-use locations and the timing and magnitude of base-flow diversions was an important step.

Capture Analysis

DNR selected several model experiments to begin characterizing spatial relationships in the model. These included changing the screened aquifer for selected wells and removing either just the pumping or both the pumping and irrigation for selected groups of permits. These experiments provided some initial insights on the effects of well location and depth and irrigation location that prompted a more systematic analysis.

The relationship between groundwater pumping at a particular location and the corresponding diversion (or capture) from a stream, from a lake/wetland, or from groundwater evapotranspiration is commonly referred to as a response function (e.g., Barlow and Leake, 2012). A response function can be plotted as a hydrograph of the rate of diversion over time. One calculates a response function with a numerical model by applying pumping at a particular location (an actual well or a hypothetical well) and then subtracting the result of interest (e.g., stream base flow at a particular point) from the corresponding value in the baseline model without the added pumping.

One may characterize the spatial relationships in the model between well locations and stream base-flow diversions by calculating the response functions for a relevant pumping pattern (e.g., representing seasonal irrigation) at many locations throughout the area of interest, a method commonly referred to as capture mapping.

The response functions are typically expressed as the dimensionless fraction of the diversion rate/volume divided by the pumping rate/volume. This provides the "capture fraction" at each tested location. In an idealized, "linear" model (a good approximation in some settings), the capture fraction does not depend on the pumping rate or other hydrological conditions in the model. In that case, one can calculate the expected diversion at a particular time as the pumping rate multiplied by the capture fraction for that time.

For a "non-linear" system like the LRCA, the capture fraction can vary with the pumping rate and the other time-dependent hydrologic conditions in the model (See DNR, 2021a for further explanation of non-linearity in the LRCA model and Barlow and Leak, 2012 for a more general description). Nevertheless, calculating capture fractions using a uniform pumping regime at each location is a useful way to make a relative comparison of the effects of pumping across the tested locations.

To fully account for the effects of ground-water sourced irrigation on computed base flows, however, one must include both well pumping and the effects of irrigation as they contrast with the non-irrigated reference crop. This presents a practical challenge for the LRCA model because the GSSHA component has a long run time.

It was straight forward applying the capture mapping technique to the well pumping only using the MODFLOW-USG model. This could provide useful information to guide a limited number of full model runs with both the GSSHA and MODFLOW-USG components to identify and test scenarios for evaluation.

To implement capture mapping, the applied pumping should represent the impact of interest and be large enough to overcome any noise due to numerical precision of the model. In addition, the pumping was applied as injection rather than as extraction to ensure that the added pumping did not cause excessive drawdown in existing wells that already were pumped in the baseline model. For these simulations, injection causes very nearly the same absolute magnitude difference in base-flow diversions as would withdrawals.

The analysis employed a typical, generic sequence of monthly pumping volumes totaling 100 acre-feet or 32.59 million gallons to the 2006 irrigation season. This follows the initial model spin-up period with monthly stress periods beginning in January 2005. Recall that the LRCA model employs monthly stress periods in which pumping rates and net recharge rates are constant within each month. The volume was distributed as 20 percent in June, 50 percent in July, and 30 percent in August. The average pumping rate during the peak month of July was 525,566 gallons per day (365.0 gpm or 0.8126 cfs). The pumping was added to the baseline model to place each model run in the existing hydrologic context. The capture fraction for comparison was taken as the monthly average difference in base flow divided by the average July pumping rate, with values calculated for July, August, and September.

The initial analysis included model runs for existing irrigation well locations within about 2.5 miles of the portion of Little Rock Creek that crosses the sand plain. This allowed comparisons of existing permits within the area closer to Little Rock Creek, beyond which the capture fractions become very small. The capture analysis was later extended to additional, hypothetical well locations to refine mapping of the boundaries where irrigation-induced base-flow diversions transition to zero within both the buried artesian aquifer system and the water-table aquifer. The next section describes delineation of these boundaries.

Initial model tests and capture mapping runs demonstrated that pumping from the water-table aquifer does not always cause more base-flow depletion than pumping from a semi-confined (artesian) aquifer. At sufficient distance from the stream network, seasonal pumping from the water-table aquifer causes less base-flow diversion than pumping from an underlying, semi-confined aquifer. Model tests suggest that this transition distance is typically within about ½ mile of the perennial stream network.

One factor behind this system characteristic is that the much larger storage release at the water table (i.e., specific yield), compared to confined aquifers causes drawdown in the water-table to propagate much more slowly than drawdown in semi-confined aquifers. Drawdown due to pumping from distant water table wells is delayed and may build up over many years. As described above, at longer time scales, the larger net recharge of irrigation offsets long-term drawdown due to pumping in the LRCA model.

Drawdown from pumping semi-confined aquifers can propagate to Little Rock Creek relatively rapidly because the confining units are leaky, vary laterally in thickness, and are thin or absent in many areas near Little Rock Creek. This is known from well boring logs and is also demonstrated by the small vertical head differences maintained throughout the year between the water table and semi-confined aquifers at an observation-well nest located near the upstream, continuous monitoring gauge on Little Rock Creek. Therefore, pumping drawdown in semi-confined aquifers can propagate more readily upward near the creek. Barlow and Leake (2012) described this type of effect of discontinuous aquitards.

Non-Irrigation Uses

The only non-irrigation, groundwater appropriation permit with wells that may substantially influence base flow in Little Rock Creek is the City of Rice municipal permit. These wells pump year-round and have a different pattern of impacts on base flow than do irrigation permits. To test the influence of the municipal permit, DNR made a separate model run with just the City of Rice wells removed. The difference in base flow between this model run and the baseline model represents the impact of this permit. This test indicated that the City of Rice municipal permit reduces base flow at the downstream gauge (15031001).

Spatial Extents of Irrigation Influence

The zone of irrigation influence defines the boundary between locations where groundwater uses for irrigation cause computed base-flow diversions and those that cause zero diversion or an increase in base flow (negative diversions). There are several complications to delineating this area.

The influence of well pumping depends on the depth of the well screen in addition to its horizontal location. For any given location, the largest difference with depth is whether the well is screened in the water-table aquifer or a buried aquifer. These differences will be discussed below in the analysis results.

The effects of groundwater-sourced irrigation on computed base flow vary with volume and timing of irrigation use and also with groundwater and stream levels (i.e., base-flow diversions are “non-linear”). This means that the boundary could vary somewhat from year to year. Therefore, one must evaluate the aggregate effects of permits under a range of relevant hydrologic conditions to delineate the zone of irrigation influence. This must include both the effects of well pumping and the effects of irrigation on net recharge (recharge and groundwater ET).

Delineation Criteria

The computed base-flow diversions should be close to zero if influential permits have been removed. The zone of irrigation influence was, therefore, confirmed by modeling the no-use model conditions within a test zone (no pumping and irrigated crops replaced by non-irrigated alfalfa) while maintaining baseline model conditions elsewhere in the full LRCA model. Pumping was also removed from the City of Rice wells, which were shown to influence the downstream gauge.

Table 2 shows the computed base-flow diversions for August and September for a scenario in which the City of Rice wells and irrigation permits with a capture fraction (ratio of computed base-flow diversion to average July pumping rate) less than a cutoff value were removed. The cutoff capture fraction was 0.019, which corresponds to a base-flow diversion of 10,000 gallons per day (6.9 gpm or 0.0155 cfs) for the pumping rate used in the capture mapping analysis.

The test scenario removed 78 permits and 90 wells as of 2013, although one of these permits has since been terminated due to a change in land use. If applied in 2021, the test would have removed an additional 6 permits and 6 wells that were added since 2013.

The computed base flows in this scenario were slightly larger than for the no-use model during most of these months (negative diversion values). This indicates that, for the remaining irrigation systems, pumping drawdown in late summer is usually offset by the longer-term, larger net groundwater balance (recharge minus ET) for groundwater irrigated crops. In 2013, however, there was a small base-flow diversion in September, and August diversions were very close to zero. These results indicate that the zone of irrigation influence was largest from late August into September of 2013.

The different result for 2013 appears to be driven primarily by the timing of groundwater uses in these years. In most higher demand years, irrigation volumes are largest in July with significant use from June through August. In 2013, irrigation use was about the same in July and August with little use in June and significant use in September. Although the computed diversions for 2013 were largest in August for the baseline model, this scenario only retained more distant permits.

A generally applicable zone of irrigation influence should include all permits that may cause some base-flow diversions in at least some years. The test results indicate, therefore, that the selected capture-fraction cutoff was an appropriate choice for identifying the group of permits that could cause base-flow diversions in the full model, given the very small, positive diversions in September 2013.

Table 2. Computed monthly base-flow diversions for a model scenario with potentially influential permits removed

Year	Upstream Gauge, August Diversion (cfs)	Upstream Gauge, September Diversion (cfs)	Long-term Gauge, August Diversion (cfs)	Long-Term Gauge, September Diversion (cfs)	Downstream Gauge, August Diversion (cfs)	Downstream Gauge, September Diversion (cfs)
2006	-0.20	-0.21	-0.18	-0.18	-0.33	-0.32
2008	-0.07	-0.10	-0.08	-0.09	-0.08	-0.11
2012	-0.11	-0.10	-0.11	-0.09	-0.19	-0.16
2013	-0.04	0.03	-0.06	0.02	-0.024	0.071

Zones for Buried Artesian and Water-Table Aquifers

The model test described above indicated that the selected capture-fraction cutoff is an effective criterion to delineate the area where groundwater pumping for irrigation near the well(s) could cause net base-flow diversions in the full LRCA model. DNR delineated a preliminary zone of irrigation influence for the buried artesian aquifer system using the capture modeling results for 132 exiting wells.

These data points provided limited spatial resolution in some areas, particularly for the water-table aquifer. An additional 151 locations were selected for capture analysis to fill gaps in both the buried artesian system and the water-table aquifer where there are no existing wells. Although there were differences in the computed capture fractions for different buried artesian aquifers at some locations, these differences were relatively small compared to the differences with the water-table aquifer.

For simplicity, DNR delineated a zone for the buried aquifer system (QBAA) and a separate zone for the water-table aquifer (QWTA). To better reflect the precision of the information and to make the boundaries more easily recognized on the ground, the zones of irrigation influence were delineated using ¼ ¼ Section increments. Figure 2 displays the zones of irrigation influence and the capture modeling data points used to delineate these zones. The aquifers may be thin or absent in some areas within each zone. Irrigation wells located outside of the relevant zone of irrigation influence are expected to have negligible or positive influence on base flows in Little Rock Creek at the three evaluation stations (upstream, long-term, and downstream).

Uncertainty in and Applicability of the Zones of Irrigation Influence

The model incorporates features of aquifer, aquitard, and stream geometries that can be discerned from available data, and provides the best information available. Nevertheless, the modeling system is an imperfect simulator of the actual hydrology, and some model uncertainty is unavoidable. One limitation to evaluating the effects of different permits/locations is that the model cannot account for unknown, local variations in aquifer-system and stream-bed properties. This means that the model simplifies and smooths out some of the local variations. The boundaries of these zones are also influenced by the sensitivity of the computed diversions to the contrasts in evapotranspiration and recharge between the baseline model and the no-use model (Scenario 2), as are the computed base-flow diversions for the baseline analysis.

It is worth noting, however, that as the distance from the stream network increases, there is a general decrease in the change in the response function with each increment of distance. For example, all other things being equal, there is a larger contrast in impacts between uses ¼ and ½ mile from the stream than the contrast in impacts between uses 1 and 2 miles from the stream. This means that, wherever the "true" boundary of the zone of irrigation influence should be in the actual aquifer system, the differences in influence near the boundary are small.

Exploration of Spatial Relationships through Selected Removal of Groundwater Use

To further explore and illustrate the relationships between groundwater-use locations and computed base-flow diversions, DNR developed a model scenario with the goal of removing selected water-appropriation permits such that base-flow diversions would have remained below the target diversion limits at the three evaluation stations. This scenario does not represent a potential management action.

Permits were selected using capture-modeling cutoff values without considering use volumes, similar to the approach taken to delineate the zones of irrigation influence. This approach did not minimize the number of permits removed but approximately minimized the acreage of irrigation removed.

Because the base-flow gain rate is generally smaller in the reaches measured by the upstream and long-term gauges, different cutoff fractions were selected for the long-term and downstream gauges. The selected capture-fraction cutoff values, indexed to the July pumping rate, were 0.16 at the long-term gauge and 0.24 at the downstream gauge. These capture fractions were estimated by assuming that the base-flow diversion attributable to each permit scaled with the capture fraction multiplied by the 2013 water use for the permit. The selected capture fractions removed the percentages of these capture-fraction based diversions equal to the necessary percentage reductions in computed diversions in the full model.

These cutoff values result in 20 permits and 20 wells removed during the 2006 through 2013 period; one newer, existing permit and well would be included (Figure 3). Four of the 20 permits plus the one, post-2013 permit exceeded only the smaller, long-term station cutoff. Four of the 20 permits did not report any use until either 2007 or 2008 but did report water use for later years (i.e., they reported use for only part of the analysis period). The 21 existing permits represent 2391 permitted acres and 2305 mapped, irrigated acres. DNR delineated irrigated acres using digital aerial photographs. There may be small discrepancies between actual irrigated acres and mapped acres, but actual irrigated acres can also differ from permitted acres. In most cases where there is a discrepancy, permitted acres exceeded the mapped irrigated acres.

Table 1 displays the computed August and September base-flow diversions for the four critical years when differences in stream habitat measures exceeded 20 percent in August, and base-flow diversions exceeded 15 percent of the reference, August median base flow (proposed sustainable diversion limit, SDL): 2006, 2008, 2012, and 2013 (DNR, 2021a and 2021b). Note that, similar to the scenario that removed all permits within a zone of irrigation influence, the maximum computed diversions were in September 2013. These maximum computed diversions were 13 to 14 percent of the reference, August median base flow at each evaluation station. For the baseline model, the maximum computed diversions were in August of 2006 and 2013.

Table 3. Computed August and September base-flow diversions for a scenario that removes 20 permits that were active within the period 2006 through 2013.

Year	Upstream Gauge, August Diversion (cfs) (SDL = 0.82)	Upstream Gauge, September Diversion (cfs)	Long-term Gauge, August Diversion (cfs) (SDL = 1.1)	Long-Term Gauge, September Diversion (cfs)	Downstream Gauge, August Diversion (cfs) (SDL = 2.9)	Downstream Gauge, September Diversion (cfs)
2006	0.58	0.33	0.91	0.56	2.3	1.6
2008	0.53	0.40	0.77	0.66	2.0	1.8
2012	0.36	0.27	0.56	0.45	1.5	1.3
2013	0.56	0.73	0.83	1.0	2.0	2.5

Evaluation of Conceptual Management Action Scenarios

This section describes model experiments designed to test four of the management concepts listed in the LRCA Plan that could increase base flow in Little Rock Creek (and in some cases Bunker Hills Creek) during critical, summer low-flow periods. These experiments do not represent complete designs ready for implementation, but they provide information on the potential of each concept.

Streamflow Augmentation with Well Water

One way to increase base flow during summer low-flow periods would be to withdraw water from wells and discharge it to strategic locations in the stream. DNR considered several factors relating to the net effects of augmentation on base flow in this initial evaluation. DNR conducted a preliminary evaluation of these factors by performing a model experiment of a hypothetical augmentation scenario. In addition, DNR identified additional concerns that would require further study to conduct environmental and permit review for an augmentation system.

Measures of Net Base-Flow Mitigation

As discussed in the Introduction, DNR assessed base-flow diversions in the recent past at three evaluation stations on Little Rock Creek. An effective augmentation system would bring net base-flow diversions above established limits at each of these stations during augmentation. Drawdown due to pumping the augmentation well will propagate to the stream and continue after cessation of pumping. Therefore, one must also consider both the resulting base-flow diversion above the upper-most discharge point during augmentation and net diversions along the entire stream length following augmentation. The drawdown at the stream could be limited by selecting a well location sufficiently far from the stream.

DNR or MPCA has made field measurements at two stations above the upstream continuous station since 2008. Table 4 lists field measurements made at the most upstream station (15029005) during periods when computed base-flow diversions exceeded limits at one or more evaluation station plus low-flow measurements in summer 2021, which were after the model-analysis period. At the measurement times in 2008 and 2021, there was no measurable flow at this station.

Table 4. Field measurements at station 15029005 during selected low-flow periods.

Date	Field Measured Streamflow (cfs)
7/28/2008	0.0
8/4/2008	0.0
9/5/2008	0.0
8/7/2012	1.0
9/11/2012	0.26
8/29/2013	0.44
7/29/2021	0.0
8/19/2021	0.0

Flows of one cfs or less were measured in 2012 and 2013. During periods of no flow, groundwater diversions are not possible, but groundwater diversions could be a concern during periods of low flow such as occurred in late summer of 2012 and 2013. Groundwater diversions could extend the length of a period with no flow, but, in most cases, flow is restored via an event that produces significant runoff and/or recharge such as the storm event on August 20, 2021.

DNR assessed net base-flow diversions in the recent past at three evaluation stations on Little Rock Creek. DNR would evaluate augmented base flow and net base-flow diversions at these evaluation stations.

Some of the augmented discharge may leak from the streambed and/or the enhanced base flow may slightly reduce groundwater discharges to the stream. This is because augmentation increases the stream stage above where it would be if in equilibrium with the water table along the stream channel, reducing the head gradient across the stream bed. Augmentation with groundwater increases base flow downstream of each discharge point. To be effective at enhancing base flow, most of the augmented discharge should reach the downstream station (i.e., the increase in flow at the downstream station should be a large fraction of the augmentation rate).

Model Experiment

The LRCA model can simulate well pumping and water discharge to a specific stream reach at uniform rates within each selected monthly stress period. Modeled augmentation provides an initial assessment of the potential effects of groundwater augmentation on stream base flow. Modeled results should be verified using field tests prior to implementing an augmentation system.

The three basic design elements for the demonstration scenario are well location(s), discharge location(s), and rate and timing of discharge. Reducing the distance from the wells to the discharge points reduces system costs. Discharge rates should be sufficient to restore base flows enough that the net of diversion and augmentation remains below the sustainable diversion limit at each of the three evaluation stations during and after the augmentation period.

The further upstream the discharge location, the longer the length of stream that is augmented. Applying the full augmentation amount too far upstream might be an excessive jump in base flow, however. In addition, all of the discharge may not be retained in the stream during the desired augmentation period.

If the pumping wells are located too close to the stream, pumping drawdown could partially offset the augmentation during the critical period of low flows. For locations greater than about 0.5 mile from the stream, pumping from the water-table aquifer causes less base-flow diversion during critical periods than pumping from buried artesian aquifers. Therefore, well and discharge locations were selected where the water-table aquifer is expected to be productive at a distance between 0.5 and 1 mile from Little Rock Creek. It is likely possible that one could select suitable buried aquifer well locations, however.

The selected well and discharge locations are shown in Figure 4. The two selected discharge locations are immediately downstream of stream measurement site H15029005 and immediately downstream of the upstream, continuous stream gauge, H15029003.

The augmentation rates for the demonstration scenario were 1.5 cfs at the upper site and 1.0 cfs at the lower site. These augmentation rates exceeded the computed diversions at the upstream and long-term gauges, and were expected to bring the net base-flow diversion to less than 15 percent of the August median base-flow at the downstream site. For this scenario, augmentation occurred when the computed base-flow diversions exceeded a diversion limit at one of the three evaluation stations. This included 2007 at the downstream gauge in addition to the periods when the base-flow diversions exceeded the limits at the other stations (2006, 2008, 2012, and 2013)

Table 5. Augmentation scenario periods and increases in August base flow over the baseline model.

Year	Augmentation Periods	Upstream Gauge, cfs (1.5 cfs upstream discharge)	Long-Term Gauge, cfs (2.5 cfs upstream discharges)	Downstream Gauge, cfs (2.5 cfs upstream discharges)
2006	Jul - Sep	1.40 (93%)	2.36 (94%)	2.27 (91%)
2007	Jul - Sep	0.23 (15%)	0.83 (33%)	0.78 (31%)
2008	Jul - Sep	1.23 (82%)	2.08 (83%)	1.96 (78%)
2012	Aug - Sep	1.39 (93%)	2.29 (92%)	1.99 (80%)
2013	Aug - Sep	1.30 (87%)	2.19 (88%)	1.87 (75%)

Table 5 lists the augmentation periods and the corresponding increases in base flows during the month of August relative to the baseline model. The percentages of the augmentation discharge that reached the station are also listed in parentheses. Table 6 lists August base flows with and without augmentation. The base flows without augmentation are the base flows filtered from total streamflow records as extended to backfill periods of missing record (See Management Goals and Evaluation Points in the Introduction). The table also lists the reference, August base flows, which are the sum of the filtered base flows and the computed diversions for the baseline model. The augmented base flows were calculated as the sum of filtered base flows and the difference between the augmentation scenario and the baseline model.

Except for 2007, the increases in base flow relative to the baseline model were 82 to 94 percent of the augmentation discharges at the upstream and long-term stations. The increase was 75 to 91 percent at the downstream gauge. In August 2007, much of the Augmentation rate was lost, especially above the upstream gauge. In August 2007, there was no computed base flow at the upstream gauge. Continuous gauging data are not available at the two most upstream gauges for summer 2007. DNR measured a flow of 0.16 cfs at the long-term gauge on August 8, 2007. During a similar, dry period in 2021, DNR measured 0.2 cfs at the long-term gauge and no measurable flow at the upstream gauge on August 19, 2021. These flows were substantially lower than during the other years. The augmentation losses are attributable to low groundwater levels and low stream stages, which are generally consistent with measurements. The augmentation caused a large jump in flow and stream stage, inducing downward head gradients from the stream to groundwater in the model.

The augmented base-flows at the two upstream gauges were close to or exceeded the reference, August base flows during all augmentation years with streamflow data. This means that the net augmentation discharges retained in the stream replaced nearly all to more than the computed diversions. At the downstream gauge, the net diversions (i.e., no-use base flow minus augmented base flow) ranged from 1.8 to 2.7 cfs compared to the diversion limit of 2.9 cfs.

Table 6. Augmentation scenario base flows at the three evaluation stations.

Year	Augmentation Periods	Upstream Gauge, Filtered Aug. Base Flow / Reference Aug. Base Flow, cfs	Upstream Gauge, Augmented August Base Flow, cfs	Long-Term Gauge, Filtered Aug. Base Flow / Reference Aug. Base Flow, cfs	Long-Term Gauge, Augmented August Base Flow, cfs	Down-stream Gauge, Filtered Aug. Base Flow / Reference Aug. Base Flow, cfs	Down-stream Gauge, Augmented August Base Flow, cfs
2006	Jul - Sep	0.91 / 2.2	2.7	1.9 / 3.8	4.2	9.3 / 14.4	12
2007	Jul – Sep	--	--	--	--	6.4 / 9.9	7.2
2008	Jul - Sep	0.86 / 2.2	2.1	1.9 / 3.5	3.9	10.5 / 15.1	12
2012	Aug - Sep	1.7 / 2.1	3.1	3.0 / 4.6	5.8	3.7 / 14.8	13
2013	Aug - Sep	1.9 / 3.3	3.2	3.1 / 5.0	5.3	4.6 / 16.7	14

The modeled augmentation scenario resulted in additional, computed diversions at the most upstream measurement station (15029005), which is located immediately upstream from the augmentation discharge.

These additional diversions varied seasonally, peaking between October and December after augmentation periods and did not fully dissipate over the winter. The residual, additional diversion decreased to 0.01 cfs in June 2011, nearly three years after the last augmentation period. but they also increased from year to year from 2006 through 2008. The maximum, additional diversion occurred in October 2007, but the largest additional summer diversions (July through September) were in 2008. Recall that there was zero flow during three field measurements from late July to early September 2008, precluding any additional base flow diversion during this time. The model tends to overpredict base flow at the most upstream gauge due to overpredicting base-flow contribution from the moraine to the east of the sand plain. The model computed base flow of 1.2 to 0.5 cfs during this period represents large percentage errors but relatively small absolute errors.

During 2013, the additional computed diversions at this station in July through September were, respectively: 0.05, 0.04, and 0.07 cfs. In late August 2013, computed base flow in the baseline model was 1.7 cfs, compared to a measured base flow of 0.44 cfs on 29 August. Given that the computed base flow was too large, the additional computed diversions may be exaggerated. Nevertheless, relative to the flow measured on 29 August, the additional computed diversions were relatively small.

Considerations for Augmentation Triggers

For a real augmentation system, base-flow diversions would not be known at the time of operational decisions. An augmentation operations plan would set streamflow/stream stage thresholds at the continuous stream gauges to trigger beginning and stopping augmentation. Augmentation may not begin or end immediately after reaching triggers to avoid cycling on and off through small runoff events. Augmentation could cease immediately if flows increase to a specified maximum. Filtered base-flow would not be available for operations decisions, hence total streamflow is considered.

Table 7 provides the maximum streamflow under primarily base-flow conditions (excludes short runoff events) when computed base-flow diversions exceeded the limits for each evaluation station. Figure 5 illustrates this for the long-term gauge in 2006. The time periods are approximate because, although the groundwater model had daily time steps, inputs were uniform across monthly stress periods. In some cases, gauged streamflow fell below these levels before computed diversions exceeded limits.

One may compare these streamflow values to the August streamflow statistics for the model-analysis period of 2006 and 2008 through 2018 (Table 8). Based on these statistics, one could consider the reference, 25-percent exceeds streamflow for August at the upstream and long-term gauges as triggers to initiate augmentation. Using these triggers (3.1 cfs at upstream and 4.9 cfs at long-term) any periods in which diversions exceeded the limits would be brief, and if diversion limits were briefly exceeded, this would occur when streamflow was not particularly low, being above the 25-percent exceeds threshold. Given the model results, one may assume that base-flow diversions are unlikely to exceed limits before July.

Although sub-monthly timing is not well resolved in the groundwater model, one may consider how the timing of computed diversions compared to these streamflow triggers as a useful approximation.

Table 7. Maximum streamflow under approximately base-flow conditions during periods in which the computed base-flow diversions exceeded limits.

Gauging Station	2006	2007	2008	2012*	2013
Upstream	1.7 (mid Jul – mid Sep)	--	2.5 (mid Jul – mid Sep)	5.5 (late July – mid Sep)	4.0 (begin Aug – early Oct)
Long-Term	2.5 (mid Jul – mid Sep)	--	3.5 (mid Jul – mid Sep)	10 (late July – mid Sep)	5.8 (begin Aug – early Oct)
Downstream	12 (early/mid Jul – early Sep)	7.5 (early/mid Jul – mid Sep)	14 (mid Jul – mid Sep)	21 (late July – early Sep)	16 (Late July - – early Oct)

* This streamflow followed a moderately large runoff event beginning 21 July. After this event, streamflow was mostly less than 2.5, 4, and 10 cfs at the three gauges, respectively.

Table 8. Median (50% exceeds) and low-flow statistics for measured streamflow and reference streamflow (2006, 2008 – 2018).

Gauging Station	50% Exceeds, cfs	50% Exceeds, Reference, cfs	25% Exceeds, cfs	25% Exceeds, Reference, cfs	10% Exceeds, cfs	10% Exceeds, Reference, cfs
Upstream	6.2	6.6	1.9	3.1	1.2	2.5
Long-Term	8.05	8.8	3.4	4.9	2.4	4.2
Downstream	19	22	13	17	10	14

The proposed operational criteria (25-percent exceeds streamflow trigger in July through September) would have resulted in augmentation beginning after base-flow diversions had begun in late June and less than two weeks before diversion limits were exceeded in mid-July in 2006 and 2008.

Diversion limits did not exceed limits at the upstream or long-term gauge in 2007 due to very low flows in the no-use model. Streamflow was likely below the triggers at the beginning of July (data only at downstream gauge), and base-flow diversions exceeded the limits by early July at the downstream gauge.

Computed base-flow diversions exceeded the limits when observed streamflow was above these triggers briefly in late July and/or early August of 2012 and 2013. As noted above under Table 7, streamflow was rapidly receding after a moderate runoff event in late July 2012. Streamflow receded more gradually in late July to early August 2013. At the long-term gauge, however, daily streamflow went below 4.9 cfs on 2 August 2012 and dipped to 4.9 cfs on 4 August 2013, both shortly after diversion limits were exceeded.

Model-Analysis Limitations

The model results provide an initial estimate of the impacts of augmentation on stream base flow, but these results should be verified through field testing. Although it is likely possible to withdraw the modeled flow rates from one or two water-table wells at each modeled well location, this could only be verified through test pumping. The modeled augmentation systems are on private land. Consideration of access to and construction suitability of these sites was beyond the scope of this analysis.

Water Quality and Other Concerns

Augmentation could raise concerns about its effects beyond measured streamflow, such as water quality and how the ecological benefits of point discharges compare to more distributed groundwater seepage that the augmentation replaces. DNR identified several of these concerns, but a thorough evaluation is beyond the scope of this analysis. Further review would be needed prior to permitting an augmentation system.

Groundwater could be a source of excess nitrate and possibly other pollutants such as pesticides. The quality of the source water would have to be verified before allowing discharges to the stream. This may require regular monitoring of the source well(s). On the other hand, augmentation with a low nitrate source could partially mitigate elevated nitrate concentrations that occur during low-flow periods.

Groundwater is usually low in dissolved oxygen. The discharge structure(s) would have to be designed to aerate the groundwater before discharge to the stream. Discharge structures would also have to be designed to prevent erosion on the stream banks or in the streambed. Both of these requirements could likely be met at the discharge rates in the model experiment.

The discharge water would be cool relative to summer air temperatures. Without groundwater diversions, seepage of cool groundwater would be more distributed along the length of the reach, however. Augmentation could cool the stream near discharge points, but the augmented water could warm up as it flows downstream. Stream temperature could be higher than for the reference condition (no groundwater diversions) at some point downstream of the augmentation discharge. Field testing and modeling could be used to test the effects of augmentation on stream temperatures.

Finally, augmentation with groundwater at a limited number of points may not have the same ecological benefits as more distributed groundwater seepage along the stream channel. In particular, locations of relatively larger groundwater seepage are important habitats for some aquatic insects and fish life stages.

Enhancing Irrigation-Water Conservation

There were limited data available to evaluate the potential for conservation practices to reduce irrigation demands in the LRCA. There is significant uncertainty in the reported use volumes. DNR does not have specific information about the technologies applied or about operational details for irrigation permits. The LRCA Plan specifically called for DNR to evaluate wider application of irrigation scheduling tools.

Model Experiment, Irrigation-Scheduling with Limited Crops

Current guidance from the University of Minnesota calls for growers to track total available soil moisture within the effective root zone, then irrigate at a trigger soil-moisture deficit to avoid exceeding a maximum allowable deficit (MAD). The trigger is typically set just above 50 percent soil-moisture deficit for most crops. This prevents the soil moisture from dropping much below 50 percent in any part of the field before the irrigation event is finished.

The MAD may be set to about 60 percent during vegetative growth stages, but values of 40 to 50 percent are recommended starting at late vegetative (corn) or early reproductive stages (Sharma, 2019). The latter growth stages occur during July and August. Growers use a lower trigger deficit of about 30 percent for potatoes to ensure crop quality. An irrigation event must start early enough to prevent any part of the field from reaching the MAD. During July and August, daily ET can exceed 0.2 inches/day (e.g., Wright, 2002). For example, during a two-day irrigation cycle, ET could approach 0.5 inches. For sandy soils with an available water content of less than 3 inches in the upper 3 feet, the soil water deficit could increase by about 20 percent of the total available water capacity in the last part of the field to be irrigated.

DNR previously applied the SWAT model (Soil and Water Assessment Tool, Neitsch et al., 2011) in a comparative analysis of evapotranspiration estimates for the LRCA area (DNR, 2021a, Appendix F). DNR refined and extended this modeling to assess irrigation demands in the LRCA for a limited set of crop rotations and soils beginning in water year 2005 (used as an initial, spin-up) through 2018. DNR then applied the resulting irrigation amounts in the LRCA model to simulate a hypothetical scenario in which irrigation-scheduling practices were used for all crop-irrigation permits.

The simulations applied the two most extensive soil mapping units to represent soils on the sand plain (Hubbard loamy sand) and adjacent areas with soils formed in wind-blown sand/silt over till (Pomroy loamy fine sand), respectively. Soil layering and properties were taken from the USDA SSURGO database. The rotations included three of the most commonly irrigated crops in the LRCA, excluding potatoes: corn rotated with either soybeans or dry beans. Table 9 lists the tested combinations of soil and crop rotation. The crop rotations alternated by permit with the permits listed in numerical order to disburse the rotations.

Table 9. SWAT modeling soil and crop combinations.

Setting / Soil	Crop Rotation 1	Crop Rotation 2
Sand Plain / Hubbard	Soybean – Corn	Corn – Dry Beans
Moraine / Pomroy	Soybean – Corn	Corn - Soybeans

The Rice and Little Falls AgWeather stations began recording data in late 2014. The simulations used the Little Falls airport weather data that was applied in the GSSHA model to backfill the wind speed and humidity data. Daily precipitation and maximum and minimum temperatures were taken from a pixel in the gridded PRISM (Parameter-elevation Regressions on Independent Slopes Model) dataset near the center of the LRCA (PRISM Climate Group, 2021). Solar radiation was calculated from the daily temperature data using the Hargreaves-Samani equation with a climatological correction to the empirical coefficient according to Samani (2000).

The data collected for the LRCA metering study (DNR, 2021c) showed that growers vary the event-irrigation amount seasonally. The effective root zone is thinner and ET rates are lower early in the growing season, limiting how much irrigation water the soil could accommodate without deep percolation. Most systems require more than two days to apply one gross inch of water. Even during peak growing season, most of the monitored systems applied less than one gross inch of water but sometimes applied back-to-back cycles.

DNR used USDA crop-progress reports and crop growing-season length to select typical planting dates for the three crops: 1 May for corn, 15 May for soybeans, and 28 May for dry beans. SWAT includes a database of default growth properties for many crops including corn and soybeans but not dry edible beans. DNR derived SWAT growth parameters for dry beans using information in Rai et al. (2020).

SWAT includes an automatic irrigation option in which irrigation is applied at a specific soil-moisture deficit, which can be changed to different values at set dates or fractions of the growing season. DNR set up auto irrigation to apply water at an appropriate MAD that corresponds to the seasonally varying available water capacity in the most active part of the root zone.

The SWAT model employs a heat unit or growing-degree day model for plant growth (Neitsch et al., 2011). The root depth of an annual crop reaches the maximum at 40 percent of the growing degree days (GDD) needed to reach maturity. For the crops applied in the SWAT modeling, this occurs in early- to mid-July, depending on seasonal temperatures. For irrigation scheduling purposes, the active zone for managing soil water reaches a maximum of 3 feet for these crops (Wright, 2002). As the effective root depth increases from emergence to the maximum, the available water capacity increases and the corresponding soil-water deficit that triggers irrigation should increase.

To implement the type of irrigation scheduling described above and be consistent with results of the metering study, DNR varied the soil-water deficit trigger and gross application amount for each crop-soil combination at several points in the season. A larger MAD was applied pre-emergence when the active zone largely overlaps with the depth of direct soil evaporation. Without this adjustment, there would be more auto irrigation early in the season than was observed in the metering study. These parameters are summarized in Table 10. In SWAT, irrigation is applied the day after the irrigation trigger is reached. Mid- and late-season event amounts were varied slightly by crop rotation to include some variability from permit to permit.

According to Washington State Department of Ecology (2005), the efficiency of a center-pivot with spray heads and no end gun can vary from 75 to 95 percent, with an average of 90 percent. With impact heads and an end gun, efficiencies are from 75 to 90 percent, averaging 80 percent. Water losses above the soil surface include: spray droplet evaporation and drift, net canopy evaporation during sprinkling, and canopy interception (e.g., Yonts et al., 2007). Crop residues, if present, can also intercept irrigation and reduce net water applied to the soil. During sprinkling, transpiration from the crop and soil evaporation are reduced but the rate of evaporation from wetted plant surfaces is larger.

Yonts et al. (2007) provide estimates of sprinkler water losses for a 1-inch, daytime application with calm wind to mature corn. For low-pressure spray heads, water losses are 0.01 inch to air evaporation and drift, 0.03 inch to net canopy evaporation during sprinkling, and 0.04 inch to plant interception. Other researchers have reported canopy interception as large as 0.2 inch for an application of 0.72 inch (Cao et al., 2020), but net evaporative losses would be smaller. Plant interception would be minimal early in the season and increase until plants reach full canopy.

This information was used to estimate seasonally varying irrigation efficiencies. The assumed losses were: 1% droplet evaporation and drift, 3% to 4% net canopy evaporation, and seasonally variable canopy interception from 0 to 0.05 inch. The percentage loss of canopy interception, therefore, varied with gross irrigation amount. SWAT allows the user to input irrigation efficiency as a fractional value of the gross application. In the simulations, irrigation efficiency varied with the application amount and time of year (Table 10).

SWAT allows the user to input irrigation efficiency as a fractional value of the gross application. In the simulations, irrigation efficiency varied with the application amount and time of year (Table 10). The efficiency is largest during the pre-emergence period when there is no plant interception. Efficiency decreases as plants grow and evaporative demand increases. After emergence, efficiency is lower for smaller application amounts because plant interception is assumed to be the same for the range of application amounts applied.

Table 10. Summary of auto irrigation parameters applied in the SWAT model simulations.

Crop-Soil Combination	Planting Date	Soil-Water-Deficit Trigger (inch)	Managed Zone Available Water Capacity (inch)	Gross Event (Cycle) Amount (inch)	Application Efficiency
Corn – Hubbard	5/1	0.45 to 1.1	0.75 to 2.5	0.315 to 0.71 or 0.75	0.96 to 0.85 or 0.87
Corn – Pomroy	5/1	0.45 to 1.29	0.75 to 2.75	0.315 to 0.75	0.96 to 0.87
Soybean – Hubbard	5/15	0.45 to 1.1	0.75 to 2.5	0.315 to 0.75	0.96 to 0.85 or 0.87
Soybean – Pomroy	5/15	0.45 to 1.29	0.75 to 2.75	0.315 to 0.75	0.96 to 0.88
Dry beans – Hubbard	5/28	0.45 to 1.1	0.75 to 2.5	0.315 to 0.71	0.96 to 0.85

Because irrigation is applied on the day following the soil-moisture deficit trigger, SWAT will apply irrigation on the same day as a rain event if rain occurs the next day. When preparing input for the LRCA model, irrigation events on days with significant rain were moved, or, if the rain was sufficient to fill the soil water deficit, eliminated.

Table 11 lists the modeled irrigation demands for 2006 through 2013. The modeled irrigation demands were less than the reported uses averaged across all permits, with the largest relative differences in wet years such as 2011. A permit-by-permit comparison is beyond the scope of this analysis. There are several factors that could contribute to this overall difference beyond the previously mentioned errors in reported water use.

Actual crop rotations were more variable than in the model experiment. Some permits included potatoes in the crop rotation at least for part of the model period. Crop rotations were modified over time for most permits. For example, some permits reported corn on corn for two or three years during this period. Some permits included irrigated alfalfa in rotations. For individual permits, there were sometimes large differences compared to most other permits in the same year and/or in multiple. Some growers use lower efficiency impact sprinklers and/or end guns or traveling gun sprinklers. It is also possible that the SWAT model under-represented actual crop water demands.

Table 11. Modeled irrigation demands, 2006 through 2013.

Year	Corn (Hubbard / Pomroy)	Soybean (Hubbard / Pomroy)	Dry Bean (Hubbard)	Reported Average, All Permits*	Mapped Acres, Reporting Permits#
2006	8.5 / 7.8	-- / 7.1	7.0	9.7	15,826
2007	11.7 / 11.7	8.8 / 8.5	--	11.2	16,935
2008	8.2 / 6.0	-- / 5.1	5.8	9.4	18,218
2009	4.4 / 5.0	4.2 / 4.2	--	7.6	18,439
2010	5.3 / 3.8	-- / 3.8	3.3	6.3	17,594
2011	3.5 / 1.8	0.9 / 0.9	--	4.8	16,760
2012	9.5 / 8.9	-- / 5.8	5.9	8.5	19,374
2013	9.1 / 8.8	8.5 / 7.9	--	10.0	20,432

* Average is weighted by permit acreage.

Permit acreage set to zero for years reporting zero use.

The irrigated acreage generally increased over time due to new and amended permits. A few active permits reported zero use in some years, however. To be consistent with the baseline model, simulated irrigation uses under each permit began in the same year that reported water use began.

Applying the modeled irrigation demands to the LRCA model resulted in the computed base-flow diversions listed in Table 12. The diversion limits were exceeded in 2006, 2008, 2012, and 2013. The differences between model scenarios varied but, in most years, the irrigation-scheduling scenario resulted in smaller base-flow diversions than the baseline model, consistent with the smaller average irrigation demands.

In 2013, however, the computed August diversions were nearly the same as for the baseline model at the upstream and long-term stations despite smaller, average irrigation use in the irrigation-scheduling scenario. The computed, base-flow diversion for this scenario was smaller at the downstream gauge.

This somewhat unexpected result for 2013 appears to be caused by differences in the timing and spatial distribution of uses in each scenario, particularly for the most "influential" permits. For example, the 10 permits expected to have the largest base-flow impact at the long-term gauge in 2013 reported only 7 percent more total use in July and August than the corresponding total for the irrigation-scheduling scenario. Among the top three most influential permits, the reported total use in July was 24 percent less than in the irrigation-scheduling scenario and was nearly the same for July plus August. It appears that reported uses for a small number of permits that had similar to much lower reported uses compared to the simulated scenario may have balanced out the computed diversions in 2013.

Table 12. Computed base-flow diversions for a scenario employing limited crops and irrigation scheduling. Baseline model-computed base-flow diversions are given in parentheses for comparison.

Year	Upstream Gauge, August Diversion, cfs SDL = 0.82	Long-term Gauge, August Diversion (cfs) (SDL = 1.1)	Downstream Gauge, August Diversion (cfs) (SDL = 2.9)
2006	1.2 (1.4)	1.6 (1.9)	3.8 (5.0)
2007	0.20 (0.20)	0.23 (0.26)	2.5 (3.4)
2008	1.2 (1.3)	1.5 (1.6)	3.5 (4.5)
2012	0.89 (1.3)	1.1 (1.6)	2.7 (3.7)
2013	1.5 (1.5)	1.9 (1.9)	4.2 (4.5)

Application and Limitations of Model Analysis

These model results suggest that more extensive application of irrigation-scheduling based on measured soil-moisture deficits has the potential to reduce irrigation demands for corn, soybeans, and dry beans relative to past reporting and could reduce base-flow diversions in most years. Despite 14 percent less total groundwater use in 2013, the irrigation-scheduling scenario did not significantly reduce the computed, August diversions at the upstream and long-term evaluation stations that year. The result for 2013 may indicate the importance of the timing and magnitude of uses for a small number of permits close to Little Rock Creek.

Potatoes are an important crop in the LRCA. The potential for reducing irrigation demands for potatoes may be smaller due to the need to maintain high soil moisture during most of the growing season. History also shows that corn may be grown on a larger fraction of the irrigated acres in some years, and alfalfa is also included in some rotations. Irrigation demands for corn and alfalfa are larger than for soybeans and dry beans due to longer growing seasons and larger peak ET rates.

It is possible that the SWAT model slightly underpredicted actual ET demands. On the other hand, some irrigated soils in the LRCA are expected to have a larger moisture holding capacity than the Pomroy series soils used to represent moraine areas. Therefore, the modeled irrigation demands may have been too large for some permits. In most cases, however, the permits located near Little Rock Creek and/or Bunker Hills Creek that cause the largest base-flow diversions irrigate areas dominated by soils with low water-holding capacity.

Despite the limitations of the irrigation-scheduling model scenario, the modeled irrigation demands appeared to be reasonable. Given the results for the tested scenario, it is likely that irrigation scheduling would have to be paired with one or more other management actions to reduce base-flow diversions below the diversion limits in all years.

Other Opportunities for Water Conservation

Additional gains through water conservation practices and technologies may be possible. Best practices for Central Minnesota remain the subject of on-going research (Sharma, 2022). Sharma (2022) described two active field studies of corn irrigation and provided interim results.

One study is testing the impact of irrigating less than the “full” amount on corn yields at groups of test plots at the Rosholt Research Farm in Pope County near Westport and at the Sand Plain Research Farm in Sherburne County near Becker. The study is funded for 2020, 2021, and 2022, but Sharma (2022) states that more than three years of data will be required to develop BMPs.

The study results varied significantly by site and by year. June through August precipitation was above average at both sites in 2020. Reducing total irrigation at Becker to 70 percent (4.8 inches vs. 6.85 inches) and reducing irrigation at Westport to 78 percent (2.5 inches vs. 3.2 inches) did not significantly reduce yields.

In 2021, June through August precipitation was only 3 inches at Becker and 4 inches at Westport. May through October precipitation at Becker was 11.9 inches but was 20.5 inches at Westport. At Becker, reducing irrigation to 71 percent (9.2 inches vs. 12.9 inches) reduced grain yields significantly. At Westport, reducing irrigation to 56 percent (4.3 inches vs. 7.7 inches) only slightly reduced grain yield, which was 236 bushels per ac (bu/ac) at full irrigation and optimum Nitrogen application. Sharma (2022) suggested that differences between sites may be explained by differences in the seasonal totals and timing of rainfall and other climatic factors and by differences in soil properties.

At Westport, the 2021 season total ET (May through October) was approximately 15 to 16.5 inches in test plots based on graphs of season total ET versus crop yield in Sharma (2022). Atmospheric demand was high in 2021. For example, reference ET at the Westport AgWeather station was just under 37 inches for May through October 2021 compared to 34 inches in 2020. Dylla (1980) reported irrigated corn growing-season (emergence to maturity) ET totals for experimental plots near Westport for 1975 through 1978. The corn was planted in early May and mature by mid-September. ET totaled 17.2 and 18.3 inches in two years in which there was significant crop damage (fungal disease, hail and wind) compared to totals of 23.7 and 24.0 inches in the other two years. Crop yields varied from 114 to 170 bushels per acre. These ET values for a shorter seasonal period were all larger but grain yields were smaller than the values found by Sharma in 2020 and 2021.

A second study examined the variability of irrigation demands within a corn field in western Stearns County and the potential for water savings using variable rate irrigation (VRI). The site is less than 20 miles south-southeast of the Rosholt Research Farm (Westport) discussed above. This field was selected for VRI because it contains soils with strongly contrasting AWC. Soils with larger AWC hold more water and require less irrigation to maintain adequate soil moisture.

The center-pivot, VRI system divided the field into three different categories based on soil type/AWC: coarse sandy loam (2.86 inches), sandy loam (3.7 inches), and loam (4.2 inches). Irrigation decisions were based on multiple soil moisture sensors placed in each type of soil. The field was divided into sectors applying either variable or uniform irrigation rates.

The VRI system applied seasonal total irrigation amounts of 11.6, 5.8, and 2.3 inches to the three soil categories, respectively. The uniform rate was 11.6 inches, reflecting the largest demand.

These results indicate that, even during a dry irrigation season, VRI can reduce total water use if a significant fraction of a field has substantially larger AWC than the soils with the lowest AWC. This was a full-scale experiment using a center-pivot system, in contrast to the small test plots at the Rosholt Research Farm. Nevertheless, the range of irrigation demands across the two sites in 2021 is notable.

Yield was slightly lower for the VRI sectors. Using a cost of water of $16 per acre-inch, however, the net income was the same for VRI and uniform irrigation. This did not factor in the cost of installing the VRI system.

One would expect limited potential for water savings where soil AWC is relatively uniform, both in the case of small AWC or large AWC. The study field was a good candidate for VRI research because of the soil heterogeneity. Most of the irrigated fields close to Little Rock Creek have relatively uniform soils with low AWC (e.g., Hubbard loamy sand, 2.5 inches AWC). Because of their proximity to the perennial stream network, these are the locations where irrigation use has the largest impact on base flows.

There are locations in the LRCA with more variable soils that include soils with AWC greater than 3 inches. This suggests that VRI might provide water-saving opportunities in some fields. The economic viability of a VRI system depends on the longer-term potential water savings and pumping costs. One must look at the full range of factors to evaluate the suitability of VRI for a particular site.

Replacement of Irrigation Wells with More Distant Wells

Moving irrigation wells that are close to the Little Rock Creek stream network to more distant locations could substantially reduce base-flow diversions. This could greatly reduce pumping drawdown caused by these systems. In addition, recharge is larger for irrigated crops than for the reference crop of non-irrigated alfalfa. With the irrigation wells farther removed, the net effect would be to move groundwater from a distant location nearer to the creek, enhancing net groundwater discharge. The effect of a net increase in the local groundwater budget would build over time toward a new dynamic with larger average groundwater discharges.

Demonstration Model Experiment

To test and demonstrate the concept, DNR developed a hypothetical scenario in which 9 irrigation wells were replaced. The wells were selected primarily based on their expected, relative impact on stream base flows. The selection also favored existing wells clustered in close proximity so that pipelines connecting replacement wells to irrigation systems could share a common corridor. Even if it may be preferable for each system to have its own pipeline for independent operation, sharing a pipeline corridor could save on construction costs.

Irrigation wells were ranked by multiplying their capture fraction (See Capture Analysis) by both the 2013 pumping volume and by permitted maximum volume at two evaluation stations (Table 13). Note that reported use exceeded the permitted maximum by more than 10 percent for some permits in 2013. Permit 2007-0387 was selected because its well is adjacent to the well for 2001-3166, and although its rank was not as high in 2013, it would be ranked highly based on permitted volume. There are likely alternative permit selections that could achieve similar results.

Table 13. Relative Permitted Volume rankings of permits selected for the well-replacement model experiment.

Permit	Rank at Long-Term Gauge, 2013	Rank at Long-Term Gauge, Permitted Volume	Rank at Downstream Gauge, 2013	Rank at Downstream Gauge, Permitted Volume
2005-3130	2	4	5	14
2014-1966	3	7	9	27
2006-0506	1	1	2	2
1976-3306	4	2	15	3
1996-3135	5	3	13	5
1977-3388	7	9	3	9
1997-3052	16	18	1	1
2001-3166	44	49	4	8
2007-0387	51	50	17	7

DNR selected the replacement-well locations (Figure 6) based on a cursory, desktop review of several factors: likely availability of aquifers; proximity to streams, wetlands, and domestic wells; and capture fraction. The water-table aquifer was preferred if a location was more than about ¼ mile from NWI wetlands and ½ mile from perennial streams. Test pumping would be required to verify the potential capacity of well locations. In addition, further, site-specific review would be required prior to permitting replacement wells.

In an initial test, the wells were replaced in the MODFLOW component of the model without any changes to the GSSHA component. This much less computationally demanding experiment approximated replacing the wells, although it did not account for the pumping wells' impacts on groundwater ET and recharge in the GSSHA model.

The test resulted in base-flow diversions less than or equal to the limits at all three evaluation stations in all years. In addition, the magnitude of the computed diversions, relative to the baseline model, decreased over time throughout the simulation period. Given this result, the well replacements were run in the full LRCA model to complete the experiment.

Table 14 lists the computed base-flow diversions for the final run through the full LRCA model. The computed diversions were below the limits except in 2008 at the downstream gauge. In addition, six permits have been added to the zone of irrigation influence since 2013, and one of these permits would rank 22 at the long-term gauge based on permit volume. To ensure that base-flow diversions remain below the limits at all three evaluation stations, it would likely be necessary to replace at least 10 total wells and/or to combine well replacements with other mitigation actions.

Table 14. Computed base-flow diversions for a model experiment in which 9 irrigation wells were replaced with more distant wells. Baseline model-computed base-flow diversions are given in parentheses for comparison.

Year	Upstream Gauge, August Diversion, cfs SDL = 0.82	Long-term Gauge, August Diversion (cfs) (SDL = 1.1)	Downstream Gauge, August Diversion (cfs) (SDL = 2.9)
2006	0.39 (1.4)	0.61 (1.9)	2.8 (5.0)
2007	0.20 (0.20)	0.14 (0.3)	2.5 (3.4)
2008	0.53 (1.3)	0.65 (1.6)	3.4 (4.5)
2012	0.10 (1.3)	0.17 (1.6)	1.8 (3.7)
2013	0.20 (1.5)	0.25 (1.9)	2.0 (4.5)

Application and Limitations of Model Analysis

The model experiment provided an example of how replacing selected irrigation wells with more distant wells could reduce computed base-flow diversions. Other configurations of removed wells and replacement locations would be possible. Field testing and analysis would be required to verify the availability of groundwater at replacement-well locations. DNR did not evaluate the feasibility of pipeline corridors.

Uniform Reduction of Irrigation-Permit Acreage

Base-flow diversions could be reduced through reductions in water use. Based on the base-flow diversions computed from the baseline model, a uniform reduction in appropriations during the analysis period would have to be at least 45 percent to bring base-flow diversions below the limits.

DNR elected to test a 50 percent reduction from reported uses. To achieve this with the fewest assumptions possible, irrigated acreage and reported volumes were cut in half for all irrigation permits within the zone of irrigation influence (Figure 7). This preserved the reported irrigation rates (inches per acre), while cutting the use in half. For permits that were amended to increase acreage after 2013, the reductions were scaled to the recent irrigated acreage.

Table 15 lists the computed, August base-flow diversions for this model experiment. The August base-flow diversions were less than the limits at each evaluation station. The September 2013 base-flow diversion at the long-term gauge was right at the limit (0.82 cfs).

Table 15. Computed, August base-flow diversions for a model experiment in which irrigated acreage and reported use were cut in half for permits in the zone of irrigation influence. Baseline model-computed base-flow diversions are given in parentheses for comparison.

Year	Upstream Gauge, August Diversion, cfs SDL = 0.82	Long-term Gauge, August Diversion (cfs) (SDL = 1.1)	Downstream Gauge, August Diversion (cfs) (SDL = 2.9)
2006	0.68 (1.4)	0.96 (1.9)	2.45 (5.0)
2007	(0.20)	(0.26)	(3.4)
2008	0.69 (1.3)	0.90 (1.6)	2.3 (4.5)
2012	0.67 (1.3)	0.87 (1.6)	1.9 (3.7)
2013	0.73 (1.5)	0.98 (1.9)	2.3 (4.5)

Application and Limitations of Model Analysis

If only permitted volumes were halved without a corresponding change to permitted acreage, use patterns would likely differ from reported uses. Nevertheless, the results provide a useful benchmark for the amount of uniform reduction that would be required to maintain base-flow diversions at or below limits.

Alternatives Comparison

The model experiments and analysis provided enough information to begin comparing management actions in terms of potential to increase base flows, relative costs, and challenges/obstacles. Table 16 provides a summary of these factors for the tested scenarios. Alternative versions of all of these management actions would be possible. Any of the management actions could be paired with enhanced water conservation. Additional gains through more aggressive conservation practices and advanced technologies are likely possible for some combinations of soils, crops, and seasonal weather, but best practices and their potential under the range of soil and climate conditions in Central Minnesota are the subjects of on-going research.

Table 16. Summary of evaluated management actions.

Tested Management Action	Maximum August Base-Flow Diversions (cfs) Upstream, Long-Term, Downstream	Relative Cost	Challenges
Augment Little Rock Creek with groundwater at two locations	0.16, -0.24, 2.8	Moderate	Ecological evaluation System management Site access
Irrigation scheduling with limited crops	1.5, 1.9, 4.2	Variable (potential loss of profits without potatoes in rotation)	Minimal reduction in diversions in one tested year Uncertainty about existing practices Verification and monitoring of practices

Tested Management Action	Maximum August Base-Flow Diversions (cfs) Upstream, Long-Term, Downstream	Relative Cost	Challenges
Replace 9 irrigation wells with more distant wells	0.53, 0.65, 3.4	High	Selection of and access to well and pipeline sites Depends on on-going irrigation with replacement supplies
Reduce irrigation use and acreage by one half	0.73, 0.98, 2.3	Very High	Reduced irrigated crop acreage / reduced total crop yields

The two types of actions with the most potential to reduce net diversions on their own are augmentation and replacing irrigation wells. Replacing irrigation wells would be higher in cost because it would require more wells and miles of pipeline, but there remains significant uncertainty in the overall ecological impacts of augmentation. There could be additional benefits to enhanced conservation, beyond impacts to stream base flows, such as reduced pumping costs and reduced risks of nitrate leaching.

Summary

DNR used the previously developed LRCA model to examine the spatial relationships between groundwater use and base-flow diversions in Little Rock Creek. The results guided development of model experiments designed to explore four types of management actions that DNR committed to evaluating in the LRCA Plan.

Model results were compared to a base-flow diversion limit of 15 percent of the reference, August median base flow at three evaluation stations: the upstream gauge (15029003), the long-term gauge (15029001), and the downstream gauge (16031001). The analysis focused on the period 2006 through 2013 because previous analyses indicated that base-flow diversions had significant impacts on stream-habitat in four of those years: 2006, 2008, 2012, and 2013 (DNR, 2021b).

The analysis indicated that 83 existing permits contribute to computed base-flow diversions in Little Rock Creek above the downstream gauge (H15031001) in at least some years. An experiment that removed 21 existing permits close to Little Rock and/or Bunker Hills creeks (25 percent of the 83 total permits) reduced maximum base-flow diversions by more than half to below the diversion limits.

Model tests suggested that augmentation with groundwater could reduce net base-flow diversions below the diversion limits. The effects of augmentation on stream water quality, temperature, and ecology require further study.

DNR modeled irrigation-water demands using the SWAT model to mimic irrigation-scheduling based on seasonally varying, soil-moisture deficit triggers for three crop types: corn, soybeans, and dry beans. The modeled irrigation demands were generally less than reported irrigation volumes and reduced computed base-flow diversions when applied to the LRCA model. The computed diversions were only slightly smaller than in the baseline model for 2013. Computed diversions remained above the limit of 15 percent of the reference, August median base flow. The potential for greater reductions in irrigation demands through other practices and technologies requires further research.

An experiment that replaced 9 irrigation wells with more distant wells indicated that such well replacement could reduce base-flow diversions below the diversion limits. One limitation of this type of scheme is that it relies on on-going irrigation at the selected permit sites near Little Rock Creek and the corresponding enhanced recharge to mitigate the aggregate impacts of all permits. Removing permits reduces net diversions less than irrigating with “imported” water.

An experiment that reduced irrigation volumes and acreage by half resulted in maximum, computed diversions that were just below the diversion limits. This provides a useful benchmark for the amount of uniform reduction that would be required to maintain base-flow diversions at or below limits.

The model experiments and analysis provided enough initial insights to begin comparing management actions in terms of potential to increase base flows, relative costs, and challenges/obstacles.

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Figures

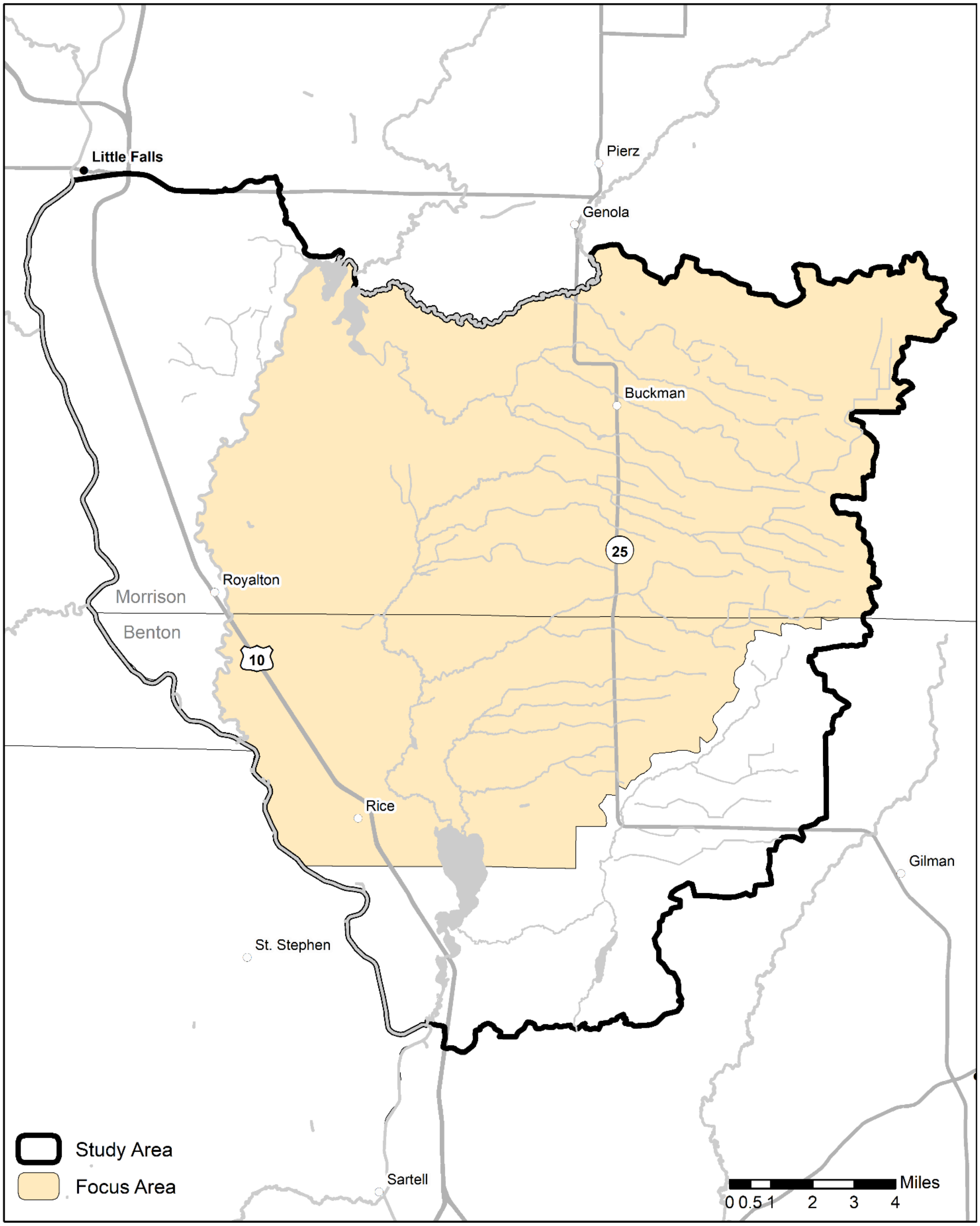

Figure 1. Location of the Little Rock Creek Area

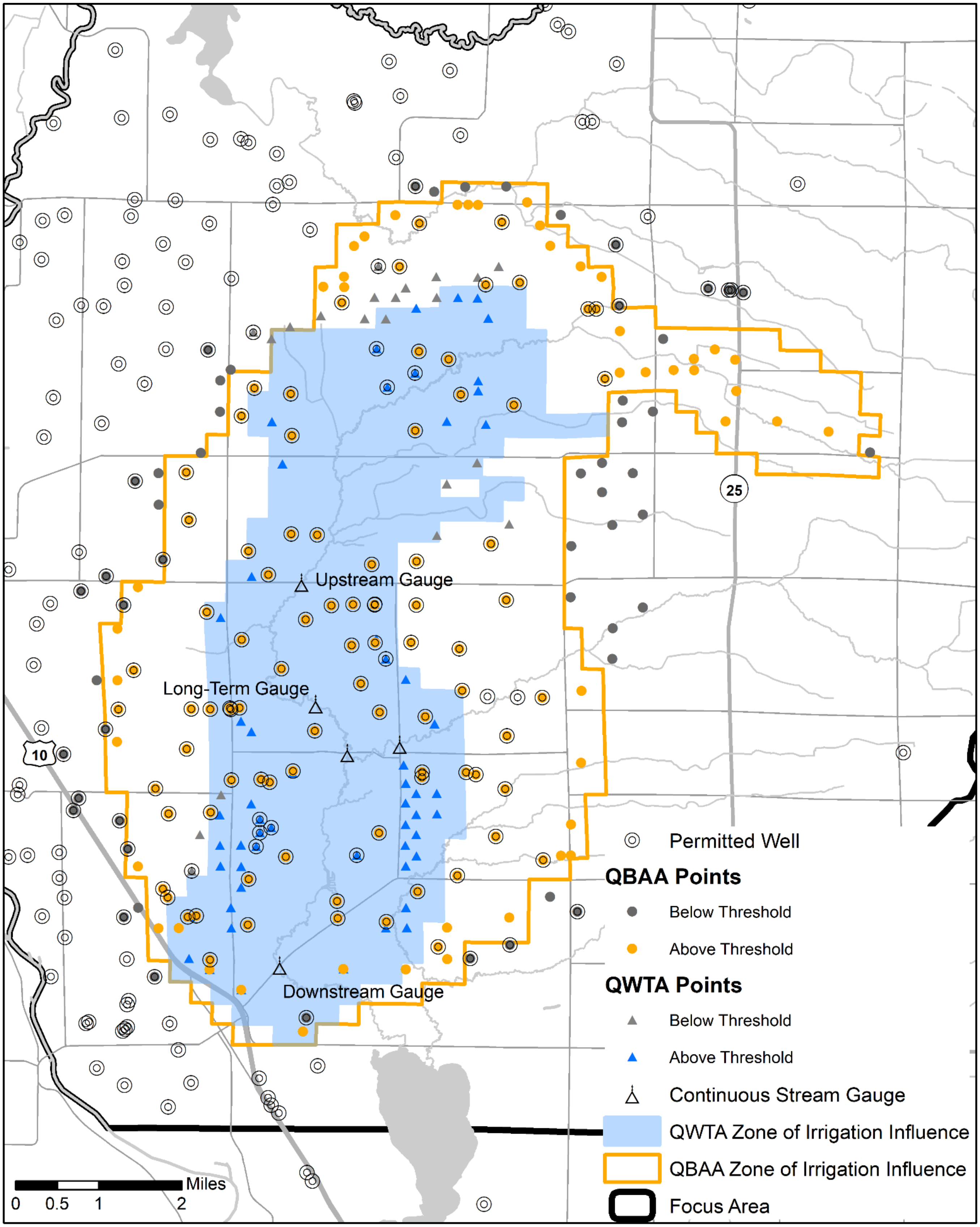

Figure 2. Capture-fraction data points and the delineated zones of irrigation influence

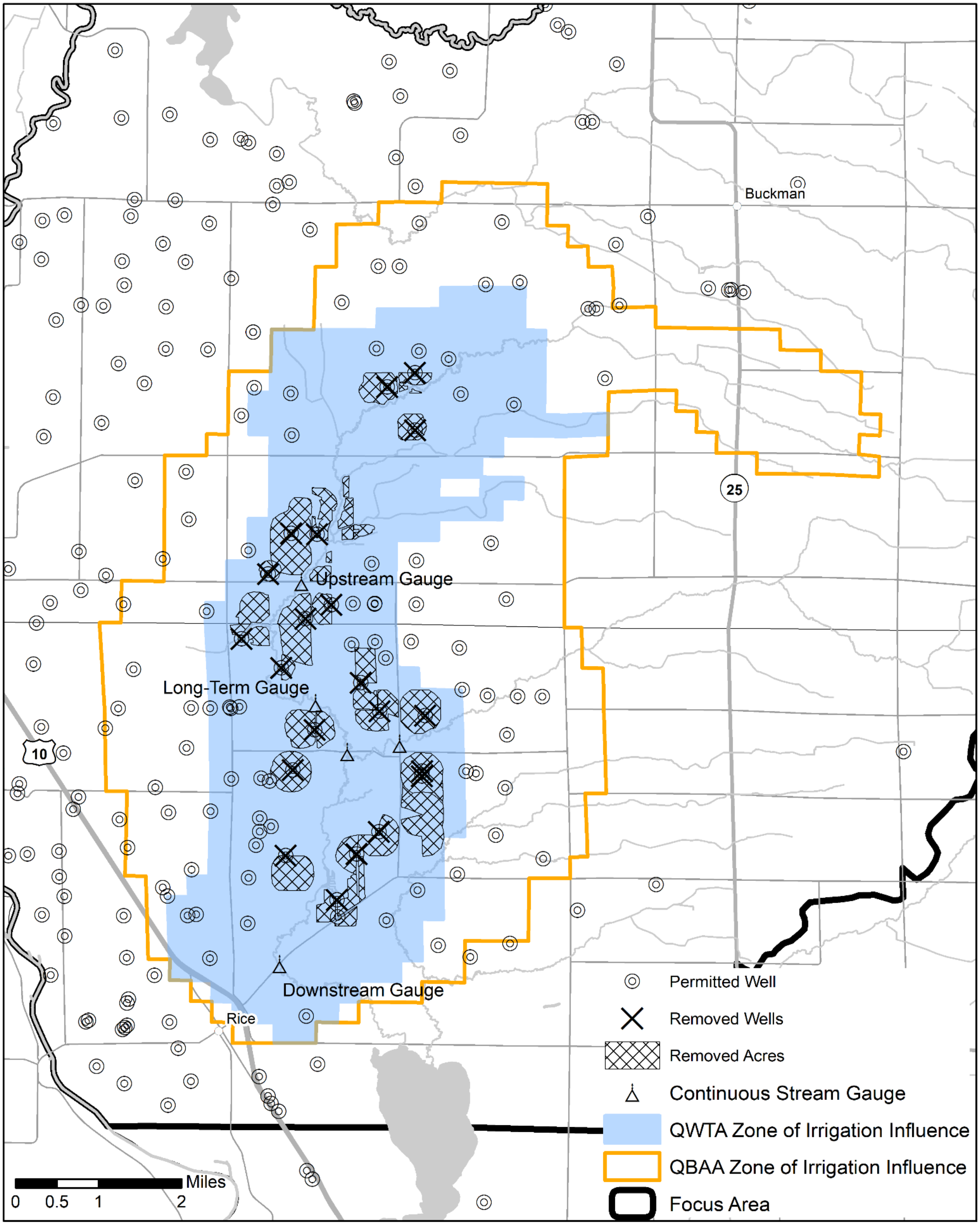

Figure 3. Irrigation permits removed in model experiment to explore spatial relationships

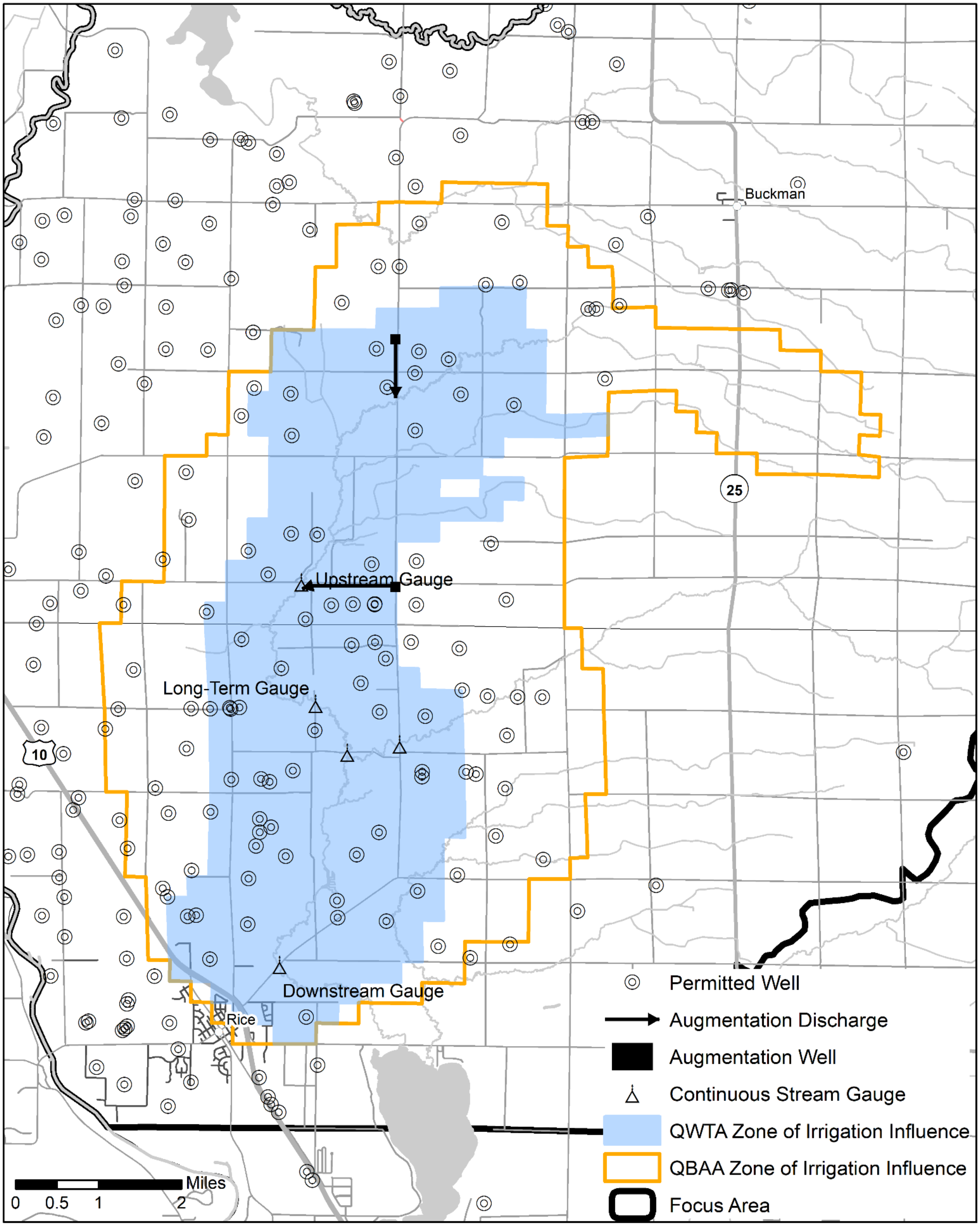

Figure 4. Locations of streamflow-augmentation in model experiment

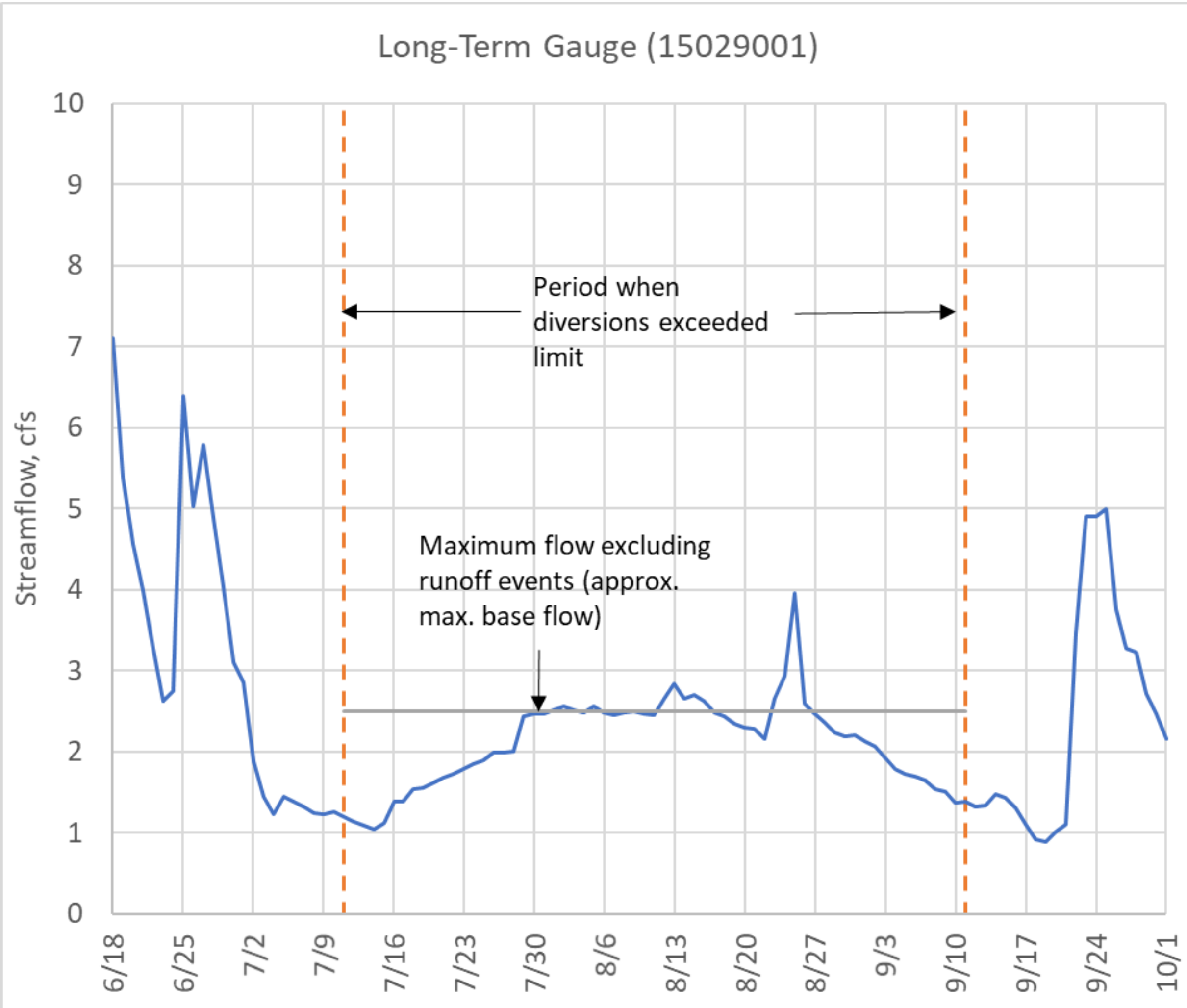

Figure 5. Streamflow at the long-term station in 2006 during the period in which computed diversions exceeded the limit.

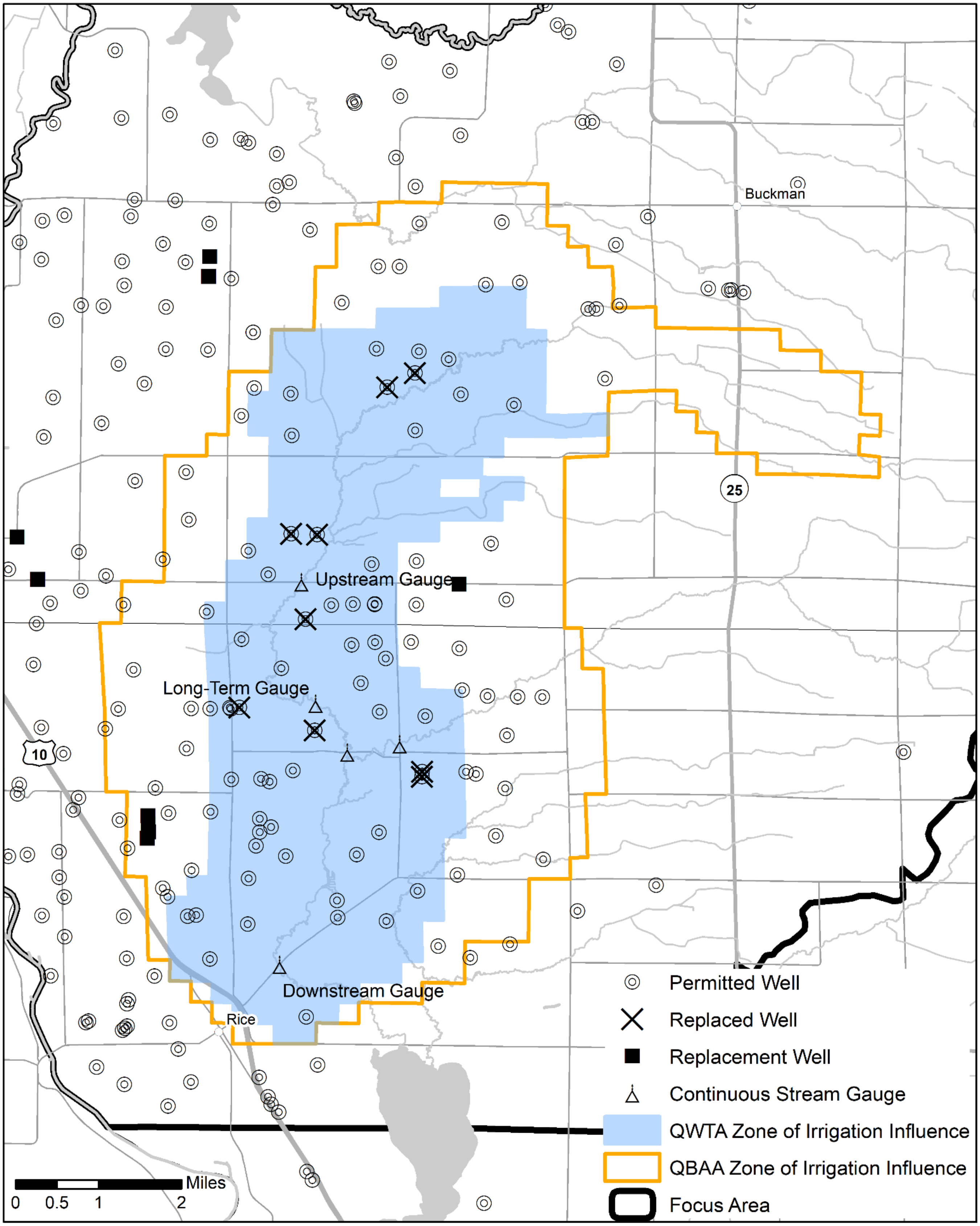

Figure 6. Locations of replaced and replacement wells in model experiment

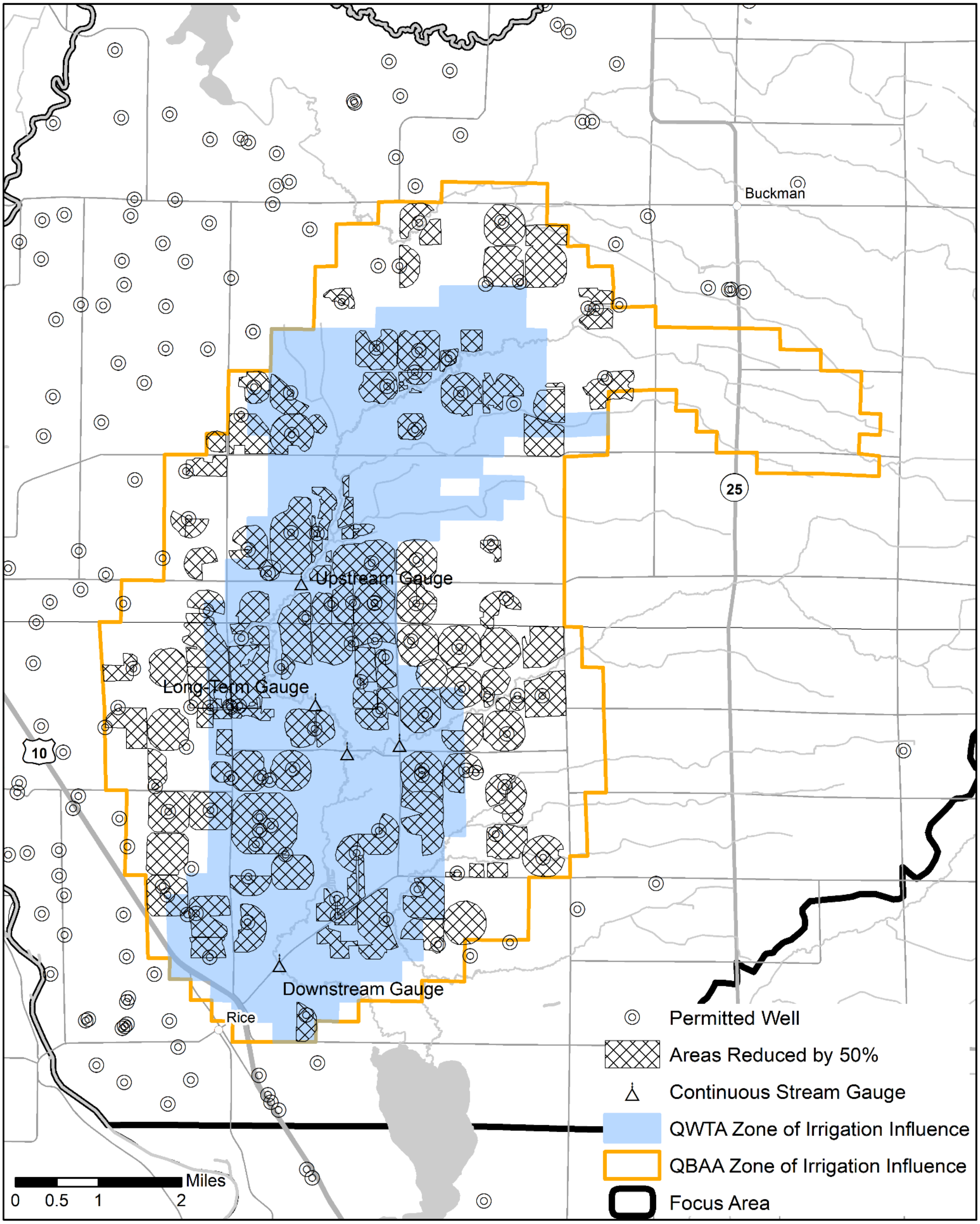

Figure 7. Reduced permits in model experiment. Some permits changed during and after the model period.