ArkDSS Memorandum
Phase 1 –Development of Unit Response Functions (URFs)
Subtask 2.8

TO: File
FROM: Kelley Thompson, P.E.; Division of Water Resources Modeling and DSS Team
SUBJECT: ArkDSS – Phase 1: Development of Unit Response Functions; subtask 2.8
DATE: May 14, 2020

INTRODUCTION

This memo describes development of the Unit Response Functions (URFs) for the Arkansas Basin (CDWR Division 2) as part of the Arkansas Decision Support System (ArkDSS) project. This memo describes development by HRS Water Consultants (HRS) as well as by Division of Water Resources (CDWR) staff.

METHODS

The following paragraphs describe methods used to develop the ArkDSS URFs.

HRS technical memo
HRS produced a technical memo for their work. This memo is attached as Attachment A.

Use of HRS aquifer areas and properties
HRS produced a coverage aquifer areas where surface water and groundwater were expected to be in hydrologic connection with a perennial (or near perennial) stream reach of the Arkansas River or one of its tributaries. HRS also contacted Water Commissioners to discuss areas of uncertainty, and some irrigated areas were included despite the fact that the associate stream does not always have live flow. These areas did not did not include designated basins, the HI model area, or areas above a known futile call. The aquifer areas were developed considering the 2015 irrigated areas and did not consider historically irrigated areas. Additionally, some areas where responses were estimated to take longer than 20 years to return 95 percent were not included. HRS emphasized developing higher spatial discretization more than defining differences in aquifer properties for development of the URFs, and as such only defined three general values for aquifer properties (transmissivity and specific yield) as:

Table 1. Aquifer Area Transmissivity and Specific Yield Values

Region / Depositional Environment	Transmissivity(gpd/ft)	Specific Yield (%)
Lower Basin channel of Ark River or Fountain Creek; small number of very narrow incised channels with adjacent irrigation.	160,000	0.23
Upper Ark thick Glacial deposits and gravel (WD 11,12,13)	60,000	0.15
Thin alluvium on side tributaries	30,000	0.18

Use of HRS stream/aquifer band zones

HRS developed a dataset of streams that was made by extensively filtering and modifying the NHD and created buffer zones for 20 distance ranges from these streams. These distance ranges are shown in the following table. HRS intersected the buffer zones with the alluvial aquifer areas mentioned above to create a coverage of aquifer band zones.

Table 2. Aquifer Band Zone Distances (feet)

Zone:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Start Dist:	0	200	400	600	800	1000	1400	1800	2200	2600	3000	3500	4000	5000	6000	7000	8000	11000	14000	20000
Mid Dist:	100	300	500	700	900	1200	1600	2000	2400	2800	3250	3750	4500	5500	6500	7500	9500	12500	17000	27500
End Dist:	200	400	600	800	1000	1400	1800	2200	2600	3000	3500	4000	5000	6000	7000	8000	11000	14000	20000	35000

Union of aquifer band zones with full (1954-current) ArkDSS Ditch Service Area

The aquifer band zones developed by HRS were unioned with the ArkDSS Ditch Service Area (DSA) coverage in ArcGIS. The DSA that was used was the full DSA which was developed by combining irrigated parcels (both crop and no-crop) and associated surface water sources from all irrigated snapshots (1954, 1975, 1988, 1998, 2010, 2013-2018). For some ditches, this may represent areas that were once irrigated but now may not be. This ensured that URFs would be developed for all ditches that were irrigated in this time period. Groundwater only parcels within discrete GW Zones were also represented in the DSA. Following the union, disaggregated polygons were dissolved such that there was one polygon per ditch/band/T area. The .dbf file for the resulting shape file was converted to an .xlsx file for reading by the automated script.

Automated Script

A script was developed to read the file developed from unioning the aquifer band areas and DSA, develop URFs using Glover, consolidate the thousands of individual URFs into a set of average patterns, wrap URFs, read HI model URFs, and produce the pattern files for use in StateMOD. The script can be rerun if the ditch/aquifer data is updated or revisions in the numerous script options are desired. The script runs a monthly Glover analysis for each ditch/aquifer band area which replicates results from AWAS. In order to replicate AWAS, the days in each month are calculated as 365/12 and for bounded aquifers the image well rate difference tolerance is set at 0.00005 ft3/day. The URF is ran out for 1000 years or until the depletion difference drops below T/1000000000. The following paragraphs generally describe options that are managed within the script.

Ditches Excluded with <30% in HRS aquifer areas

Some ditches may be partially located with the HRS mapped aquifer areas but have some portions that extend outside of the aquifer areas. Many cases, many ditches had small portions that extended outside the mapped boundaries although this proportion got higher for some very small ditches. In other cases, parcels outside the aquifer areas were historically irrigated but are not currently irrigated, and for this reason may have not been considered by HRS. The 30% measure was based on area, and areas outside the boundaries were essentially not considered in the resulting URF. Ditches with <30% coverage would not have an associated URF in the pattern file.

Some Ditches were manually added or removed
HRS developed its aquifer mapping based on the 2015 irrigated lands coverage. Some historical ditches may be important to have in the model. Three ditches were added that were located within the area flooded Trinidad reservoir; 1900517,1900516, and 1900540. Parameters of T, S, and distances were defined in the script. Two ditches were removed whose URFs were characteristic of very long steady state patterns and were not similar to any of the other URFs; 1800539 and 1800540. It may be beneficial to add/remove other ditches upon further consideration.

Glover's bounded aquifer solution used rather than infinite aquifer
The HRS aquifer areas are throught to define areas of transmissive materials that are bounded by less transmissive materials that are not in connection with the stream. The bounded aquifer solution has been used in other cases Division 2. Therefore, Glover's bounded aquifer solution was used rather than infinite aquifer. The bounded aquifer case significantly reduces long tails in the resulting URF.
Looking closer at a few examples, the bounded aquifer case significantly reduces the long tails.

Aquifer Boundary for Ditch approximated with largest band end distance
Ditch areas were divided into distance bands; up to 20. For each ditch band area, the Glover centroid distance (i.e. "X" distance) was taken as the "mid distance" for each band. However, for each ditch, the aquifer boundary distance for the Glover solution (i.e. "W" distance) was approximated as the end distance for the most distant band. This is a good solution in many cases where the ditch extended near to the edge of the aquifer area mapping. In cases where the ditch did not extend near to the aquifer edge the URF may be somewhat "shorter" than it ideally should be. Aquifer boundary distances for individual ditches could be individually defined in the script if desired.

Individual ditch/band area URFs composited into single ditch URF
The Glover solution was used to develop an individual URF for every ditch/band/T area for a maximum of 100 years. Some ditches had as many as 35 band and T (aquifer parameter) combinations so the total number of individual URFs developed for the ArkDSS dataset approached 10,000 URFs. For each ditch, the individual band/T URFs were weighed by area and combined into one composite ditch URF. These individual URFs were not "wrapped" in any way prior to combination.

Ditch composite URF wrapped using several criteria (20yr/95%/10yr/90%)
Several "wrapping" actions were applied to each ditch composite URF. First, the composite URF was "wrapped" to 20 years if it was originally longer. Second, a 95% wrap back was applied. In this case, the cumulative amount for each URF month was calculated and the month found that equaled or exceeded 95%; any total URF amount for any later months was distributed back to the earlier months. Third, if the resulting wrapped URF exceeded 10 years in length, then the URF was rewrapped using a 90% wrap. (These option amounts can be changed in the script, and an option to wrap month amounts that fall below a threshold value such as 0.001 can also be applied in the script)

URF wrapped using "Even Distribution" option
For each wrapping action, the "even distribution" wrapping option was used rather than the "percentage" script option. With "even dist", the tail portion to be wrapped is divided by the number of months prior to the wrap so that each month receives an equal portion of the wrapped amount. In the "percentage" option, each month receives a portion of the tail amount that is weighted by that month's portion of the remaining total. The "even dist" wrapping method was recommended by HB13-1248 Criteria and Guidelines as the tail that is being wrapped represents slowly returning water and shouldn't

be reallocated mostly to the first months as is done with the "percentage" option. However, it is believed that the percentage option has been more widely used in water rights cases (option can be changed in the script).

Matched ditch URF with a set of averaged URF patterns

Over 1200 ditch composite URFs were developed for the ditches in the ArkDSS dataset. StateMod can only define a limited set of URF patterns for use in the model, so the number of URF patterns had to be reduced significantly. The ditch composite URFs were used to develop of much smaller set (<70) of "average" patterns, and the script then reevaluated each ditch URF to find the most similar average URF pattern. To establish both average patterns and similarity, the script used 25 time period "bins" (starting at one per month but then going to more and more months).

Average Pattern URFs limited to 0.001 threshold

The last few months of the longer average patterns can be very small numbers due to averaging of individual ditch URFs with different tail lengths. Average pattern values below a threshold value of 0.001 were wrapped back, although this script option can be adjusted.

Several URFs were maintained for particular PRWCD ditches

Five ditches in the Purgatoire River Water Conservancy District (PRWCD) with longer and relatively "unique" URF patterns were not included in an "average pattern"; rather their unique ditch composite URFs were included as explicit patterns. These were the Picketwire (1900584), Enlarged Southside (1900598), John Flood (1900572), Model (1900552), and Hoenhe (1900571) Ditches.

Script outputs pattern (.dly) file and wdid/pattern (.csv) file

The script outputs a pattern file for use in StateMod that lists a pattern number, the number of months in the pattern, and the monthly URF values. A separate csv file lists each WDID and the corresponding pattern file number. At present, 68 average patterns were used along with 5 explicit ditch URFs.

Explicit H-I model URFs, wrapped using same criteria plus reach threshold (0.006-0.01)

URFs for H-I Model ditches were developed using a 2-D superposition groundwater model as part of Kansas v. Colorado. Each ditch has separate patterns for water contributing to each separate H-I Model river reach, and these patterns were normalized so that each separate pattern summed to one rather than the patterns for all reaches summing to one. Normalized URF amounts were then wrapped using the same criteria as the composite ditch URFs described above (95% wrap back applied then if still exceeded 10 years in length rewrapped using a 90% wrap). Finally, reach URFs were not considered if the reach percentage was less than 0.006 of the total ditch response (30 reach URFs were removed). There were no reach percentages between 0.006 and 0.01 so this was effectively a 0.01 threshold. The reaches that were removed were examined in GIS, and all the reaches were located upstream or downstream of the irrigated acreage (ie from a perpendicular line from the edge of the DSA). Reach percentages were recalculated after removal of these smallest river reach impacts so the sum of reach percentages summed to 1.0. Each renormalized pattern was output in the pattern file, while the river reach and reach percentage were also included (as well as the wdid and pattern number) in the csv file. Tailwater percentages contributing to each river reach were also included in the csv file. H-I Model URFs for groundwater pumping areas as well as URFs for three canals whose seepage is modeled with explicit URFs rather than ditch URFS were also included in the pattern and csv files; Ft Lyon Storage Canal (1700648), Ft Lyon Canal (1700553), and Amity Canal (6700607).

Attachment A - HRS Memo

Arkansas Decision Support System

Task 2.8 Technical Memorandum

Development of Unit Response Functions

Prepared for:

Wilson Water Group

Colorado Water Conservation Board

Colorado Division of Water Resources

Prepared by:

HRS Water Consultants

May 13, 2020

HRS Job No. 17-03

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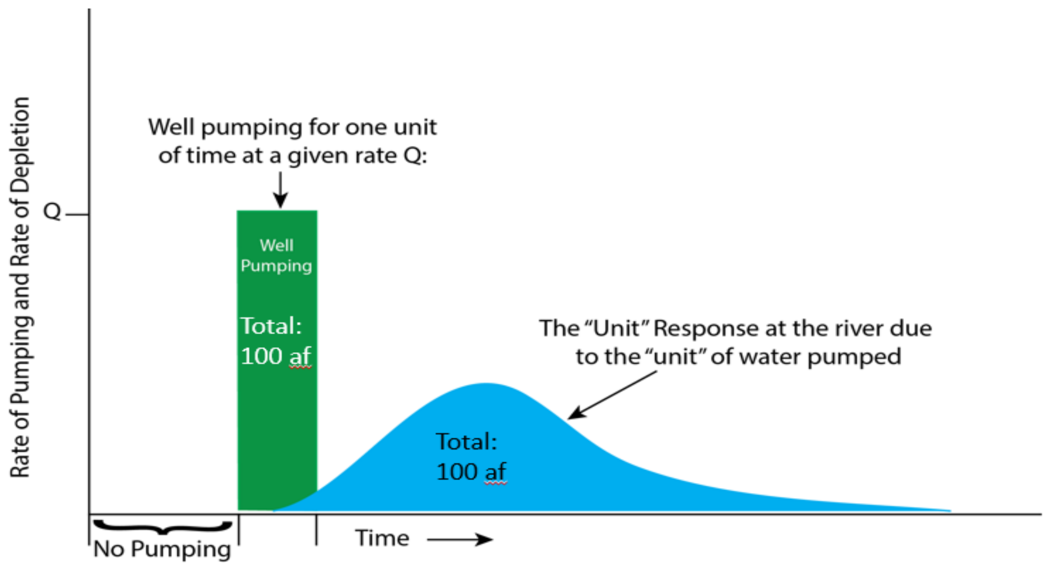
Introduction

The goal of ArkDSS Task 2.8 is to prepare Unit Response Functions (URFs) for irrigated parcels and key ditches outside of the HI Model area (i.e., outside of the Arkansas River alluvial aquifer downstream of Pueblo Reservoir). A URF is a function that is used to estimate and apportion the delayed impacts of groundwater recharge or pumping to a hydrologically connected river over time.

Unit Response

The term "unit response" indicates that the function describes the volumetric rate of depletion or accretion[1] that results from pumping (or recharging) one unit volume over one unit of time (e.g., the response at a river after pumping one-hundred acre-feet over a period of one month) (Figure 1).

Figure 1. Unit Response



If defined using an analytical solution such as the Glover-Balmer equation[2], one hundred percent of the depletion or accretion volume is ultimately manifested as an impact at the nearest point on a hydrologically connected river. This often provides a conservatively high accretion or depletion volume. In many cases a significant portion of the pumped water is derived from a decrease in shallow evapotranspiration (ET), infiltration of previously rejected aquifer recharge, a permanent decrease in aquifer storage (aquifer mining), or induced infiltration from sources of water other than the nearest

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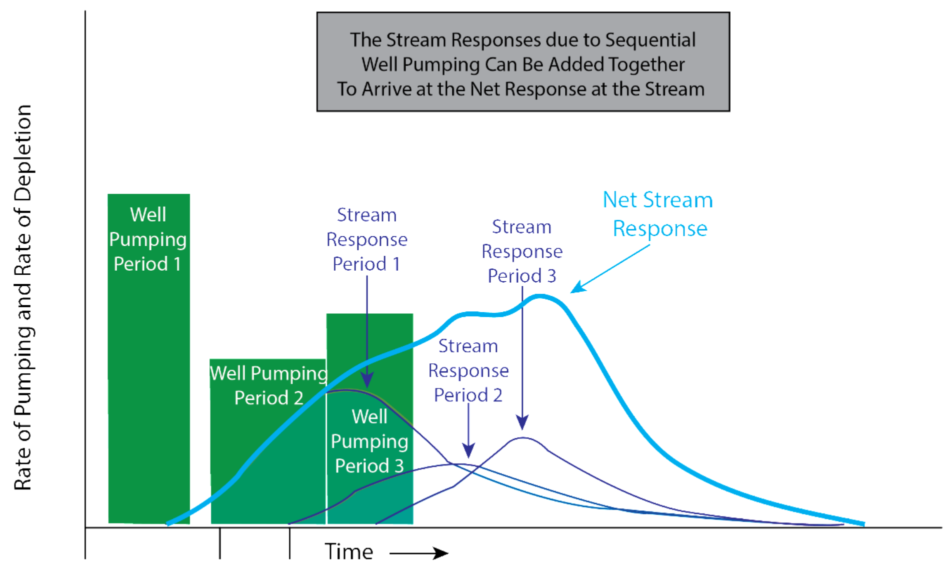
[1] URFs are the same whether depletion (from well pumping) or accretion (from aquifer recharge or groundwater return flows) is being calculated. For readability, some text in this technical memorandum refers to just depletion or accretion when discussing URF effects in general; any general comments about URF timing, however, apply to both accretion URFs and depletion URFs.

[2] Glover, R.E., and G.G. Balmer. 1954. River depletion resulting from pumping a well near a river. Trans. Am. Geophysical Union 35, 468-470.

stream[3]. In his classic 1940 paper on the sources of water derived from a pumping well, C.V. Theis concludes "All water discharged by wells is balanced by a loss of water somewhere. This loss is always to some extent and in many cases largely from storage in the aquifer. Some groundwater is always mined."[4] However, for hydrologic settings such as our URF model boundary where a well or recharge site (i.e., irrigated parcel) is in an unconfined aquifer that is hydraulically connected to flow in a nearby stream, the Glover-Balmer method is judged to be a reasonably accurate simplification of a more complex system.

An analytical solution URF can be applied to complex recharge and pumping schedules with varying rates and can account for the combined effects of multiple wells, ditch loss return flows, and irrigation return flows (Figure 2).

Figure 2. Combined Unit Response Functions



The overall goal of creating the URFs under ArkDSS Task 2.8 is to examine the timing, location, and amount of depletions and accretions in a large portion of CDWR Division 2 at the "planning model" level (see "Planning Level Model Discussion" section).

The Glover-Balmer equation (Figure 3) is a modification of the Theis equation[5]. The Theis equation predicts water level changes over time due to pumping or recharge for varying distances and aquifer properties. The Glover-Balmer equation extends the Theis equation by modeling the effects of a stream. Glover-Balmer adds a stream that fully penetrates the aquifer and can provide or receive all accretions and depletions (in effect acting as the boundary of accretion or depletion impacts). The Glover-Balmer

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[3] Konikow, L.F. and Leake, S.A., 2014. Depletion and Capture: Revisiting "The Source of Water Derived from Wells". USGS Staff published research 832.

[4] Theis, C.V. 1940. The source of water derived from wells – Essential factor controlling the response of an aquifer to development. Civil Engineering 10: 277-280.

[5] Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am Geophys. Union Trans., vol. 16 pp. 519-524.

equation and associated URFs are not affected by the volume of pumping or recharge (i.e., the URF timing pattern is the same regardless of recharge or pumping volume).

Figure 3. Glover-Balmer Response Function

$$\frac{q}{Q} = \mathrm{erfc}\left(\frac{a}{\sqrt{\frac{4tT}{S}}}\right)$$

Where:

q = rate of depletion to stream (L^3/t)

Q = rate of pumping or recharge (L^3/t)

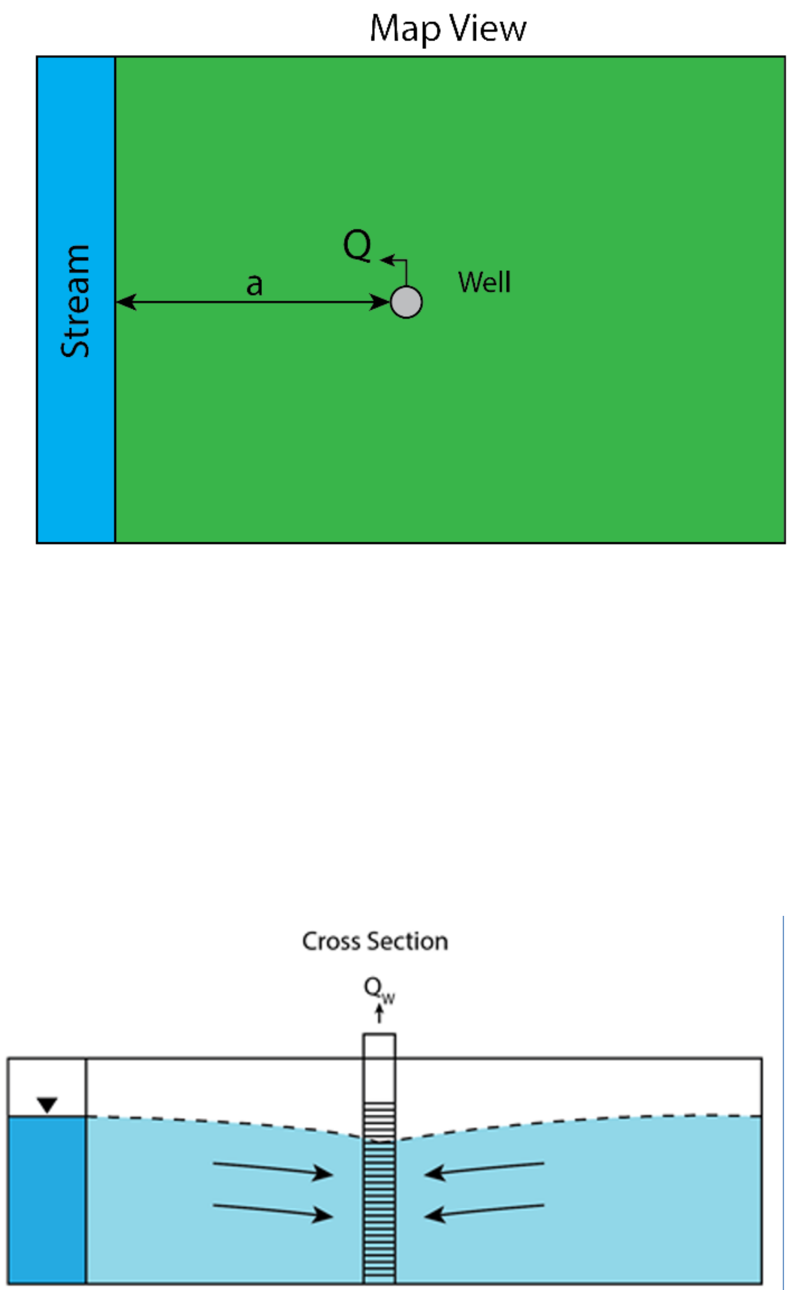
a = shortest distance from well or recharge point to stream (L)

t = time (t)

T = aquifer transmissivity (L^2/t)

S (or S_y) = aquifer specific yield (unitless; percentage)

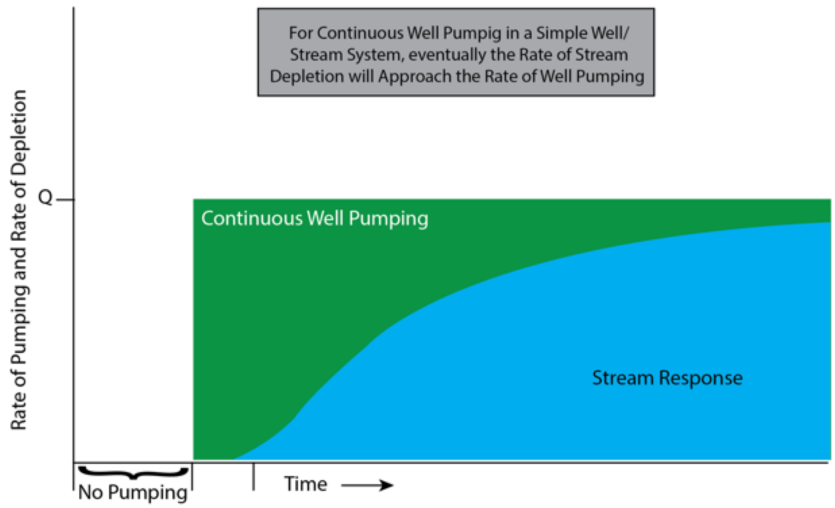
erfc = complementary error function



Response Function

The equation shown in Figure 3 solves for the ratio of the rate of stream depletion (q) to the rate of well pumping (Q). Given the assumption that all pumped water is ultimately drawn from the stream, over time q/Q approaches 1 with continuous pumping (i.e., the rate of stream depletion eventually equals the rate of pumping). Once the well is turned off, post-pumping depletions continue to impact the stream. A graph of q/Q is referred to as a **response function** graph (Figure 4).

Figure 4. Response Function – depletion rate approaches pumping rate over time



The **unit** response function shows the rate of depletion over time for just a unit volume and a unit time of pumping.

Stream Depletion Factor and Sensitivity of Distance to River

Jenkins (1968)[6] used the Glover-Balmer equation to define a term called the "Stream Depletion Factor" (SDF). Jenkins uses the same solution as Glover-Balmer, but the SDF term provides a useful means to understand the relatively large effect of **distance** on stream depletion and accretion timing as opposed to the aquifer properties of transmissivity and specific yield. The SDF is the time (typically reported in days) from the start of continuous pumping until the time that the cumulative depletion is 28 percent[7] of the pumped volume.

[6] Jenkins, C.T., 1968. Techniques for computing rate and volume of stream depletion by wells, Ground Water, vol. 6, no. 2, pp. 37-46.

[7] The 28 percent number was used because it simplifies the SDF definition in Jenkins (1968) and makes the defined SDF value easier to use in depletion timing calculations.

Figure 5a. SDF Equation

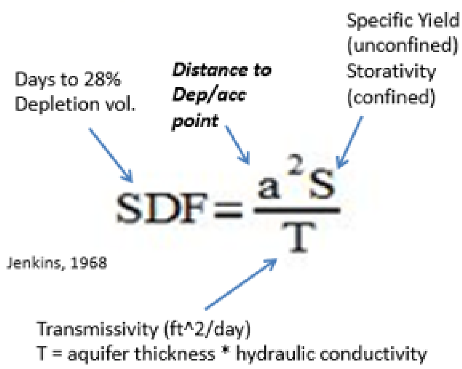


Figure 5b. Example of Changing Distance and Transmissivity

a (feet)	Sy	T (ft2/day)	SDF (days)
100	0.2	1000	2
200	0.2	1000	8
100	0.2	1000	2
100	0.2	2000	1

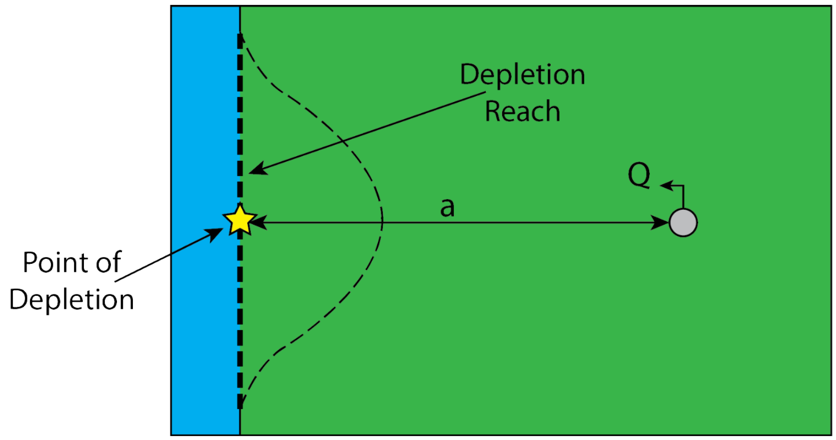
Using the units shown on Figure 5a, The SDF term is the time (in days) when 28 percent of accretions or depletions have accrued to the river. As shown in Figures 5a, the distance to the point of accretion or depletion (i.e., the distance to the river, defined as 'a') is the only term with an exponent greater than one in the equation. This means that the SDF value is very sensitive to the squared distance term (a) as opposed to the aquifer property terms (S or S_y, T). Figure 5b presents example SDF input variables where the distance (a) is doubled from 100 to 200 feet and example values where aquifer transmissivity (T) is doubled (from 1000 to 2000 ft^2/day). Doubling the distance from 100 to 200 feet increases the SDF by 400 percent (six additional days), while doubling aquifer transmissivity only decreases the SDF by one day.

Considering the sensitivity of the distance term in the SDF (and URF) results, our approach included a high degree of spatial discretization using a "banded URF" layout discussed later. For the current URF area, the value of the distance to river term (a) in the URF solution is typically more certain and finely discretizing the URF distances has a larger benefit in terms of URF accuracy than could be obtained by contouring detailed maps of hydrogeologic properties (e.g., S_y, T contour maps). There are few rigorous tests of aquifer properties outside of the HI Model area.

URF Point of Depletion / Accretion

Both the bounded and unbounded analytical Glover methods use the shortest distance to the river to define the distance term used in the equation. The actual depletion or accretion effects are spread along a reach of the river, with the total effect integrated along the river (Figure 6).

Figure 6 URF Groundwater Zones



The depletion reach is relatively short for wells located near the river, but can extend for miles for wells (or recharge sites) located far from the river. Glover (1978)[8] includes a solution that can be used to estimate the depletion amount by river reach within the depletion reach (for the unbounded aquifer case). Most of the Arkansas basin irrigated acreage is located within the flat irrigable lands adjacent to rivers, so in most cases using the shortest distance to the river provides a reasonable representation of accretion location. Areas that are farther from the river will typically have a larger accretion reach.

Planning Level Model Discussion

Due to geologic heterogeneity in the large study area and guidance from Wilson Water Group (WWG), Colorado Water Conservation Board (CWCB), and Colorado Division of Water Resources (CDWR) to limit the maximum number of unique URFs and the maximum response time to twenty years, the URFs presented herein are viewed as a planning-level deliverable that HRS anticipates will be modified to some degree by the CDWR, CWCB, and/or WWG prior to importing the final URFs into StateMod for use in ArkDSS depletion and accretion timing calculations. Our Task 2.8 approach balanced the need to provide reasonably accurate depletion and accretion patterns over a large area using the available data with the generalized level of URF detail needed to provide useful input to the StateMod model.

Various methods of modeling more complex hydrogeologic scenarios, such as the United States Geologic Survey's (USGS) MODFLOW groundwater model code or finite element modeling codes, can also be used to create URFs. If adding hydrogeologic complexity is supported by the data, a MODFLOW model would allow for a more detailed and accurate timing estimate. Creating a regional MODFLOW model, however, requires sufficient data and would be a major undertaking for such a large area for the sole purpose of developing URFs. That being said, there is the potential that a regional MODFLOW model for the ArkDSS

[8] Glover, Robert E. 1978, Transient Ground Water Hydraulics, Water Resources Publications, Fort Collins, CO, 413 pages, see: chapter 10, pp 149-155 for bounded aquifer solution.

will be developed in the future for larger planning purposes, at which point MODFLOW-derived URFs could be developed and used to revise the URF estimates developed in this task. In our professional judgement, using the relatively simple Glover-Balmer analytical solution for Task 2.8 is a reasonable approach given: 1) the task goals, 2) the proximity of most alluvial wells to the depleted reach, 3) the lack of detailed hydrogeologic data in many areas, 4) the need to limit the number of URFs, 5) the proximity of most ditches and irrigated parcels to the river, and 6) the overall hydrogeologic conceptual model of shallow alluvial aquifers.

In some areas, CDWR/CWCB may wish to use the Task 2.8 GIS coverages along with site-specific aquifer property reports (see Appendix B) as a starting point to develop a more detailed analytical URF calculation or a groundwater numerical model. For example, the alluvium of Fountain Creek may be a worthwhile location for additional modeling given the relatively high amount of geologic data in the area and its and importance to CDWR Division 2 water users. The USGS is currently in the process of creating a MODFLOW model of the Wet Mountain Valley area[9] (Water District 13). Once completed, the USGS' Wet Mountain Valley groundwater model and hydrogeologic data release could be used to update the URFs in this area.

While URFs were not calculated within the HI model area under this scope of work, HRS completed a driller's log database and aquifer transmissivity post map using well data within the HI model area and Fountain Creek drainage (See HRS memorandum for ArkDSS Task 2.7.1 Drillers Log Database). That work will facilitate updated aquifer mapping and possible future modeling of those areas.

URF Tail Wrapping

URF patterns often have a very long "tail", or period of time past the peak of the graphed URF where accretions extend far into the future, often at very low rates (e.g., Fig 1). In Colorado water rights work, it is customary to truncate the final 5 percent of the accretion volume and add that volume back into the previous 95 percent of the URF. The total of the wrapped URF should be 100 percent. CDWR specified that URFs should be limited to a maximum time of 20 years to reach 95 percent accretions.

The SDF value multiplied by 128 provides the time (in days) for 95 percent of depletions or accretions to accrue. The SDF value multiplied by 32 provides the time (in days) for 90 percent of depletions or accretions to accrue. The number of days required to account for 95 percent of depletions is four times longer than the number of days required to account for 90 percent of depletions. Given CDWR's guidance to limit the URFs to a maximum of twenty years, we recommend that the final ArkDSS URFs wrap the last 10 percent of the URF tail. This approach will capture the majority of the response and will significantly speed up the late time URF and associated small rate of accretions. It will also simplify StateMod modeling input without changing the total ultimate accretion or depletion volumes.

HRS prepared a URF spreadsheet (Appendix A) that includes URFs for both a 5 and 10 percent tail wraps using the Glover-Balmer solution.

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[9] Connor Newman, P.G., Hydrologist, United States Geological Survey. Personal communication with M. Seitz, HRS Water Consultants, Inc. February 2020.

Approach and GIS Coverages

In coordination WWG, CDWR, and CWCB, HRS created three GIS coverages that can be used in conjunction with our estimated average aquifer properties to prepare URFs for most of the irrigated acreage, alluvial wells, and ditch return flow areas included in Task 2.8. The three coverages are listed below and described in more detail in the following sections.

1. **URF Boundary**: The URF boundary coverage is HRS' interpretation of areas where surface water and alluvial[10] groundwater are in hydrologic connection with a perennial (or nearly perennial) stream reach of the Arkansas River or one of its tributaries.
2. **URF Reaches**: The URF reaches coverage contains stream reaches within the URF boundary coverage that are judged to be perennial or nearly perennial and to typically be in hydrologic connection with the Arkansas River.
3. **URF Bands**: The URF bands coverage contains a series of bands located at specified distances from the URF reaches coverage. The irrigated fields, alluvial wells, and ditch reaches within each band are assigned a set distance from the stream for use in URF timing.

Appendix C contains these GIS coverages. The coverages are provided in ESRI's Map Package format (.mpk) for viewing using ArcGIS™. The GIS coverages are also provided in shapefile format which can be imported using other commercial software or a free open source GIS such as QGIS.

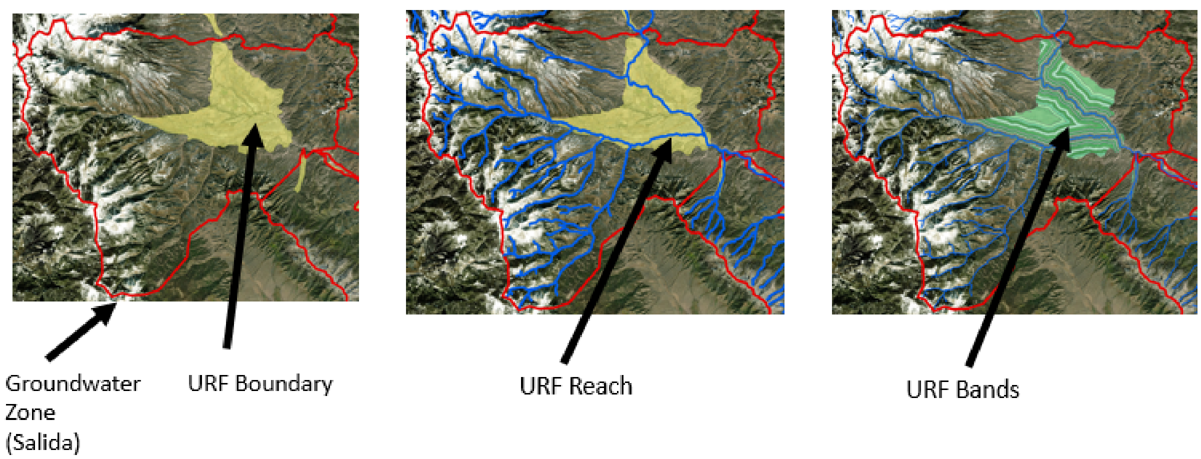
As noted earlier in this report, the distance from the accretion point to the stream (i.e., the URF Reach) is a highly sensitive and relatively clear-cut parameter in the Glover-Balmer analytical solution. The enhanced spatial discretization provided by the URF band method greatly improves URF accuracy compared to estimating the distance to the stream using just one generalized recharge point that represents the spatial centroid of numerous irrigated parcels.

The features in each of the above GIS coverages are located within "Groundwater Zones". The groundwater zones coverage was created by CDWR and is used to subdivide CDWR Division 2 into smaller areas of interest, often with similar hydrogeologic and/or administrative conditions. The groundwater zones coverage is delineated using a mix of several criteria including CDWR Water District, surface water drainage basin (i.e., Hydrologic Unit Code or HUC), county, Designated Basin, and HI Model area. In some cases, a groundwater zone is based on multiple boundaries, such as Designated Basin and Water District. While the GIS deliverables cover the entire study area, they can be cropped by Groundwater Zone for cases where the entire study area coverage is not needed. HRS tracked much of the geologic data we reviewed according to its Groundwater Zone (see Appendices B and C). Figure 6 presents the location of the Groundwater Zones in CDWR Division 2. Figures 7a-7c present an example of the GIS deliverable coverages within the Salida Groundwater Zone.

[10] Alluvial groundwater is stored within the pore spaces of unconsolidated (non-cemented) alluvium such as sand, silt, and gravel.

Figures 7a-7c. Example of GIS Coverages used in URF Development

7a. URF Boundary 7b. URF Reach 7c. URF Bands



HRS reviewed over 1,000 well records, 25 geologic reports, and numerous topographic and geologic maps across CDWR Division 2 to prepare the URF Boundary coverage and to assign estimated aquifer properties.

Approach Constraints

HRS' URF approach was designed to limit the total number of URFs to a hydrologically representative but logistically manageable number for input to StateMod. HRS elected to use the Glover-Balmer (1954) version of the depletion/accretion solution, commonly referred to as the "unbounded" or "semi-infinite aquifer" version for the following reasons:

- Using the "bounded" version of the Glover equation (Glover, 1978), which includes a stream boundary **and** a no-flow boundary at the edge of the aquifer, greatly increases the number of URF zones. When using the bounded Glover URF approach, it is not possible to assign the actual distance to the aquifer boundary to each band as this varies within each band (i.e., the bands are defined by the distance from the river and cannot be defined by the distance from the river **and** the (varying) distance from the aquifer boundary.
    - CDWR has prepared a modified version of HRS' URFs that uniformly assigns the farthest distance to a no-flow boundary to each URF band. This is a reasonable modification that will speed up the URFs. See CDWR's Task 2.8 memo.
    - Wrapping the last 10 percent of the URF, as recommended by HRS, also speeds up the URF.

- URF timing using the unbounded version of Glover is essentially the same as the bounded version for cases where the distance to the aquifer boundary is greater than about five times the distance to the river. This is the case for much of the irrigated acreage in CDWR Division 2, which tends to be close to the river relative to the aquifer boundary.

URF Boundary Coverage

The URF Boundary coverage was created using an Arkansas Alluvial Aquifer GIS coverage provided by CDWR as a starting point. This alluvial aquifer coverage contained extensive mapping of the Arkansas River alluvium and tributary alluviums in CDWR Division 2. However, the coverage did not include all areas of unconsolidated saturated alluvial material and areas where alluvial groundwater is in connection with the Arkansas river system. HRS examined topographic maps and over 1,000 well logs to assess the extent of additional unconsolidated deposits that would act as a groundwater flow return pathway for irrigated lands or pathway for pumping depletions. HRS examined the well logs for unconsolidated near surface sand and/or gravel deposits as well as signs of saturated thickness as evidence to expand the original alluvial aquifer coverage. Figure 8 shows the original CDWR alluvial aquifer coverage and the expanded alluvial coverage used to define the URF Boundary coverage. Topographic maps and geologic reports were also used to interpret areas of saturated unconsolidated valley-fill or river deposits. The original alluvial coverage covered approximately 1,100 irrigated fields. The expanded coverage (the URF Boundary coverage), included approximately an additional 3,500 irrigated fields. Developing the URF boundary coverage was a time-consuming but important portion of Task 2.8.

Areas Outside of URF Boundary Coverage

Some irrigated parcels, ditches, and wells are not underlain by saturated alluvium. These areas often overlie thin partially saturated soils which are underlain by low-permeability bedrock formations (such as the confined Pierre shale). These geologic settings typically result in a URF that is much longer than 20 years. They also involve much more geologic complexity and uncertainty than can reasonably be accommodated using analytical solutions such as bounded or unbounded Glover. The complexities imposed by partially saturated vadose zone flow and changes in the unconfined versus confined conditions in the aquifer(s) render analytical equations not well suited for calculating URF timing outside of the URF Boundary coverage.

For cases outside of the URF boundary coverage where CWCB/CDWR/WWG believe that applied irrigation water is returning to the river system faster than 20 years, we recommend assigning a fixed percentage of applied water as instantaneous return flow based on the Water Commissioner's and/or others' knowledge of local irrigation practices and runoff patterns. This return flow pattern occurs where irrigation water is applied, but the underlying thin soil and bedrock aquifer cannot readily infiltrate and move the applied water because it is not composed of permeable alluvium; in such cases, the non-consumptive portion of the applied water may collect in local drainages and be transported to the river quickly as surface water flow. In these cases, the applied water should be treated as surface runoff rather than lagged groundwater return flows with an associated URF. One such area exists in the Penrose area north of the Arkansas River (Figure 6). This area contains significant irrigated acreage that overlies low-permeability bedrock (i.e., there is no alluvium beneath many of the irrigated parcels). Smaller but similar areas include irrigated parcels at the center of Water District 15 and Two Butte Creek.

URF Reach Coverage

The URF Reach coverage represents the streams and rivers that are either perennial or are typically in hydrologic connection with the Arkansas River. The URF Reach coverage was used in GIS to create the buffered zones of distances to the stream or river. HRS used the USGS' National Hydrography Dataset (NHD) as a starting point to identify perennial river reaches connected to the Arkansas River (Figure 9). The NHD dataset contains mapped streams, rivers, canals, artificial paths, etc. and sub-classifications such as intermittent, ephemeral, or perennial streams. HRS reviewed two main sub-classifications in the NHD:

- FCODE 55800 – denoting an artificial path.
- FCODE 46006 – denoting a perennial stream/river.

In addition to the above NHD codes, HRS considered these factors:

1. Almost the entirety of the Arkansas River (main channel) was denoted as an Artificial Path, in the NHD coverage, so other Artificial Path reaches were evaluated to see if they needed to be included.
2. If Groundwater Zones or stream reaches were noted as a "futile call' area or reach by CDWR, any discontinuous perennial reaches in these areas were not included.
3. Any perennial reaches overlying a Designated Groundwater Basin were not included. By definition, Designated Basin Groundwater does not impact the surface water system.

Due to the methodology used to create the NHD dataset, there are numerous "small flecks" of perennial stream/river ranging from a few feet to a few hundred feet long. These were scattered throughout the entire dataset and were often at least miles from a lengthy mapped perennial stream. Unless they had a clear connection to a nearby mapped perennial river, these were manually removed to allow for the creation of URF Bands. There were also similarly sized gaps in the perennial river coverage, again from a few feet to approximately a couple thousand feet. Due to the highly variable and discontinuous nature of the reach "fleck" issue, the project team decided to treat these gaps as artifacts of the NHD dataset's creation process and manually reconnected these streams perennially with the Arkansas River. Like the URF Boundary GIS work, this process was time-consuming but important.

The Groundwater Zones and stream reaches designated as a futile call indicate that changes to the accretion or depletion pattern are not expected to result in the resumption of live flow to the Arkansas River, and therefore do not need to be treated as being hydrologically connected to the river and modeled using a URF. Per the NHD dataset, there are large perennial reach gaps, primarily in the western Groundwater Zones that were not just a short distance (i.e., a few hundred feet like discussed above), but on the order of five to ten miles. CDWR Districts 16, 18, 79, and Fountain Creek did not have a futile call designation but had large perennial gaps in tributaries to the Arkansas River such as the Cucharas, Huerfano, and Apishipa rivers. Along with these larger tributaries, there were also smaller areas within Groundwater Zones that had a sizeable amount of irrigated acreage near an intermittent stream, such as the Blackwell Arroyo or Jimmy Camp Creek. After conversations with CDWR Division 2 staff and the local Water Commissioners, the team decided to include both the main tributaries and selected smaller tributaries in the URF Reach coverage and treat them as being perennial to the Arkansas River and include their associated mapped irrigated acreage by creating the URF Boundary coverage in these areas.

URF Band Coverage

HRS created twenty URF Band zones based on distance from the URF Reach coverage and bounded by the URF Boundary coverage.

Table SEQ Table * ARABIC 1. Buffered URF Zone Distances and Percent of 2015 Irrigated Acres within Each Zone (5 percent wrap)

Zone Information						
zone	Start Distance	End Distance	Mid Distance	Range size	Percent of Parcel Centroids in Range	Cumulative Percent
1	0	200	100	200	4.10%	4.10%
2	200	400	300	200	9.51%	13.61%
3	400	600	500	200	9.03%	22.64%
4	600	800	700	200	7.57%	30.21%
5	800	1000	900	200	5.52%	35.73%
6	1000	1400	1200	400	9.53%	45.26%
7	1400	1800	1600	400	5.96%	51.22%
8	1800	2200	2000	400	5.58%	56.81%
9	2200	2600	2400	400	4.62%	61.43%
10	2600	3000	2800	400	4.01%	65.44%
11	3000	3500	3250	500	4.23%	69.68%
12	3500	4000	3750	500	3.90%	73.58%
13	4000	5000	4500	1000	5.50%	79.08%
14	5000	6000	5500	1000	4.28%	83.35%
15	6000	7000	6500	1000	3.18%	86.54%
16	7000	8000	7500	1000	2.07%	88.61%
17	8000	11000	9500	3000	5.04%	93.65%
18	11000	14000	12500	3000	2.88%	96.53%
19	14000	20000	17000	6000	2.68%	99.21%
20	20000	35000	27500	15000	0.79%	100.00%

Because URF timing quickly becomes longer with increasing distance and distance is typically the most well-known parameter in a URF calculation, care was taken to include less than ten percent of the approximately 4,500 irrigated parcels in each URF band (based on the 2015 irrigated acreage coverage). The width of the bands starts out more finely discretized near the URF Reaches (i.e., 200-foot wide bands) and increases with increasing distance from the URF Reach, ending at maximum URF Band thickness of 15,000 feet between 20,000 and 35,000 feet from the reach. As can be seen in Table 1, there is a much larger density of irrigated acreage close to the URF Reaches than farther away. Over half of the irrigated acreage is included within the first seven URF Bands (i.e., within 1,800 feet of the river).

This method worked well in most areas of CDWR Division 2, but not in a few select areas where irrigated acreage was closer to a URF Reach which was located in an adjacent but hydrogeologically disconnected valley that was separated by an unsaturated zone or bedrock outcrop. This most often happened in small branching tributaries with alluvium or areas like the Cañon City floodplain. In these cases, additional buffered URF Bands were created using a single point deemed as the nearest hydrogeologic connection, assigning a more accurate distance to the irrigated acreage in these areas.

Aquifer Properties

Along with the distance to the river, the aquifer properties of transmissivity (T)[11] and specific yield (denoted as "S_y" for an unconfined aquifer)[12] are variables in the Glover-Balmer equation. HRS reviewed 25 hydrogeologic reports that covered large parts, but not all, of the study area. Many reports focus on the HI Model area due to its economic importance and high use of alluvial groundwater with fewer data available outside of the HI Model area. CWCB and the Colorado Geological Survey (CGS) published a helpful compendium of hydrogeologic reports in CDWR Division 2[13]. The CWCB/CGS study includes full references and notes on which reports include data on aquifer properties. It also has a GIS coverage that spans each report's study area to allow for location-based searches for all reports in an area. HRS also created a GIS coverage of the location and T and S_y values of CDWR Division 2 aquifer tests from CWCB's Circular 11 (the "Rainbow Book"). The third major source of aquifer property data was CDWR drillers' logs and pump installation and testing reports. The pump installation reports were used (primarily in the five Fountain Creek Groundwater Zones) to prepare an estimate of transmissivity using pumping rate and water level drawdown data[14].

Due to the large study area, the limited aquifer property data, and the need to maintain a manageable number of URF zones, HRS reviewed the above sources of geologic information and used it to define three regions in the study area with fixed T and S_y values (Table 2).

Table 2. Aquifer Regions and Properties

Code	Region / Depositional Environment	Transmissivity (gpd/ft)	Specific Yield (%)
A	Lower Basin channel of Ark River or Fountain Creek; higher hydraulic conductivity sand/gravel deposits	160,000	0.23
B	Upper Ark thick glacial deposits and gravel	60,000	0.15
C	Thinner sandy/silty alluvium on side tributaries	30,000	0.18

[11] Transmissivity is a measure of the ease of groundwater flow through a unit width of aquifer. It is equal to hydraulic conductivity (similar to permeability) multiplied by aquifer thickness. Transmissivity is often reported in units of gpd/ft or ft2/day.

[12] Specific yield is the percent of water per unit volume of aquifer material that drains by gravity.

[13] Topper, Ralf, October 2008. Aquifer Studies in the Arkansas River Basin – A Digital, Geographic Bibliography. Colorado Geological Survey.

[14] ASTM Standard D5472/D5472M-14. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well. http://www.astm.org/cgi-bin/resolver.cgi?D5472D5472M-14

Figure 10 shows the aquifer regions and properties labelled with the codes in Table 2. As much of the documentation used to derive the above aquifer property estimates is lengthy, Appendix D contains HRS' notes on the hydrogeology and streams for selected Groundwater Zones.

Generalizing heterogeneous aquifer properties over the large study area required taking a 'big picture' view of the approximately or reasonably representative properties for the regions. If more site-specific aquifer properties are needed, they may be available in one of the reports listed in the CGS spatial bibliography or in Appendices B or D. HRS limited the review of reports in the CWCB/CGS spatial bibliography to those references that, 1) were part of either "small" or "medium" sized studies as defined by CGS, 2) were flagged by CGS as containing aquifer property data, 3) were not only located within the H-I Model area, and 4) contain at least some irrigated acreage.

URF Results and Notation

The Appendix A spreadsheet[15] provided with this report contains the URFs for the 5 percent and 10 percent URF tail wrap conditions. The URFs are calculated on a daily basis using the median distance to the river for each URF band and the aquifer properties for the area. Each URF in Appendix A includes a "URF_CODE" that uniquely identifies the parameters used to calculate the URF pattern. The URF code is comprised of:

<mid point distance of buffered zone to stream>_ <aquifer specific yield>_ <aquifer transmissivity in gpd/ft>

For example, URF banded zone 5 in Table 1 has a buffered zone midpoint distance of 900 feet. If this zone was located in the Upper Ark glacial deposit area (S_y = 0.15 and T = 60,000 gpd/ft) its URF code would be 900_15_60000. The URF Appendix A spreadsheet includes the URF_CODE for all patterns that achieve over 90 or 95 percent accretions within twenty years.

Tail-Wrapped URF Results

Tables 3 and 4 indicate with an 'x' which banded URF zones reached 95 percent and 90 percent for the given distance and regional aquifer property group (codes A, B, C in Table 2).

Table 3

95% URF Zones Included

Mid Distance	A	B	C
100	x	x	x
300	x	x	x
500	x	x	x
700	x	x	x
900	x	x	x
1200	x		x
1600	x		x
2000	x		
2400			
2800			
3250			
3750			
4500			
5500			
6500			
7500			
9500			
12500			
17000			
27500			

20 total

Table 4

90% URF Zones Included

Mid Distance	A	B	C
100	x	x	x
300	x	x	x
500	x	x	x
700	x	x	x
900	x	x	x
1200	x	x	x
1600	x	x	x
2000	x	x	x
2400	x		x
2800	x		x
3250	x		x
3750	x		
4500	x		
5500			
6500			
7500			
9500			
12500			
17000			
27500			

32 zones total

As distance from the stream increases, some zones do not surpass more than 95 percent of accretions within twenty years. Accretions that take longer than twenty years will have very small accretion rates and small year-to-year changes as the impacts are attenuated over time. Using a 95 percent metric (i.e., wrapping the last 5 percent of accretions), there are 20 URF zones that extend as far as 2,200 feet from the stream that receives the accretions. Therefore, irrigated parcels that are past 2,200 feet from the stream do not meet the 20-year criterion and should be modeled as steady state accretions provided

[15] File: 20190813a_URFs.xlsx

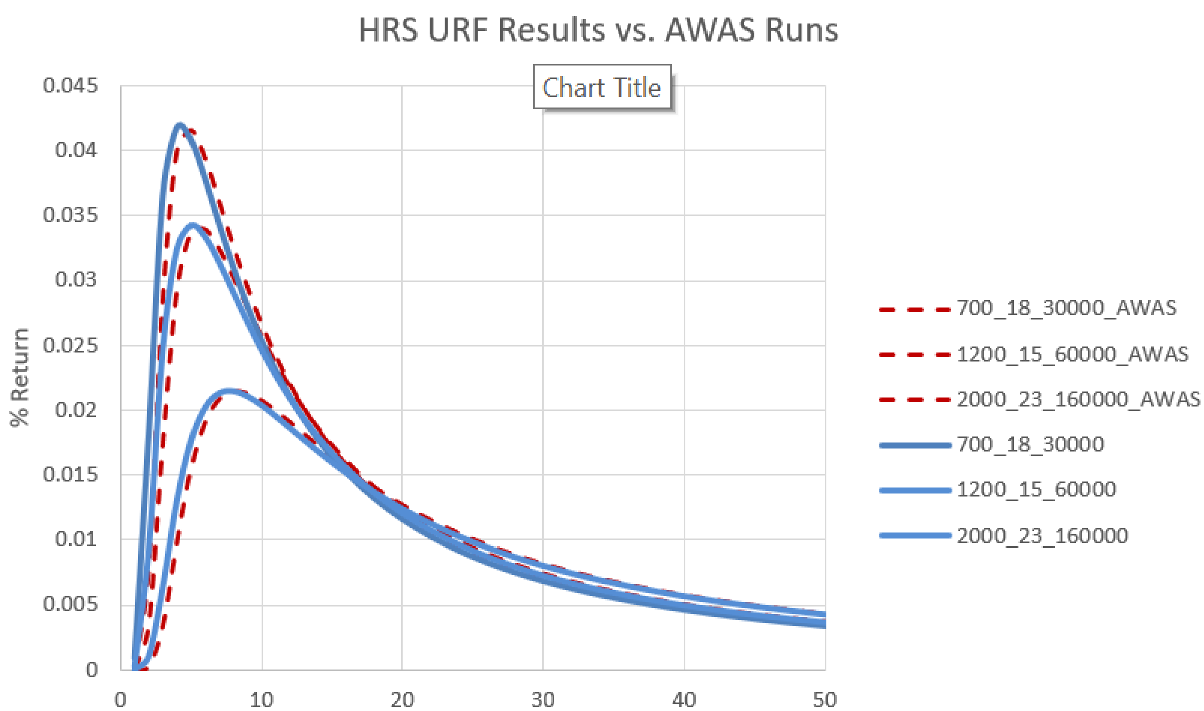
that the parcels have been irrigated consistently for a long period of time, or have a portion of irrigation water treated as instantaneous surface water return flow if local knowledge dictates.

HRS also prepared URFs for a 10 percent wrap condition. This resulted in 32 total URF zones.

Comparison of Results to AWAS

HRS completed a comparison of the Appendix A unbounded Glover-Balmer URF calculations against AWAS[16] (Alluvial Water Accounting System) results. This program, developed by Colorado State University, calculates river depletions with a user-specified method, in this case the Glover-Blamer method. The URF patterns representing the three different aquifer geologic reginal property groups were chosen and run against the AWAS results.

Figure 11.



The results match except for a small offset likely caused by the type of solver used by MSExcel and AWAS for the complementary error function. This step was completed to check the URF results in Appendix A using the widely accepted AWAS software.

[16] Downloaded from: http://www.ids.colostate.edu/projects.php?project=awas

Comparison to HI Model URF Method

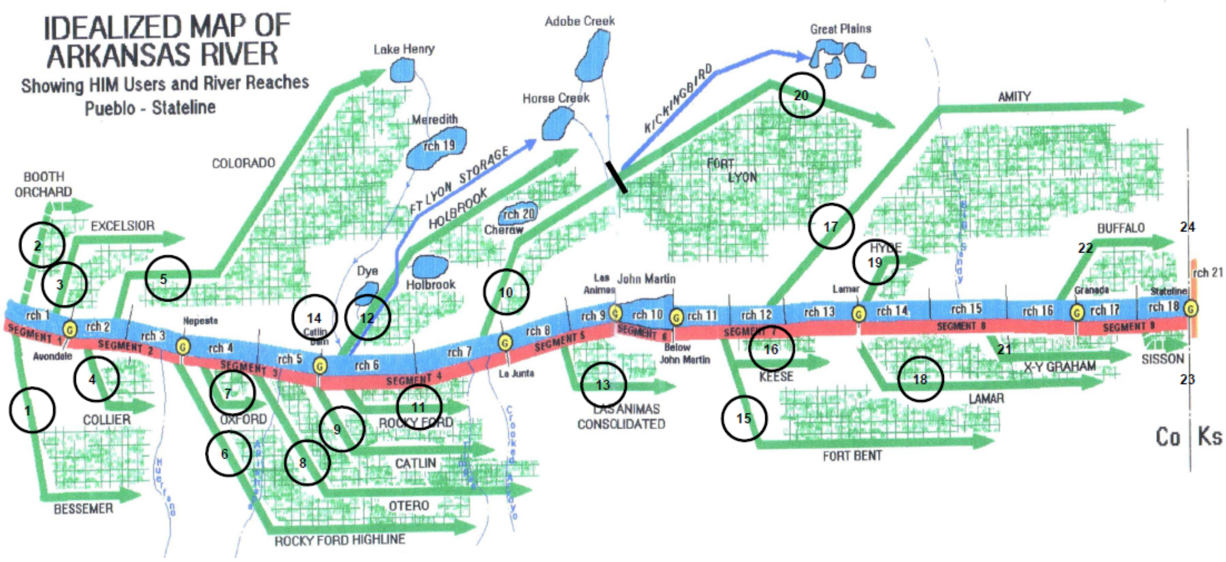
WWG requested that HRS compare example Task 2.8 URFs to URFs developed using the final HI model in the Kansas v. Colorado Supreme Court case. The following discussion of the HI model setup and URFs comes from the Special Master's 1994 Report[17], and discussions with CDWR and Principia Mathematica (a Colorado groundwater modeling firm involved in reviewing the HI Model work). HRS could not locate a technical report documenting the development of the final HI model URFs. Such a report would presumably include aquifer property data, the basis for the modeled aquifer boundary conditions, and other model input data used to develop the URFs.

We understand that the Court-selected HI Model runs from January 1950 through December 1985 and has two finite element model reaches - one reach extending from below Pueblo Reservoir to John Martin Reservoir, and the second reach extending from below John Martin reservoir to the State Line. The model accounts for major diversions, irrigation pumping, ET, groundwater inflows, and transbasin diversions among other factors. Each irrigation ditch service area was divided into a set of model nodes with modeled depletions and accretions from those nodes distributed to selected stream reaches. For each ditch service area, there are two URFs: one for groundwater depletions and one for surface water accretions. After an unsuccessful attempt to calibrate the model to groundwater levels, the model was calibrated to wintertime stream flows, although the reliability of this calibration was contested during the trial. The URFs were prepared by 'switching' pumping and recharge on and off in successive model runs, with the URF being calculated as the difference in modeled streamflow between the pumping and non-pumping modeled conditions. The HI model was reviewed and critiqued by Colorado's Experts DeWayne Schroeder (CDWR) and Devraj Sharma of Principia Mathematica among others. The HI model used for the final URFs was prepared by groundwater modelers representing the State of Kansas including Tim Durbin and Steven Larson.

In the HI Model there are 24 irrigated parcel groups linked to 21 discretized river reaches (and two reservoirs) for surface water accretions and groundwater depletions. The HI Model area, irrigated parcel groups ("Users"), and river reaches are shown in Figure 12. Most often a given ditch service area impacts multiple reaches and the response function patterns, developed on a monthly time scale, reflect both the response function and the portion of return flow or depletion that impacts each river reach. For example, Ditch Service Area 1 "Bessemer" returned 65% to reach 1, 25% to reach 2, and 10% to reach 3 of surface water return flows. As such, the response function for reach 1 sums to 65%, reach 2 sums to 25%, and reach 3 sums to 10%. For rough comparison to the HRS banded URF method, unit response functions in the HI Model can be developed by scaling the response function to reflect 100 percent.

[17] Littleworth, Arthur L. July 1994. Special Master's Report (Volume 2). Kansas v. Colorado No. 105. https://www.supremecourt.gov/SpecMastRpt/ORG105V2_071994.pdf.

Figure 12. Idealized Map of Arkansas River



While it is important to note they were created for different areas using different methods, HRS completed a comparison of two Task 2.8 URFs and HI Model URFs. We compared the reach-aggregated HI model surface water URFs for the Las Animas and Otero ditch service areas to Task 2.8 URF Bands 3250_23_160000 and 4500_23_160000[18]. These URF were selected for comparison on the basis of similar average distances to the river and presumed similar aquifer properties (although this is less certain as we did not find documentation of HI model aquifer properties).

The compared Task 2.8 URF patterns were chosen by selecting high transmissivity values (i.e., those judged to be closer to the HI model values) and URF bands where the distance to the river was close to the distance from the HI model's centroid distance to the river for the ditch service area. The HI Model URFs from each river reach were combined to create a single pattern representing the full URF to the river and then plotted against the example Task 2.8 URF patterns (Figures 13, 14, 15, and 16)

[18] URF Band is composed of: midpoint of band distance to river, the band's assigned specific yield, and the band's assigned transmissivity in gpd/ft.

Figure 13. Comparison of HI Model URF for Las Animas and Task 2.8 URF 3250_23_160000

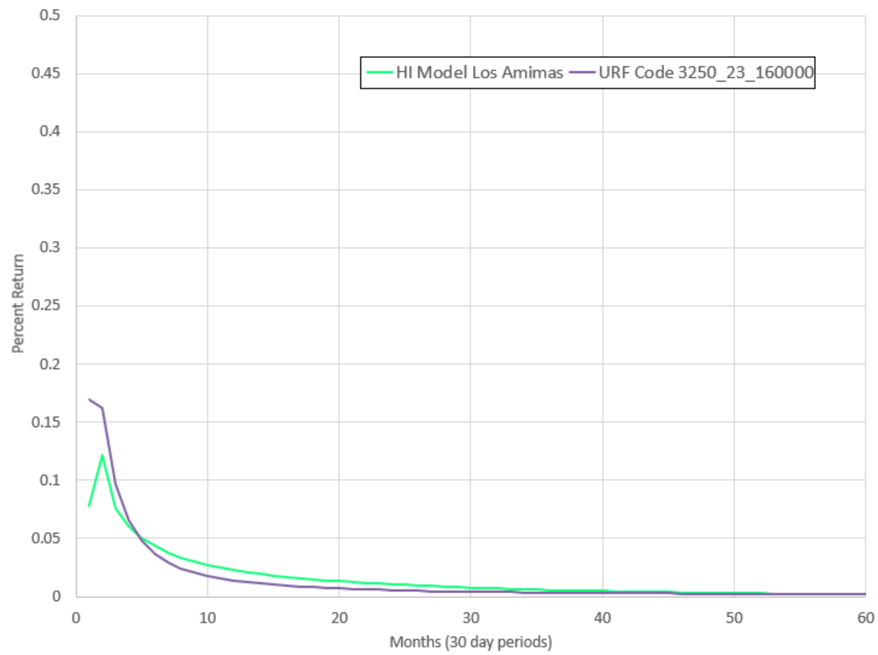
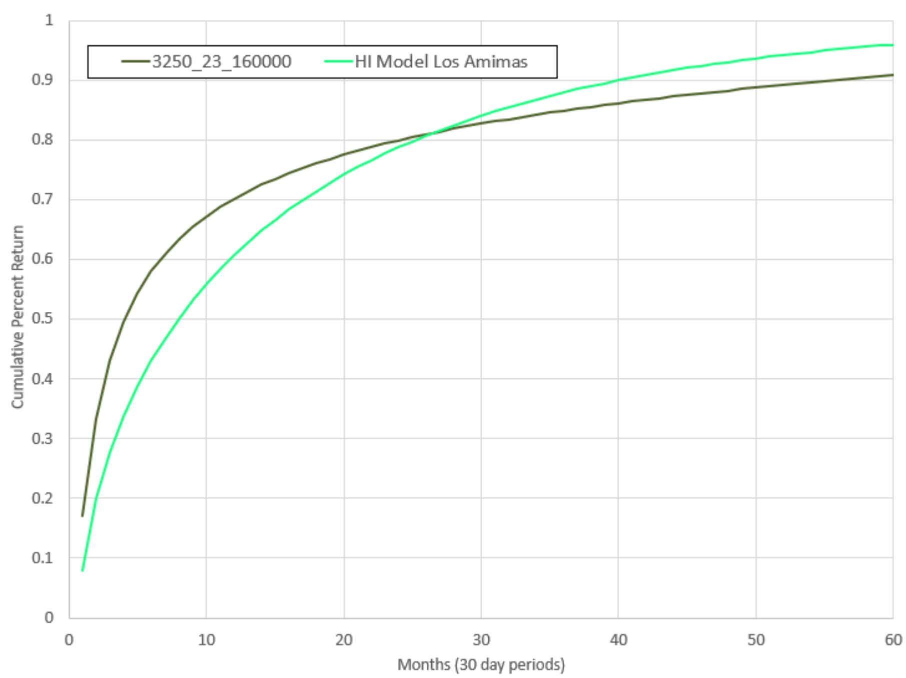


Figure 14. Comparison of HI Model URF for Las Animas and Task 2.8 URF 3250_23_160000 (Cumulative Return)



The results show a similar pattern between the example HI Model and Task 2.8 URFs when the distance to the stream value is similar.

Figure 15. Comparison of HI Model URF for Otero and Task 2.8 URF Code 4500_23_160000

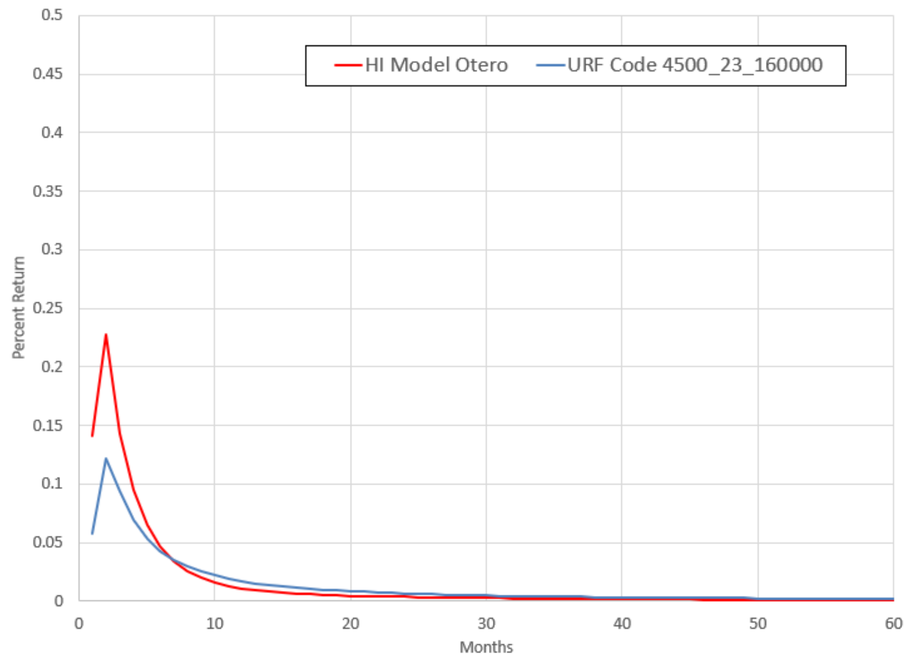
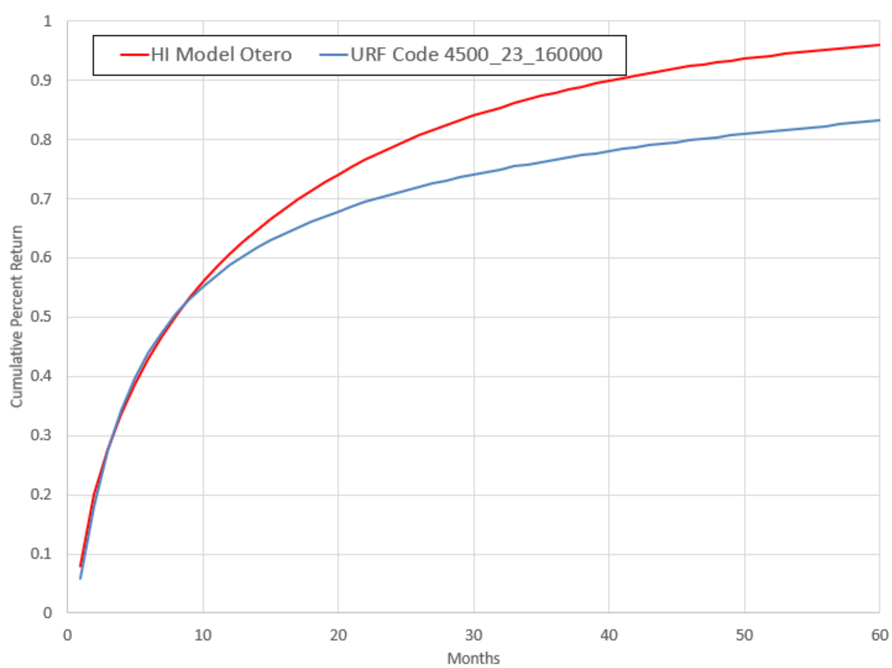


Figure 16. Comparison of HI Model URF for Las Animas and Task 2.8 URF 3250_23_160000 (Cumulative Return)

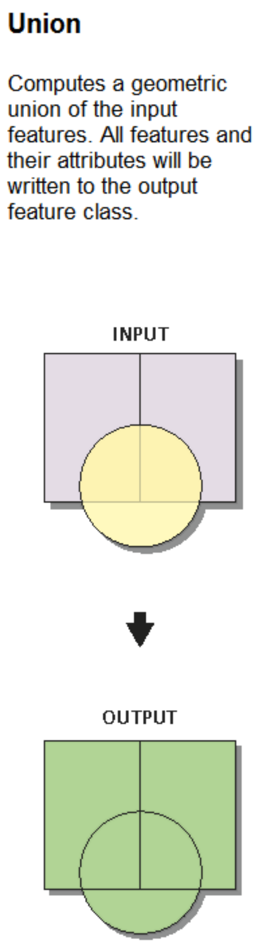


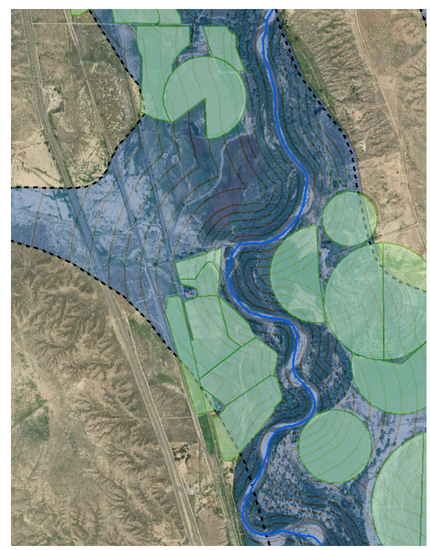
The results show a similar pattern between the example HI Model and Task 2.8 URFs when the distance to the stream value is similar.

Steps to Calculate Accretion Timing Using Irrigated Acreage and GIS Coverages

The steps below provide a description of how the URF Bands and URF spreadsheet can be used in conjunction with existing or future irrigated acreage coverages, alluvial well coverages, and ditch coverages to model accretions and depletions. The steps below refer to geoprocessing commands in ArcGIS, a commercial GIS, but these geoprocessing steps can also be completed using free open source GIS software such as QGIS.

Figure 17. URF Processing Steps





Steps to time accretions for irrigated acreages[19]:

1. Run Union tool with two input GIS coverages: Irrigated Acreage and URF Bands
2. Use Select by Location to select all portions of irrigated parcels that are within the URF boundary (shown in blue[20])

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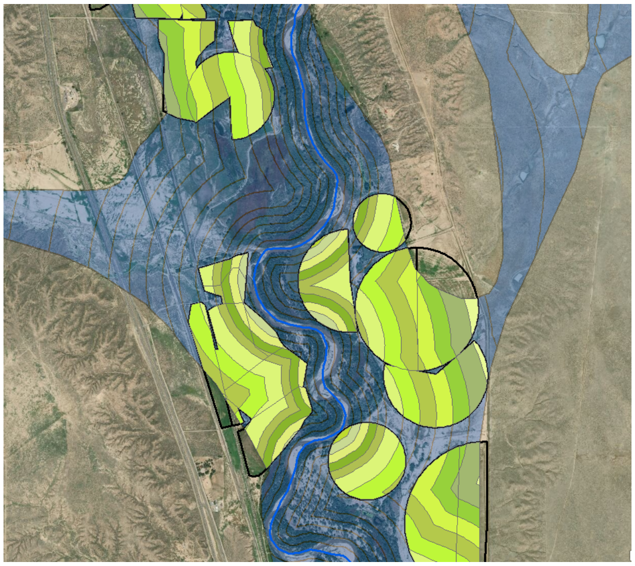
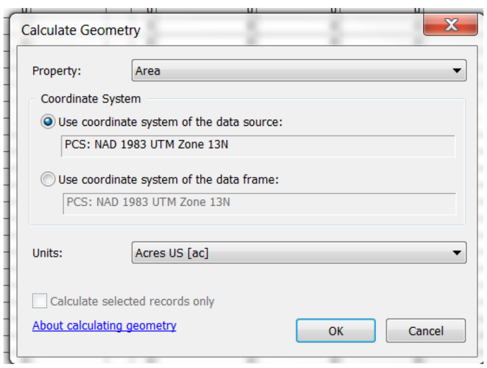
[19] This general process can also be used to assign URF zones to wells and URF zones to ditches prorated by length per URF zone for timing ditch loss return flows.

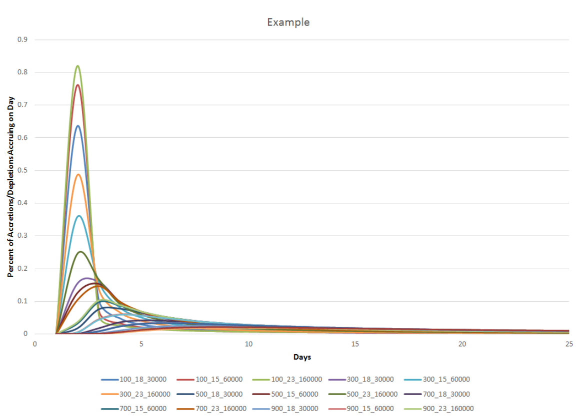
[20] Alternately, small areas in portions of parcels that are just outside of the URF Boundary could be included and assigned the properties of the neighboring URF band.



3. Export selected records to new GIS coverage. This coverage is all the irrigated fields within the URF boundary. All banded portions of a given field that are within the URF boundary now have an assigned URF_CODE based on the underlying URF Band coverage.
4. Make a new field in the coverage table; right click new field and use "Calculate Geometry" to calculate acreage for all parcels with assigned URF band properties.



5. Export GIS table to spreadsheet. Aggregate total acreage according to model input subregions (e.g., Groundwater Zone) and URF_CODE. After this step, the data will show the total acreage for each URF_CODE in the user-defined subregion.



6. Input acres and corresponding URF patterns from spreadsheet to model. Use URF patterns in spreadsheet to model timing based on crop CU and URF. (select either 5% wrap or 10% wrap [recommended] URF.)
7. Areas outside of URF zone: recommend treating as instantaneous surface water return flow (a percentage of applied water) or a steady state return flow based on local Water Commissioner's guidance.